UNIVERSITAT POLITÈCNICA DE CATALUNYA
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PROCEEDINGS OF

4th Edition

SYMPOSIUM ON SPACE EDUCATIONAL ACTIVITIES

April 27th, 28th, 29th 2022

Barcelona, Spain

Inspiring through space

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First edition: julio de 2022

Oficina de Publicacions Acadèmiques Digitals de la UPC
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ISBN: 978-84-19184-40-5

Preface

The 4th Symposium on Space Educational Activities (4th SSEA) was hosted at the Universitat Politècnica de Catalunya (UPC) · BarcelonaTech in Barcelona, Spain, from 27th – 29th April 2022. It was co-organized by the European Space Agency (ESA) and the UPC. The event represented the 4th edition of a successful Space Education symposium that began at the University of Padova, Italy, in 2015, followed by the 2nd Symposium hosted by the Budapest University of Technology and Economics, Hungary, in 2018, and the 3rd Symposium hosted by the University of Leicester, UK, in 2019.

This long-awaited edition exceeded all expectations and gathered more than 500 attendees in Barcelona. The 4th SSEA Organizing Committee developed a compelling outreach campaign that reached to more than 2000 departments and universities. It raised support from more than 10 private companies, and it had wide support from the local, regional and country-level institutions. During the three days of the event in UPC's venue Edifici Vèrtex, the attendees engaged in fruitful research discussions, established connections among the European sector and learned from the latest projects in space education and student-led projects.

The transformation of the space sector, as a result of new technology, business and policy trends, creates new challenges for the education system, which must adapt to new sector needs. NewSpace, artificial intelligence, machine learning, additive manufacturing… All these advances create new needs for a more interdisciplinary education. This is the real meaning of an event like the Symposium on Space Educational Activities.

Here we present the symposium proceedings that summarize all the presentations held during the event. We also introduce a summary of the symposium organization, events and awards.

4th SSEA22 group picture

Keynote Speaker Jordi Puig Suari at the Venue

Gala Dinner at the Fabra Observatory

Organizing Institutions

The 4th Symposium on Space Educational Activities (SSEA) was organised by the European Space Agency (ESA), through the ESA Academy programme of the ESA Education Office; and the Universitat Politècnica de Catalunya · BarcelonaTech (UPC). It was organised in partnership with the IEEC, ICCUB and i2cat research centres, as well as with the institutional sponsorship of the Generalitat de Catalunya.

The ESA Academy, part of the ESA Education Office, is ESA's overarching programme for University students from ESA member states, Canada, Latvia, Lithuania, and Slovenia. The ESA Academy provides students with access to both Hands-on Projects and a Training and Learning Programme, as well as supporting, through organisation and funding, the Symposium on Space Educational Activities.

The Universitat Politècnica de Catalunya · BarcelonaTech (UPC) is a public institution of research and higher education in the fields of engineering, architecture, sciences and technology, and one of the leading technical universities in Europe. UPC's schools devoted to research and education on the aerospace field are: ESEIAAT, EETAC, and ETSETB.

Organizing Committee

The 4th SSEA was a reality thanks to the work of a diverse team of committed and hard-working members. Following the motto of “a Symposium made for students – by students”, the Organising Team was balanced mix of professors and students and included members from different backgrounds and institutions.
The core Organising Committee was composed by:

- Dr. Miquel Sureda Anfres (UPC · BarcelonaTech) – General Chair
- Mr. Ramón M. García Alarcia (ISAE – SUPAERO) – Vice-chair
- Mr. Guillem Megías Homar (Stanford University) – Vice-chair
- Dr. David González Díez (UPC · BarcelonaTech) – Vice-chair
- Dr. Daniel Garcia Almiñana (UPC · BarcelonaTech) – Vice-chair
- Dr. Gisela Detrell (University of Stuttgart) – Co-chair of technical and educational activities
- Ms. Magda Escorsa (UPC · BarcelonaTech) – Co-chair of technical and educational activities
- Dr. Anna Ferré-Mateu (Instituto de Astrofísica de Canarias) – Co-chair of technical and educational activities
- Dr. Alberto García-Rigo (Institut d’Estudis Espacials de Catalunya) – Co-chair of technical and educational activities
- Mr. Alexander Kinnaird (ESA Academy) – Co-chair of technical and educational activities
- Ms. Laia López (International Space University) – Co-chair of technical and educational activities
- Ms. Anna Ruiz Ayala (INECO) – Co-chair of technical and educational activities
- Dr. Núria Salán (UPC · BarcelonaTech) – Chair of Gender equality, Diversity and Sustainability Board
- Dr. Adriano Camps (UPC · BarcelonaTech) – Chair of Scientific and Technical Activities Board
- Ms. Carme Fenoll (UPC · BarcelonaTech) – Chair of Logistics Board

For better preparation and organisation of the event, the Organising Committee created and supervised several autonomous boards tackling different aspects such as communications; logistics; scientific and technical activities; sponsors; sustainability, equity and diversity; etc.

The **Communications Board**, in charge of social media, newsletters, and the event’s communications and image in general, was composed of:

- Ms. Laia López Llobet, Chair
- Ms. Àurea Cors
- Ms. Blanca Pavón
- Ms. Lídia Fuentes
- Ms. Marina Cante
- Mr. José Ángel Gómez
- Ms. Gemma Domènech
- Mr. Arnau Amorós

The **Logistics Board**, in charge of the event logistics and suppliers, timetable, and social events, was composed of:

- Ms. Anna Ruiz Ayala, Chair
- Mr. Juan Francisco Lopera Zafra
- Mr. Daniel Sors
- Ms. Laura González
- Mr. Sergio Tabasco
- Ms. Núria Escursell
- Ms. Ariadna Anguita

The **Scientific and Technical Board**, in charge of the Call for Abstracts, paper selection, and preparation of Proceedings, was composed of:

- Prof. Adriano Camps (UPC · BarcelonaTech), Chair
- Dr. Daniel Garcia Almiñana (UPC · BarcelonaTech), Executive Chair
- Dr. Gisela Detrell (University of Stuttgart)
- Dr. Silvia Rodriguez-Donaire (UPC · BarcelonaTech)
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- Dr. Maria de Soria (Jet Propulsion Laboratory)
- Ms. Beatriz Jilete (GMV)
- Ms. Armelle Frenea-Schmidt (Swedish Space Corporation)
- Mr. Borja Lázaro Toralles (Manufacturing Technology Center)
- Mr. Jonathan Becedas (Elecnor Deimos)
- Mr. Jordi Escofet Miró (INS Terrassa)
- Mr. Domingo Escutia Muñoz (ESERO Spain)
- Dr. Ed Chester (Goonhilly Earth Station Ltd)
- Dr. Nicolas Nolhier (University Paul Sabatier of Toulouse)
- Ms. Clara Cruz Niggebrugge (ESA Academy)
- Mr. Josep Virgili Llop (Space X)
- Mr. Alexander Kinnaird (ESA Academy)
- Ms. Ariane Dedeban (ESA Academy)

The **Sustainability, Equity and Diversity Board**, in charge of ensuring the meeting of the event's social goals and assigning scholarships, was composed of:

- Dr. Núria Salán, Chair
- Dr. Anna Ferré-Mateu

The **Sponsors Board**, in charge of securing funding through sponsors, taking care of their needs, and maintaining external relations, was composed of:

- Mr. Guillem Megias Homar, Chair
- Dr. David González
- Ms. Magda Escorsa

Picture of the organising team during the event

Volunteers

Besides the organising team, the 4th SSEA would not have been possible without the help of many more volunteers, who selflessly devoted their time working hard before and during the event days. They are listed below, alphabetically:

- Adrià Rovira
- Adrian Nicolae
- Alba González Prieto
- Alexandru Zagorodniuc
- Alex Pous
- Anna Güeto
- Antoni Abelló Sanz
- Arès Quetglas
- Arnau Amorós
- Ben Thomas
- Carolina Olivan
- David Ferrer
- Guillem Iborra
- Iset Tejero Gómez
- Ivan Garcia Astudillo
- Jesús Ordoño
- Jithin Njondimackal
- Marc Canadell Salada
- Maria Riquelme
- María Martínez Galisteo
- Miriam Martínez Ambrosio
- Oriol Bernal
- Oumaima Tabiti
- Pere Garcés
- Ricard Mata
- Roger Martínez
- Rosa Galan
- Silvia Gómez Blanco

Sponsors

The 4th SSEA had a plethora of supporters that contributed immensely to the development and success of the event. We are grateful to all the institutional and commercial sponsors. For reference they are listed below in the different sponsorship tiers:

Main sponsor

GMV is a privately owned technology business group founded in 1984. #1 worldwide Ground Segment provider for satellite Commercial Telecom market. Involved in more than 850 satellite missions, GMV is the world´s foremost Ground Segment turn-key provider, along with operations support, for Satellite Operators and top supplier for Satellite Manufacturers and Space Agencies.

Platinum sponsor

GOMSpace is a globally leading manufacturer and supplier of CubeSats & small satellite solutions for customers in the academic, government and commercial markets. With 15 years of experience in the market and a track record of multiple successful missions accomplished, they have developed profound knowledge and competencies within systems integration, cubesat platforms, advanced miniaturized radio technology and satellite operations.

Gold sponsors

Open Cosmos is a space company that develops satellite missions from start to finish. Offering a comprehensive service that addresses the entire value chain of the space sector, design, manufacture, mission management and launch of customized satellites for companies, institutions and governments worldwide. Their satellites are primarily used to collect critical earth data for economic, environmental or security decisions; provide telecommunications services on a global scale; or develop space science and technology.

Sateliot is the first satellite communications operator to provide IoT connectivity over standard 5G NB-IoT. Their constellation work as cell towers in space, extending mobile operator's coverage and providing global connectivity to unmodified commercial terrestrial devices wherever they may be. Sateliot is the key contributor to the development of the space 5G NB-IoT standard and will be the first company on earth to provide the standard based communications service via satellite.

Alén Space is a cutting-edge tech company who offers integral solutions in design, manufacture and operation of small satellites. It has a highly qualified team of engineers with more than 12 years of experience in the New Space sector. Its main objective is to help clients to put its business ideas into orbit as quickly as possible.

Standard sponsors

The **Solar-Terrestrial Centre of Excellence (STCE)** is a tight collaborative network for Belgian sun-space-earth research and services, gathering activities of 3 Federal Scientific Institutes. The STCE's expertise in solar observations and research combined with the experience of its GNSS and solar particle radiation group recently proved to be crucial to set up space weather services for civil aviation.

Carrying a solid background built on more than 30 years of state-of-art and cutting-edge projects alongside major contractors, **GTD** specializes in developing ground and on-board systems for space mission-critical computer environment. GTD's bespoken solutions cover the whole project life-cycle: planning, analysis, design, development, integration, testing, maintenance and support to operations, ensuring that clients' critical systems and processes embody highly reliable software.

SATLANTIS is a Spanish technological SME specialized in developing customized, reliable, and innovative satellite solutions that fully meet customers' demands. SATLANTIS provides HR/VHR cameras, plus End-to-End solutions, data and value-added products designed to fulfil users' needs in a range of downstream applications including environmental monitoring, oil and gas and infrastructure.

Angelantoni Test Technologies is a key player in the Aerospace testing sector since 1988: after the 1st Thermal Vacuum Chamber, ACS brand is well known by worldwide Space Centers testing satellites and components.

isardSAT is an R&D enterprise with the mission to improve the knowledge of our planet Earth through Remote Sensing. isardSAT is a leading expert on satellite technologies, mission design, and proprietary algorithms' design and implementation for climate and environment applications. In 2018, isardSAT created its climate services unit, Lobelia, working with Earth Observation and climate models to assess vulnerabilities, risks and opportunities associated with the climate emergency.

The **National Commission for Space Activities (CONAE)** , under the Ministry of Science, Technology and Innovation of Argentina, is responsible for designing and executing the National Space Program. Through this program of actions and projects, satellite Earth observation missions are conducted in Argentina for the benefit of the country and the Latin American region, with the purpose of generating adequate and timely space information about the continental and maritime territory.

Keynote speakers sponsors

Some keynote presentations had the gracious support of the following companies and institutions:

Awards

1 - Best Oral Presentation

Title: *Development of a Low-Cost Ground Segment Capable of Receiving Data from Nanosatellites: a Partnership between Brazil and Portugal*

Authors: Júlio Santos, Jeremy Silva, Joí£o Braga, André Teixeira, Marcos Kakitani and Henrique Alves

2 - Highly Commended Oral Presentation 1

Title: *The effect of previous spaceflight on otolith-mediated ocular counter-roll in cosmonauts after long duration spaceflight*

Authors: Catho Schoenmaekers, Floris Wuyts and Steven Jillings

3 - Highly Commended Oral Presentation 2

Title: *ASCenSIon Innovative Training Network: mid-term overview and lessons learned*

Authors: Alessia Gloder, Martin Tajmar and Christian Bach

4 - Best Poster

Title: *Analysis of Impulsive and Low-Thrust Transfer Orbits for ESA's LISA Mission under Third-Body Perturbations*

Authors: Juan Palomares, Oriol Lizandre and Blanca Tejedor

5 - Highly Commended Poster

Title: *An Augmented Reality App teaches volcano monitoring from Space in Schools with Sentinel-1 data*

Authors: Claudia Lindner, Christian Nadolsky, Carsten Juergens, Karl-Heinz Otto and Andreas Rienow

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ABSTRACTS

Papers

Challenge-Based Learning and the Barcelona ZeroG Challenge: A Space Education Case Study

Antoni Perez-Poch[1,2],Jordi Torner[1],Daniel V. González[3,6],Laura Gonzalez-Llamazares[4],Maria Josep Martí[5],Rosa Pasquets[3],Francesc Alpiste[1],Miguel Brigos[1],Gloria García-Cuadrado[6]

Abstract

Challenge-Based Learining is a STEM Education methodology that has been used as a collaborative and hands-on approach to encourage students to put their knowledge in practice by addressing real-life problems. Space Education is a field particularly suited to apply it, with hands-on research projects which require students to take actions and communicate their efforts in a multicultural, international scenario in order to produce an optimal response a specific goal. We herein present a successful Challenge-Based Learning Case Study which involves designing, implementing, and actually flying a microgravity experiment in parabolic flight. The Barcelona ZeroG Challenge is an international competition addressed to University students worldwide. It challenges students to build a team with a mentor, propose, design, build and fly their experiment in microgravity and finally communicate their findings. The experiment has to meet the requirements of a unique microgravity research platform available in Barcelona for educational and research purposes.

More than fifty students have flown their experiments on board an aerobatic CAP10B aircraft in Barcelona in previous educational campaigns; having published their results in relevant symposiums and scientific journals. These campaigns have always attracted media attention. The current edition is underway with the winner team expected to fly their experiment before the end of 2022. This edition is jointly organized by Universitat Politècnica de Catalunya, the Barcelona-Sabadell Aviation Club and the Space Generation Advisory Council. Up to fifteen projects have been submitted to this edition, an unprecedent number so far. A panel of experts from the European Space Agency Academy conducted the selection of the winner team, who receives a 2500 euros grant to develop its experiment, aside from the opportunity to fly it in parabolic flight. Furthermore, students from our own University have also the opportunity of designing and testing their microgravity experiments during their studies.

Principles of Challenge-Based Learning are herein described as well as how this methodology is applied to this Case Study. Results from our experience are very satisfactory as most of the students who have been involved in it perceive this experience as a boost for their careers. Three key factors to success have been identified: a strong involvement from students' associations, a need for international cooperation and the quality of the students’ mentoring. The experience can be of interest for other organizations to conduct a successful CBL educational project.

Keywords

Aerobatics, Challenge-based learning, Microgravity, Parabolic flight, Space education.

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[6]Brainstorm SL, Spain.

Acronyms/Abbreviations

CNES *Centre National d'Études Spatiales*

EASA *European Aviation Safety Agency*

ESA *European Space Agency*

HEI *Higher Education Institute*

IAF *International Astronautical Federation*

ISU *International Space University*

SSP *Summer Space Program*

SEMA *Spanish Society of Aerospace Medicine*

SGAC *Space Generation Advisory Council*

STEAM *Science, Technology, Engineering, Arts and Mathematics*

UPC *Universitat Politècnica de Catalunya*

VFR *Visual Flight Regulations*

1. Introduction

Parabolic flights have been conducted for a long time as a way of performing short-time duration experiments and technical demonstrations [1, 2]. Aircraft parabolic flights provide up to 25 seconds of reduced gravity. They are used for conducting short investigations in Physical and Life Sciences, both for senior researchers and for international student experimentation and motivation, and public outreach.

We report on educational experiments conducted in the Barcelona parabolic flight platform (Sabadell Airport, Barcelona, Spain) with single-engine aerobatic aircraft such as the CAP10B (Figure 1), achieving up to 8.5 seconds of microgravity in its cockpit.

The flight profile results coming from a steady flight profile an introductory pull-up maneuver is performed at increased acceleration (roughly 3-3.5g for these aircraft), pilot reduces thrust and, with throttle or idle engines the airplane follows the parabolic trajectory of a free-flying body. As a consequence, after a short phase of transition, microgravity is obtained for 5-8 seconds.

After the recovery maneuver at increased acceleration (2.5-3g), the airplane flies again horizontally to the ground level for some minutes before introducing the next parabola. During one flight mission typically 10-15 parabolas are performed. Larger aircraft provide between 20-25 seconds of microgravity thanks to a more powerful engine.

The European Space Agency (ESA) has used since 1984 six types of aircraft to conduct its parabolic flight campaigns [3]: the KC-135, the Caravelle from CNES, the Russian Ilyushin Il-76 MDK, the Cessna Citation II, the Airbus A-300/A-310 'zero-g' from Novespace, all of them with 2 or 4 engines. An important number of physical and life sciences experiments have been conducted showing the success of this kind of access to microgravity.

Our approach is different from the successfully previously reported parabolic flights as we propose the use of a small single-engine aerobatic plane. This kind of aircraft (Figure 1) is certified to conduct this manoeuvre and could also be used for professional experiments, testing technology and educational and outreach campaigns as well. Hypogravity is experienced within the cockpit for about 8 seconds with a flight profile significantly different from that of larger aircraft [4].

Figure 1. Mudry CAP10B aerobatic aircraft used for educational parabolic flight campaigns. (Credit: Barcelona-Sabadell Aviation Club)

Parabolic flights have been used very successfully by the space agencies to conduct student campaigns with the aim to motivate the youth to take part in aeronautical and space research. This project is inspired by the ESA Academy hands-on educational projects and, in particular, by the very successful ESA Fly Your Thesis Program [5].

2. Objectives

The objectives of parabolic flights with an aerobatic single-engine aircraft are as follows [4, 6]:

2.1. Scientific & Research

-To study different processes in which abrupt changes of gravity workload are applied. In particular hyper (3 – 3.5g) to hypogravity (0.05g), and hypo to hypergravity periods.

DOI: 10.5821/conference-9788419184405.001

-To analyse transient phenomena that may occur after short periods of hyper and hypogravity.

-To allow experiments for testing the equipment in a real parabolic flight, with the opportunity to manually interact with the equipment and provide a proof-of-concept before accessing other microgravity research platforms.

-If the experiment can be run in less than 8 seconds of exposure to hypogravity, and the residual acceleration of 0.05 g is acceptable, then quantitative and qualitative measurements can be made, thus providing meaningful data. The parabolic flight can provide up to 20 parabolas in a single flight, and weather permitting the procedure can be repeated in a single day.

-In regards to human physiology or physical experiments in which and the hypo and hypergravity environment plays a role, the facility enables different experiments to be tested inside the cockpit, one by one on board (Figure 2). More information can be found at our laboratory website (CSmicrogLab.upc.edu)

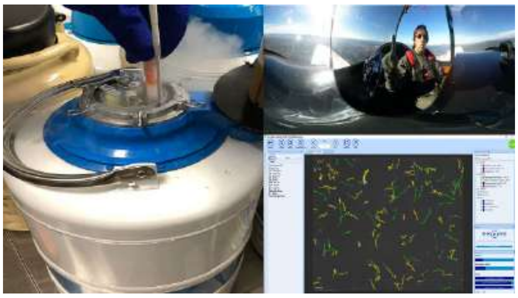

Figure 2. Human reproduction studies conducted in this platform [7]. (Credit: Institut Dexeus, UPC & Barcelona-Sabadell Av. Club)

2.2. Technological

- Assessment of technological equipment behaviour in a hyper and hypogravity environment with abrupt changes in a tiny environment.

- Safety assessment of experiments and technological demonstrations within a parabolic flight aircraft cockpit.

- Training of wannabe or future astronauts for foreseen private or public space missions.

2.3. Education & Outreach

- Allowing students to conduct hands-on experiments in a real weightlessness experience.

- Increasing their interest for studying Science, Technology, Engineering, Arts and Mathematics (STEAM) syllabus, in particular in the aerospace field.

- Providing students from different backgrounds and nationalities with the opportunity of working as a team with a common goal, while interacting with space professionals.

- Raising public interest in space research.

- Creating the opportunity for students to write and present their space research in relevant journals and congresses, and also to further apply to the space agencies educational programs building up their curriculum.

3. Challenge-Based Learning

Challenge-Based Learining (CBL) is a STEAM Education methodology that has been recently introduced as a collaborative and hands-on approach to encourage students to put their knowledge in practice by addressing real-life problems. In 2008, the concept CBL was first named by the technology enterprise Apple® as a methodology to meet the XXIst Century demands [8]. Higher Education Institutions (HEIs) have seen in the recent years how their role had to adapt itself to the arising changes in our society and in particular, STEAM Universities [9]. Our colleges are becoming facilitators for the students' training, including in their syllabus competencies (such as teamwork, creativity or innovation skills) to be acquired, which are required in nowadays' scientific endeavours. Space Education is a field particularly suited to apply CBL, with hands-on research projects requiring students to work with teammates, mentors and experts. They are expected to take actions and communicate their efforts in a multicultural, international scenario in order to produce an optimal response a specific goal.

We herein present a successful CBL Case Study which involves designing, implementing, and actually flying a microgravity experiment in parabolic flight.

4. The Barcelona ZeroG Challenge

The Barcelona ZeroG Challenge is an international competition addressed to University students worldwide (Figure 3). It requires the students to build a team with a mentor, propose, design, build and fly their experiment in microgravity and finally analyze the results and communicate their findings.

DOI: 10.5821/conference-9788419184405.001

Figure 3. Barcelona ZeroG Challenge announcement. (Credit: SGAC)

The experiment has to meet the requirements of a particular platform of microgravity research available in Barcelona for educational and research purposes [10].

More than fifty students have already flown their experiments on board an aerobatic CAP10B aircraft in Barcelona in previous educational campaigns; having published their results in relevant symposiums and scientific journals [4]. These campaigns, inspired by the well-known ESA Student's Parabolic Flight campaigns, have attracted media attention and have promoted public awareness on STEAM studies as well. Four previous editions of the Barcelona ZeroG Challenge have taken place since 2010, with a significant number of the International Space University (ISU) students being involved [11,12, 13, 14,15]. Three workshops had been held in the Summer Space Program and in the Master Space Program of ISU. A new edition of this contest is underway [10], with the winners expected to fly their experiment in 2022. This edition is organized by Universitat Politècnica de Catalunya (UPC), the Barcelona-Sabadell Aviation Club and SGAC, the Space Generation Advisory Council well-known students association. Multidisciplinar, diverse and minority teams of students were encouraged to apply. An independent panel of experts from the European Space Agency (ESA) Academy conducted the final selection of the winner team. In the current edition, the selected students' team receives a 2500 euros grant to develop its experiment, as well as the opportunity to fly it in parabolic flight. An unprecedent number of 15 proposals have been received. Students from 23 different countries submitted their proposals (60% life sciences experiments; 40% physical sciences). Among the participants 63.3% came from Europe, 14.3% from America and 13.4% from Asia. The winner team consists of four female students from the University of Antioquia: Luisa Fernanda Mendoza (spokesperson), Paulina Quintero, Oriana Mejía and María del Pilar Monsalve. The team is called 'Vera Gravitas', which in Latin means 'true gravity', and it also refers as well to Dr. Vera Rubin, a famous astronomer who made important contributions to science [16]. They are part of the Colombian Association of Women in Aerospace, which aims to arise women's interest in this science. The team also has a mentor, Professor Liliana Marcela Bustamante Goez, from the Department of Mechanical Engineering at the University of Antioquia (Figure 4). Their proposed experiment is entitled "Deposition of tin droplets on electronic components in the absence of gravity."

Figure 4. 'Vera Gravitas' Team, winners of the Barcelona ZeroG Challenge 2021.

The experiment seeks to study how soldering electronic components is affected by microgravity, a research topic that may have many applications in the near future. Currently, this team is working with the advice of researchers from UPC and experienced pilots from the Barcelona-Sabadell Aeroclub in order to develop their experiment, adapt it to the cockpit of the plane and fly it this year 2022 at Sabadell Airport. The team is also engaged in an outreach project to diffuse their findings [17].

Furthermore, students from our own University, have also the opportunity of designing and testing their experiments during their studies with a singular hands-on training and an introduction to space research [4, 11]. Master and Doctoral Thesis are good frameworks to include students' advances and contribute to their graduation with a singular experience.

5. Discussion

We first reported a successful series of parabolas performed with a light single-engine aerobatic plane with a life sciences experiment on board. Between 5 to 8.5 seconds of microgravity were achieved with a limited operational cost. The optimization of the manual piloting has made possible to provide a quality of g between 0.05g and 0.005g with a g jitter reduction depending on the strength of wind gusts. Very limited time is needed to prepare and perform the experiment so this approach is specifically suited for those kind of rapid prototyping technology tests, or simple experiments that do not need huge or sophisticated equipments. These parabolic flights are not designed to compete with those from space agencies requiring larger aircraft, instead, they rather extend the range of possibilities available to the researchers and students interested in microgravity research. Among the limitations of small aerobatic aircraft are: limited cockpit size, reduced hypogravity time, no electricity plugs available, only one experimenter at a single flight, higher g jitter sensitivity and a more aggressive flight profile. However, from the point of view of providing a hands-on experience to students it has proven very successful at a reasonable cost.

Educational activities have been from the beginning an essential part of our motivation, and have provided meaningful results and a number of flight opportunities for students' experiments, as well as tutorials after data collection.

Only two mild episodes of motion sickness have been reported in more than 10 years of eductional activities. The visual flight configuration of this platform allows the participant any inconvenience during the flight, and following the pre-established protocol, he or she would be safely held on ground in less than 15 minutes with specialized medical care available on site. Mandatory safety briefings are conducted pre and post-flight.

Students' associations such as the Space Generation Advisory Council (SGAC), are currently involved in this endeavour. Some of the prior participants have declared their excitement for having the opportunity of actually making space research in microgravity, providing outreach to the public, and later publishing the results in selected conferences and indexed journals.

Three key factors to success have been identified from our years of experience: 1- A strong involvement of students' associations, 2- International cooperation and 3- Quality of students' mentoring.

Space students associations are one of the most valuable assets in the astronautical field to promote motivation, mentoring and a meaningful career for their members. They spread the word of the opportunities that eventually arise, and provide an important contacts network which are essential to build up a diverse team such as that requested in this singular challenge. International cooperation involves making use of the professional societies such as IAF to reach the necessary stakeholders for starting and mantaining an educational endeavour.

Last but not least, in the cases that a highly involved mentor was engaged with their students project, there was a unique boost to the quality of their research product. Some mentors even attended all briefings, supervised the experiment in a particular field in which they were recognized experts and researchers, and contributed substantially to the success of their students.

6. Conclusions

We have reported on the educational and outreach activities of an innovative microgravity platform based on single-engine aerobatic planes in Barcelona (Spain) which is ongoing, making a significant impact and inspiring students around the world to get an interest on space medicine and research. Therefore, we plan to continue these activities and expand them in the near future. Among the lessons learned, the students' involvement and international cooperation have been the most important factors that have led this platform successful. Good mentoring is a key factor for the success of students involved in complex Challenge-Based Learning activities.

Acknowledgements

Many people have contributed over the years to these Barcelona parabolic flights with single-engine aerobatic aircraft. In particular, we wish to thank our colleagues from the Barcelona-Sabadell Aviation Club and those flight surgeons from the Spanish Society of Aerospace Medicine (SEMA) who have volunteered contributing to the safety of operations. We are likewise grateful to all the students and flight participants and their mentors for their support and contribution, and also to SGAC and ESA Academy for their current involvement and support. Previous participation of some of the authors in ESA hands-on educational activities have been a great source of inspiration.

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Final testing, pre-launch activities, launch and post-launch analysis of a sounding rocket made by students in Spain

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Abstract

This paper summarizes the final launch preparation tests, the operations before, during, and after the launch, and the results of the launch of a supersonic sounding rocket developed by university students in Spain with the collaboration of INTA (National Institute of Aerospace Technology). The students are part of the Cosmic Research association, based at the Polytechnic University of Catalonia ESEIAAT, and the rocket is called Bondar. INTA is a Public Research Organization under the Spanish Ministry of Defense dedicated to scientific research and development of systems and prototypes in the fields of aeronautics, space, hydrodynamics, security, and defense. The staff of the El Arenosillo Experimentation Center (CEDEA) collaborated in the Bondar mission with their knowledge and launch capabilities. The launch of the rocket took place on the 30th of November of 2021. Two students from BiSky, a rocketry team from the University of the Basque Country, also participated in this project, specifically in the development of the on-board and ground-based avionics subsystems. The paper presents information on the mission systems, the operations before, during, and after the countdown to the launch, the documentation required by INTA-CEDEA for the launch, and the results of said launch. In short, the systems developed by Cosmic Research for the launch are: the rocket, the launch pad, the rocket transport box, the flight simulator, and the ground-based rocket tracking station. The documentation required by INTA includes: a detailed description of the systems, a ground risk assessment, a flight risk assessment, structural analysis, aerodynamic analysis, and a list of countdown operations. Launch post-analysis activities evaluate the performance of systems and operations during the most critical phase of the mission. The Bondar Mission, due to its technical and operational complexity, was the most ambitious project ever developed by students in Spain in the field of rocketry. After a successful launch, Bondar became the highest-flying Spanish student-made rocket, with its apogee around 8 km AGL (Above Ground Level).

Keywords

INTA, launch operations, sounding rocket, Spain, students.

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Acronyms/Abbreviations

CEDEA	*Centro de Experimentación De El Arenosillo*
CR	*Cosmic Research*
ESEIAAT	*Escola Superior d'Enginyeria Industrial, Aeronàutica i Audiovisual de Terrassa*
INTA	*Instituto Nacional de Técnica Aeroespacial*

1. Introduction

CR (Cosmic Research) is a student association founded in 2016 with the mission of launching suborbital rockets for the benefit of society. Since its foundation, the CR's team has launched 37 rockets and more than 100 CanSats. With the launch of Resnik in 2017, the association set the Spanish altitude record at student level, achieving an apogee of 2 km.

Following its trail, the Bondar mission was started in 2020, whose goal was to develop all the technologies necessary to launch a stratospheric rocket. This paper aims to give an overview of the steps followed up to the end of the launch campaign.

2. Mission Systems

2.1. Rocket

Bondar is a 2.6 m long, passively stabilized, supersonic, aluminum rocket. It is fitted with custom avionics for apogee detection and separation, and data downlink. It is a sounding rocket with payload capabilities up to 0.5 kg.

Figure 1. Bondar rocket

2.2. Launchpad

Horizontally-stabilized structure with variable elevation angle. It is formed by a six meters tall tower and rail to provide mechanical guidance for the rocket during lift off.

Figure 2. Launchpad

2.3. Rocket transport box

A 2895 x 580 x 690 mm wooden box filled with custom antistatic and antivibration foams fitting the rocket shape that prevents it from sliding to ensure safe transportation during operations.

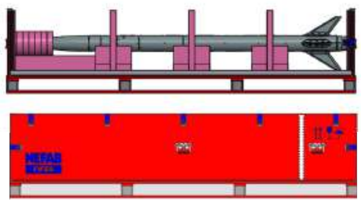

Figure 3. Rocket transport box

2.4. Flight Simulator

CR's own simulator is a 6-Degrees of Freedom stochastic simulator based on MATLAB, which uses semi-empirical aerodynamic models to predict the rocket trajectory.

2.5. Ground-based rocket tracking station

Two antennas were installed on CEDEA's optronic systems to process the in-flight telemetry data by a custom made ground tracking station and send this information to the control center.

3. Operations

In this section, the operations before, during, and after the countdown will be presented. These operations start with the review after transport of all the systems of the mission and end once the team arrives at the headquarters after the launch.

3.1. Pre-launch operations

This group is the most extensive. It comprises activities before arriving at CEDEA and also operations in the spaceport.

First of all, there is a review of all the mission systems. When all the systems are checked, the launch campaign officially starts. This is followed by the sorting and packing of all the components. Then the team proceeds to the transportation. Once in the spaceport, there is the assembly of all the systems, with the exception of the motor, the electronics bay and the recovery bay of the rocket, which are reserved for the launch operations.

During this phase, 3 tests were conducted. The verification of the data reception regarding the avionics and the ground stations, the data injection verification and a launch operations simulation. When all the tests were passed, the last step was the flight trajectory simulations.

3.2. Launch operations

The launch operations start with the motor assembly and end when the motor is ignited. The most critical operations are reserved for this period. In short, these activities are, in chronological order: the assembly of the motor, the final assembly of the recovery bay and electronic bay with the rocket structure, the introduction of the motor inside the rocket, the transportation and placement of the rocket in the launchpad, the final avionics tests and simulations, the introduction of the ignitor, the final security checks regarding the drop area security footprint of the spaceport, and the ignition of the motor.

Since this group includes the most critical operations, it was necessary to detail also the holding operations, the GO/NO-GO criteria and the emergency procedures.

The holding operations comprise all the procedures that solve a possible problem during the countdown. Their importance derives from the necessity of knowing in each moment how to solve a problem, given the tension of the countdown period. Also, it is extremely important to know how much time it can take to solve a problem in order to decide whether the launch operations should be postponed until the next launch window or not.

The GO/NO-GO criteria includes all the conditions that must be met in order to authorize the start of the launch operations. Some examples are: to not surpass the wind limits defined by the simulations, to have favorable weather conditions, to have all the systems ready and all the flight permissions.

The emergency procedures include the instructions to follow if one or more of the potential risks of the launch operations occur. All the team members must be familiarized with these protocols and must have a copy with them.

3.3. Post-launch operations

These operations start once the motor is ignited and finish when the team arrives at the headquarters. They are divided into two groups: the post-launch operations at the spaceport and the post-launch operations outside of it.

The post-launch operations at the spaceport start with the lift off of the rocket. It leaves the launchpad at an approximate velocity of 40 m/s. The powered flight lasts 6 seconds, in which the motor burns all its propellant. Then, the motor runs out of propellant and it continues its ascent for approximately 30 seconds. Once the rocket reaches the apogee, the avionics command the separation of the recovery bay from the avionics bay and the drogue parachute is released. At the same time, the motor bay and the recovery bay are discarded into the sea. The upper stage descends at an approximate velocity of 17 m/s for 8 minutes and then it is recovered from the sea.

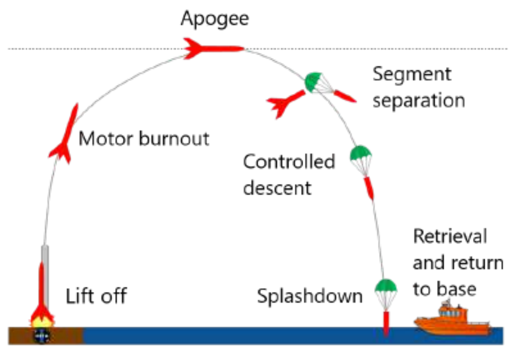

Figure 4. Post-launch operations

Once the avionics bay is recovered, the electronics team proceeds to recover all the electronic components and the SD card. They return to the spaceport and the team starts sorting and packing all the systems. Finally, the team proceeds to the transportation of all the material to the headquarters.

4. Documentation

The safety requirements set by the launch site demanded the production of various documents to ensure system integrity and operational safety before, during and after the launch.

4.1. System description

To better understand the Bondar rocket and serve as reference, a detailed description of all the components of each system was provided, including dimensions, materials, and other complementary information.

4.2. Ground Risk Assessment

For security reasons all risks that might interfere with the mission were identified, assessed, and classified. The risks were evaluated taking into account severity and frequency, following a method proposed by INTA [1][2], to ascertain their criticality. These values were used to determine if mitigation strategies were necessary to reduce their criticality to an acceptable level.

The estimations were based on CR's previous work and other reliable documents. To ensure quality the document was reviewed by both INTA and ASPY, a risk prevention company.

4.3. Flight Risk Assessment

Following the same line of work as the ground risk assessment, this document compiles all the risks associated with the flight of the rocket.

It includes, but is not limited to: motor explosion, premature separation of recovery devices, structural failure (specially the fins and their supports), pitch-roll coupling, high roll rates, and aeroelastic phenomena.

CR's simulator was used to study some of these risks and propose adequate mitigation measures, but literature was also consulted for certain cases.

4.4. Structural Analysis

For both the rocket and the launchpad a FMEA (Failure Mode and Effect Analysis) study was carried out, identifying the most critical failure modes and how to prevent them. For those failure modes related to mechanical overload, a FEA (Finite Element Analysis) was performed. The position and magnitude of the loads experienced in-flight for specific structural parts were determined with simulator data, and CAD models for those parts were designed. With these models, the NX Nastran Design solver was used, alongside Siemens NX software, to obtain the strain and stress profiles for all parts. These results were compared with the maximum yield values of the material, thus providing a theoretical Safety Factor, ensuring that the systems could withstand their expected loads. Other studied failure modes, making use of the Hyperworks suite, included: vibrational modes, local and global buckling, and fin and ogive overheating.

4.5. Aerodynamic Analysis

The aerodynamic analysis of the rocket comprised many aspects. First, it offered a detailed description of the flight simulator, followed by the input parameters. The stability of the rocket was verified under nominal flight conditions, and the expectable values of certain parameters were studied throughout the flight, to serve as inputs for the structural analysis. Risks associated with aerodynamic phenomena were also studied. Finally, the trajectory of the rocket under variable weather conditions was studied for both nominal and adverse conditions (motor explosion, loss of fins, premature separation), to ensure the spaceport footprint was respected.

5. Results and discussion

The data used to perform the analysis of the flight comes from three different sources:

a. CR's simulator: used during launch operations to predict the rocket trajectory and ensure safety.
b. On-board avionics: developed by BiSky Team, transmitted data every 0.3 s to the ground stations.
c. INTA's tracking devices: offer trajectory data at a 50 Hz rate, starting at 1.16 s into the flight due to a tracking error during lift-off.

5.1. Acceleration

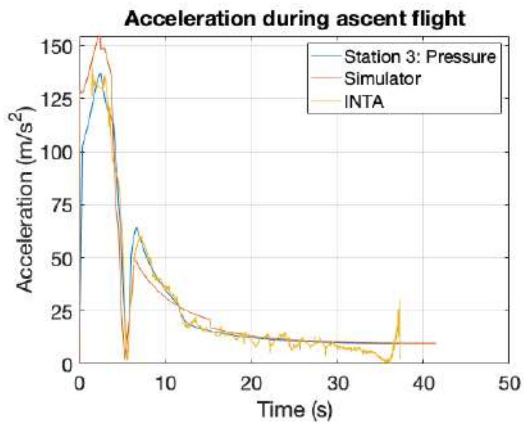

Figure 5. Acceleration during ascent flight

Figure 5 shows the absolute value of the acceleration during ascent flight. The acceleration phase lasts approximately 6 s, and the rest is deceleration.

The readings obtained from the avionics and INTA are almost identical, except from the noise present in the latter due to the higher sampling rate. The divergence at the end is not significant and is attributed to the distance between the rocket and the tracking device.

The simulator predicted a higher acceleration rate during the powered flight, which might not have been achieved due to subpar motor performance and higher drag forces.

The latter can be also observed in the deceleration phase. A higher peak after motor burnout indicates a higher supersonic drag, which quickly decelerates the rocket to the subsonic region (around 12 s after lift-off). The simulator predicted a longer supersonic phase, lasting until around 15 s.

Acceleration rates in the subsonic region are almost identical, which leads to the conclusion that drag discrepancies must be associated with supersonic drag (associated mostly to shock waves). The numerous bolts and rivets in the fuselage, as well as the voluminous fin supports are believed to be the origin of this increased drag. Efforts in the simulator have to be made to adequately characterize the rocket drag (updating current models based on [3]), and constructive improvements are needed for future rockets.

5.2. Velocity

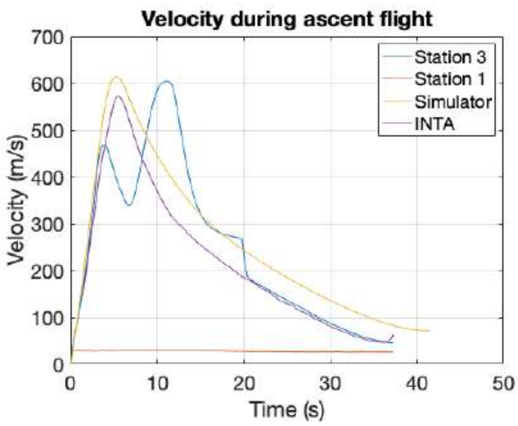

Figure 6. Velocity during ascent flight. Raw data

Figure 6 presents the velocity readings from the two ground stations. Station 1 did not receive consistent data at any point, while station 3 is not accurate during the majority of the flight, since it offers a velocity profile characteristic of a two-staged rocket. The root of the problem has not been identified, and can be associated either with data reading, transmission or reception. Since acceleration readings are correct, the velocity will be obtained through integration (using an explicit scheme), taking into account the Euler angles (which define the orientation of the rocket).

After manipulating the avionics data, the results in figure 7 show a better correlation with reality. The slight difference can arise from the acceleration discrepancies, inaccuracy of the Euler angles measured, or due to the numerical integration scheme.

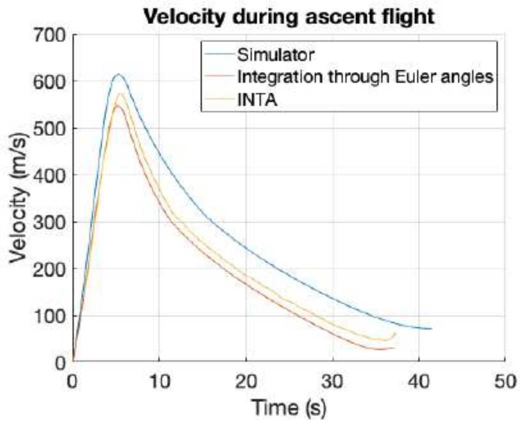

Figure 7. Velocity during ascent flight. Manipulated data

The effects of increased supersonic drag can be seen also in this figure, since the change in slope becomes significant after around 300 m/s (in the transonic region). This strengthens the hypothesis presented from the acceleration data.

The deceleration rates after going below Mach 1 are similar and the model for predicting subsonic drag (also extracted from [3]) is assumed to be accurate.

5.3. Trajectory

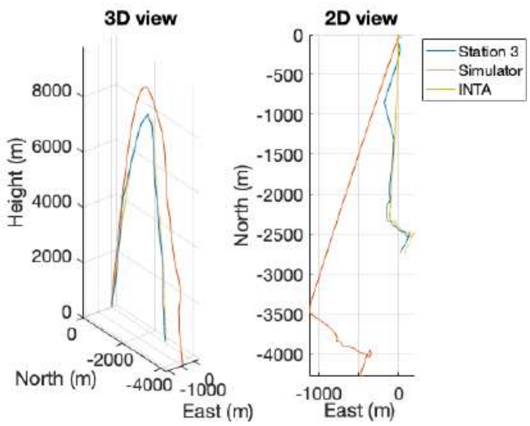

Figure 8. Rocket trajectory

Figure 8 shows the trajectory of the rocket according to the three sources.

Once again, the level of accuracy of the avionics, as received by ground station 3, is high. However, Global Positioning System (GPS) data is not completely accurate during the higher speed segment of the flight. This causes the divergence towards the west during the ascent. If the time is taken into account, it could also be observed that the GPS information is lagging behind during this part, and recovers precision once the rocket moves slowly.

The information from INTA was given in Universal Transverse Mercator (UTM) coordinates defined over the EUROPEAN DATUM 1950 ellipsoid, while the GPS offered geographical coordinates. The discrepancies between both can be appreciated in the descent segment when plotted over a flat surface.

On the other hand, the discrepancy in terms of apogee is clearly observed on the left plot. The expected apogee of around 10 km was approximately 2 km above what the rocket actually achieved. This is the effect of the higher drag force and lower motor thrust explained previously.

In terms of operation, launch platform orientation can be extracted from figure 8. The right subfigure clearly shows how the platform was not adequately oriented at 190º azimuth. This was detected during pre-launch operations after the platform was fixed to the ground. The large safety margins used in terms of wind tolerance and the high variability accepted in the MonteCarlo analysis eliminated the need to correct it, which would have been very time-consuming.

As for the elevation, an angle of 8º was measured with respect to the vertical, only 2º shy of the desired 10º. Since the result fell within the MonteCarlo variability, it was deemed acceptable. The difference cannot be observed on the graph.

6. Conclusions

This mission served as a means to grasp the sheer amount of systems involved even in a stratospherical launch such as Bondar's. Extensive testing, documentation, and careful operations, among other things, were key to carry the mission to successful completion under INTA's stringent requirements. Nevertheless, such an environment was enriching and a viewing window to what a commercial launch might entail.

Well defined operations specially, and carefully prepared protocols, allowed for a fast reaction to unforeseen circumstances and thus contributed to the success of the launch campaign.

Bondar's launch served as a valuable validation of CR's simulator, shedding light on the areas requiring further refinement. A bigger focus on the aerodynamics of the rocket fuselage is necessary for future rockets, as it plays an important role on the performance of the supersonic flight. If those aspects can not be tackled, better models for the characterisation of the rocket should be explored in order to increase the accuracy of the predictions.

Increased drag, coupled with alleged subpar motor performance, limited the apogee of the rocket to 7.8 km, 2.2 km shy of the expected 10 km. With a maximum speed of 572 m/s (according to INTA), the rocket reached Mach 1.7, and withstood accelerations up to 14 g. However, it did not prevent the rocket from becoming the most powerful ever launched by Spanish students.

Acknowledgements

Cosmic Research members gratefully acknowledge support from all the entities sponsoring our project. We would like to give special thanks to INTA and CEDEA personnel, as well as BiSky Team.

Additional thanks to ESEIAAT, the Polytechnic University of Catalonia, the Generalitat of Catalonia, HP, Siemens, ASPY and the city of Terrassa. A complete list of sponsors is available on our website [4].

Finally, a heartfelt thanks to all the former members that contributed significantly to the success of the Bondar mission.

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A student perspective into ESA Academy Space Systems Engineering Training Course

Davide Bellicoso[1]

Abstract

The ESA Academy's Space Systems Engineering Training Course is a unique educational opportunity offered by the European Space Agency's Education Office. It allows Bachelor, Master and PhD students to learn about the fascinating world of Systems Engineering and its applications within the space sector, while bringing this captivating framework of challenges and satisfaction to life for the participants of the Training Course. During this course, the whole life-cycle of a space project is explored from a System Engineering viewpoint, and students can learn about the challenges of Space Systems Engineering. Moreover, the Systems Engineering process is explored in detail [1]. Taught by ESA experts, the Training Course is delivered through formal lectures, with a heavy emphasis on the interaction with the students. During the course, students take part in group exercises aimed at putting the theory learnt into practice. This paper purposes at giving an overview of the training course, as it took place online on the 12th-20th of July 2021, and at addressing the benefits of the Author's participation into the Training Course for his studies and future space career.

Keywords

Systems Engineering, ESA Academy, Training Course

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Acronyms/Abbreviations

ARCADIA	*Architecture Analysis & Design Integrated Approach*
ASEP	*Associate Systems Engineering Professional*
INCOSE	*International Council on Systems Engineering*
MBSE	*Model-Based Systems engineering*

1. Introduction

Nowadays, System Engineering plays a crucial role in all space missions, as the inherent complexity of such projects is extraordinary suitable to be addressed by it. Systems Engineering approach has proved to be capable of reducing the costs of late design changes by a 50x factor [2].

The International Council on Systems Engineering (INCOSE) defines Systems Engineering as “an interdisciplinary approach and means to enable the realization of successful systems” [3], while for ESA it is “an interdisciplinary approach governing the total technical effort to transform requirements into a system solution” [4].

When it comes to space projects, Systems Engineering is a powerful approach which aids the development of the mission along its whole lifecycle, from Phase 0 to Phase F. Thus, the System Engineer must have interdisciplinary knowledge related to all subsystems and in general they must have a comprehensive view of the entire mission, needs and activities.

However, the aforementioned background knowledge is not sufficient to qualify somebody as a skillful Systems Engineer. A lot of experience in the field is required, in order to master the extensive methodology related to the Systems Engineering domain.

Therefore, the ESA Academy’s Space Systems Engineering Training Course explored in this paper, has the two-fold objective of providing students not only with the theoretical notions necessary to understand the framework in which Systems Engineering takes place, but also to allow them to take part in group exercises in which these notions are put in practice, by means of the application of Systems Engineering practices to a Mars Sample Return Mission.

2. Training course overview

All lectures were delivered online in real time to 30 University students from ESA Member and Associate States. Moreover, students could count on a single website which gathered all useful links and information, such as general communications and training material.

Table.1 Training Course Schedule

Day 1	Introduction, scope and context of Space Systems Engineering, tasks of a System Engineer, how to represent a system
Day 2	System Engineering process and system requirements, requirements capture and specifications
Day 3	Concurrent Engineering, system options and trade-offs, mission architecture
Day 4	Budget and margins, mission timeline and system modes, system design loop
Day 5	Development and verification approach
Day 6	Project, engineering and quality management
Day 7	Risk management and LEOP

The course covered all aspects of Systems Engineering applied to space missions, extensively going through the processes of requirements definition, architecture definition, budgets and margins management, system design, quality assurance, verification and validation, operation and lifecycle management. It also gave students valuable insight into Concurrent Engineering design and model-based systems engineering as well as the interactions with project management, including project planning and risk management.

Apart from theoretical lectures, participants were divided in small groups of five and took part into group exercises aimed at getting them familiar with Systems Engineering practices and some real-world problems faced by space systems engineers. The numerous group sessions were part of a unique exercise which challenged students in the preliminary sizing of the subsystems needed to perform a Mars Sample Return Mission, and went through the processes of requirements capture, mission architecture definition and trade-offs, preliminary system design, launcher selection and budget finalisation.

After completion of the Training Course, the link to the Evaluation Questionnaire became available for the students. The test was mandatory in order to get the participation certificate, and consisted of several multiple-choice questions. The students had 30 minutes to complete it.

3. Educational benefits

The Training Course provided participating students with an overview of the scope and context of Systems Engineering in general, then it proceeded outlining the role of a system engineer. It also gave extensive explanation of the Systems Engineering practices which are usually implemented in a space mission. The Training Course allows participating students to unlock the path for a career in a new domain, which they only heard about at University. In fact, further ways to be involved in the role of System Engineer and learning opportunities are described during the Training Course.

For example, the Author decided to take up further educational opportunities related to the field of Systems Engineering. In particular, he prepared and passed INCOSE ASEP Certification, completed an online course regarding Model-Based Systems Engineering (MBSE), and became acquainted with relevant software such as Capella MBSE Tool. This ESA course boosted his interest in learning more about the methodologies used to perform Systems Engineering in space missions, so he discovered ARCADIA approach and was motivated to acquire proficiency in using Capella MBSE Tool to implement all Systems Engineering practices in an MBSE environment for a space mission, including requirements management, Operational Analysis, System Analysis, Logical Architecture, Phyisical Architecture, but also modes management, mission Phases definition, Concept of Operations and AIV/AIT plan development. The Training Course played a key role in bringing these additional opportunities to the attention of students, and to boost their ambition to further develop the knowledge acquired through the Training Course.

Thanks to his participation in the Training Course, the Author has received many inputs for the development of his future career in the Space sector. Moreover, he has been exposed to intense interaction with the other participating students coming from other institutions and professionals such as the ESA Education organisers and ESA experts. Getting in contact with students from several universities enabled the participants to enrich their network and to share their educational paths.

The possibility of accessing the trainers and organisers' biographies has been of great value for collecting essential information regarding different backgrounds that bring someone to work in the Space sector, especially in the Systems Engineering domain.

Thus, taking part in the ESA Academy's Space Systems Engineering Training Course the Author got more familiar with Space initiatives and gained important knowledge and experience for his future Space career.

Fig. 1 (Partial) Group photo

Acknowledgements

The Author would like to acknowledge the entire ESA Education Office team, as well as the ESA experts who taught the lectures, for the excellence of the Training Course and the possibility to take part in it. They have been inspiring mentors throughouth all the Training Course.

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Come fly with us: services provided by the Space Weather Education Centre

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Abstract

The Solar-Terrestrial Centre of Excellence brings together and supports sun-space-earth research and services present at the federal level in Belgium. In 2019, the STCE was a founding member of a European network, PECASUS, that provides space weather services for civil aviation. Our expertise in solar observations and research combined with the experience of our Global Navigation Satellite System and solar particle radiation group proved to be crucial.

The STCE also strongly invests in education and training as these are a backbone of quality research and services, and therefore created the Space Weather Education Centre. This centre offers the Space Weather Introductory Course covering the Sun, solar storms, heliosphere, ionosphere, magnetosphere, instruments and methods to observe solar and space weather activity, as well as reading and interpreting our space weather bulletins. This course is taught to future space weather advisory staff, both military and civilian. It is based upon the STCE's expertise gained through scientific research, involvement in space missions and space weather monitoring, and on its forecasting capabilities. The course is given by qualified staff.

In addition to the Space Weather Introductory Course, the STCE has been and remains involved in a wide range of outreach activities, from public lectures, over dedicated classes and workshops at schools, organization of public events like open doors, publications in popular journals and on online media, scientific newsletters and press releases, to the participation in science festivals and the organization of events for the scientific community.

In this paper, we present more details of our educational programme, reflect on the methodologies used, and provide an overview of the obtained results.

Keywords

Space weather, outreach, education, aviation

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Acronyms/Abbreviations

BIRA-IASB	*Royal Belgian Institute for Space Aeronomy*
GNSS	*Global Navigation Satellite System*
JSWSC	*Journal for Space Weather and Space Climate*
KNMI	*Koninklijk Nederlands Meteorologisch Instituut*
PROBA2	*Project for On-Board Autonomy*
RMI	*Royal Meteorological Institute of Belgium*
RNLAF	*Royal Netherlands Air Force*
ROB	*Royal Observatory of Belgium*
STCE	*Solar-Terrestrial Centre of Excellence*
SWEC	*Space Weather Education Centre*
SWIC	*Space Weather Introductory Course*

1. Introduction

The Solar-Terrestrial Centre of Excellence (STCE) brings together research, expertise, and services regarding sun-space-earth sciences that are present in the three institutes located on the Belgian Space Pole: the Royal Observatory of Belgium (ROB), the Royal Meteorological Institute of Belgium (RMI) and the Royal Belgian Institute for Space Aeronomy (BIRA-IASB). This overarching structure creates synergies, new collaborations and an increased visibility for the Belgian expertise in these fields.

An important focus of the STCE activities is on space weather, which describes the conditions in space in the vicinity of Earth under the influence of solar activity.

When the STCE was founded in 2006, a communication, education and public outreach cell was included to address the clear need for information about space weather. At that time, the societal awareness of space weather and its effects on biological and technological systems was still very low. As a result, the STCE strongly invests in education relying on a firm academic and service experience. Our Space Weather Education Centre (SWEC) [1] offers tailored courses and dedicated training modules. Through its activities and expertise, SWEC raises awareness of the existence and consequences of space weather effects to third parties. Companies with space related activities, companies with an interest in navigation and radio-communication, energy plants, and the aviation industry are important targets.

In this paper we present a number of educational activities undertaken by the STCE, with a focus on the Space Weather Introductory Course (SWIC).

2. The STCE communication, education and public outreach cell

To spark interest in space weather, solar and atmospheric sciences, we address scientists, students, professionals and non-professionals, children and the general public; and target each of those groups with the most appropriate tools.

The broad public are citizens with no formal scientific solar education and not linked professionally to solar research. The STCE communicates with this target audience through websites, press releases and news articles, educational packages, face-to-face encounters such as open doors and public talks, social networking and science fairs. One example of a popular educational package set up by the STCE is 'PROBA2@School' [2]. In this project we targeted Flemish schools (both on primary and secondary level) and offered tailored workshops concerning space weather and the second Project for On-Board Autonomy (PROBA2) satellite [3], ranging from 1 hour up to 3 days in duration.

Communication with the solar scientific community occurs mostly through interactive websites, meetings, scientific articles, the weekly STCE newsletter [4], and user guides combined in our Space Weather Shop [5]. The STCE also operates the Editorial Office of the Journal for Space Weather and Space Climate (JSWSC - [6])

These user guides are also of interest to the non-solar scientific community affected by space weather, such as aviation advisory staff. The shop provides an excellent introduction to the topic, which users can digest at their own pace. For those who need more in-depth training on space weather and its effects, we provide the Space Weather Introductory Course.

3. Space Weather Introductory Course

The SWIC was initiated in 2016 on request of the Dutch and German military forces who wanted a space weather course for their space officers and weather forecasters. The main goal of the course was that the participants would gather a basic understanding of space weather and learn to correctly interpret the URSIgram or similar daily space weather bulletins, to relay the necessary info and warnings to the field personnel. As such, they were called "space weather operators", and the logo for the SWIC originates from there (Figure 1).

Figure 1. SWIC Logo

The Koninklijk Nederlands Meteorologisch Instituut (KNMI) joined in the development of the course shortly after. Now also the duty officers of the PECASUS [7] service follow the SWIC. PECASUS provides advisories on enhanced space weather activity for civil aviation. The STCE supports this service in the form of the SWIC, which is open to all PECASUS partners. The first SWIC took place in May 2017, with the fourteenth edition in March 2022. No courses took place in 2020 due to the outbreak of the COVID pandemic. In total, already more than 100 trainees took part in this course.

The course is intended as an entry course on space weather. It provides an elementary overview of the relevant aspects of space weather without invoking complicated background physics. The course is intended for meteorologists and space staff that will be providing space weather information to military and civilian end users.

Aside from individual participation, it is also possible for an institute to request a SWIC to be organized for their employees. Depending on their academic level, the institute can choose to refresh certain physical and mathematical basics to allow the trainees an easier understanding of the SWIC's main portion. This is called the pre-SWIC and is given by the requesting institute itself. Similarly, this institute may also elect to educate the trainees on the space weather effects on the specific equipment they handle (e.g. the military). This so-called post-SWIC takes place after the main SWIC and is again the responsibility of the requesting institute. For obvious reasons, the pre- and post-SWIC are not a systematic part of the main SWIC.

The introductory course can be extended with topical modules or tailored to the specific needs, background level and interests of the participants. An end user from the aviation or telecommunication sector, for example, has other needs than a space weather forecaster in a solar research centre.

The programme focuses on gaining knowledge by fact-learning and training skills through easily accessible methods like repetition and games. The on-site editions include a visit to the beating heart of our service centre and a ‘Meet & Greet’ with scientists and forecasters. SWIC has the tools to evaluate the participants and can provide an examination certificate.

The SWIC is taught by qualified and experienced staff with extensive expertise in relevant domains such as scientific research, solar physics, space weather, forecasting, engineering, communication and outreach, and teaching.

Due to the COVID pandemic, the courses planned in 2020 were canceled as participants were unable to travel to the STCE. From 2021 onwards, we restarted with a fully online version of the course. The encounters with STCE scientists were replaced by guest lectures and the exercises were reinvented using existing, easily-accessible online tools. The added benefit of having a fully online version of the course is that it allows us to reach an audience that cannot easily travel to Belgium. We organized for example a tailored course for members of the United States Air Force for whom travelling to Belgium for a 3-day course is too time-consuming. Online participation is also advantageous for environmental and climate reasons and to avoid extra financial costs. We plan to continue organizing the SWIC alternating between online and on-site editions.

3.1. Course Contents

The content focuses on space weather and the effects on man-made infrastructure and its functionality.

We discuss solar eruptions of very high-energy matter and electromagnetic radiation, which inject massive amounts of energy in the Earth's magnetosphere and ionosphere leading to pronounced impact on navigation, communication and energy transport.

The basic concepts and drivers of space weather are described first, with an added overview of the different sensors used to monitor the activity. From the Sun, we move to the magnetosphere, thermosphere and

DOI: 10.5821/conference-9788419184405.004

ionosphere and discuss how they are impacted. The impacts on aviation specifically, in particular in the framework of PECASUS, is described in much detail on the last day of the course.

By the end of the course, the trainees understand the basics of space weather and know about the potential impact on technology. The students are also able to understand and interpret the space weather information provided by the space weather forecast centers.

3.2. Didactic Methods

The SWIC caters to a very diverse public, which are not always trained extensively in mathematics and physics. While we only expect a medium secondary school knowledge of mathematics and physics, most of the participants have working experience in weather forecasting or engineering, and have an interest in natural and technical sciences. From time to time we have participants that are working as civil servants in risk assessment. Their knowledge of physics is usually limited, and then we adapt the course accordingly by expanding more on the basic principles. Everyone is required to have a good working knowledge of English since that is the teaching language.

In the course we focus on the physical principles of space weather without working out the details mathematically. There are little to no equations shown in the course notes. All principles and concepts are explained verbally and with graphics and movies, making use of comparisons to known concepts wherever possible. We intentionally keep the number of participants low (up to 8 trainees per SWIC in the more recent editions) such that we can monitor their understanding and progress closely.

The on-site course comprises three days, while the online course is spread out over four days. There is a huge amount of material for the students to absorb. We found that when teaching online it is harder for the students to concentrate for an extended period of time, also because we cannot do site visits in this case, which tend to make the day somewhat lighter. Therefore, we spread the online course over more days. For the on-site course the trainees have to travel to the STCE and so it is best to comprise it into fewer days to reduce the total time spent on the course.

Starting 2022, the concluding online evaluation of the course was moved to the week after, so that there is more teaching time left and the trainees have more time to study the course material before being tested. Throughout this week the teaching staff is available to answer any remaining questions.

In the course of a lecture day, we alternate between didactical methods and tools. The basic principles of space weather are mostly explained through direct teaching, aided by presentations. The three experienced teachers that are responsible for the bulk of the course collaborate closely to harmonise their presentations. They also make sure to involve the audience through questioning and interactive slides, and encourage questions from the trainees. The program alternates these teaching periods with exercises, games and recapitulation moments. The main concepts and principles are repeated constantly such that the students can absorb the theory simply by attending the course. The trainees also have their own job to attend to and will have little free moments to spend on studying outside of the course time. We anticipate this by including the repetition in the course program.

The exercises include hands-on material where the students work with real-life space weather data and learn to interpret them. The games such as pictionary, taboo, ringing sunspots [8] and bingo are meant as a moment to relax and bond, but also serve as an opportunity for questions, recapitulation and repetition. During these exercises we can correct any misinterpretations as well. Additionally, each course day starts with a recapitulation of the previous day and a Q&A session.

For the online version of the exercises, we use Google Jamboards [9], which are free interactive whiteboards on which the students can work together. The courses are taught using the Zoom teleconference software [10] and we use many of the interactive features there such as the annotation option to make explanatory drawings, the breakout rooms to allow students to work on the exercises in small groups and the poll feature for quick tests. The final evaluation of the trainees takes place online through the STCE website.

The slides of the presentations are provided to the students and serve as course notes. They are accompanied by explanatory text, of which the content is much broader than what was discussed during the course itself and which includes useful links. The slides serve as a

DOI: 10.5821/conference-9788419184405.004

reference for the trainees when executing their future job interpreting space weather forecasts.

4. Discussion, feedback and reflections

Throughout the SWIC, much attention is spent on feedback from the students. At the end of each day and at the end of the course, we ask the trainees for their reflections, comments and suggestions. For the students that prefer to share their opinion in private, we invite them to do so once more when we deliver them the course certificate. The teaching staff can easily be contacted by the trainees and actively encourage the students to reach out with questions and feedback.

Throughout the years, this open attitude has allowed us to improve the course, for example in refining the order in which the different subjects are tackled and adding extra course time at the start to introduce basic concepts that are needed throughout the course.

Also, when transitioning to the online version, the feedback of the students was much needed, for example on which online tools were easy to use and accessible to them. Note that some work in restricted environments where the installation of new software is not allowed.

After each edition, the teaching staff holds a meeting to critically evaluate the SWIC and to plan the next one. In these meetings exercises and course material are fine-tuned. One of the decisions that came out of them is to decrease the number of participants in the more recent editions, allowing for a closer monitoring of the students as well as more interaction between them.

5. Conclusions and Outlook

The SWIC has been a major success for the STCE, allowing us to reach a new public of meteorologists and aviation staff. The STCE already had a strong position in public outreach and communication towards the solar scientific community, yet it is very hard to cross the borders to other disciplines. Space weather is by definition an interdisciplinary science with a broad range of impacts. Through the SWIC, we can raise the awareness of other research institutes, companies and nations to space weather threats. The continued interest in the course shows there is a real need for this training. To our knowledge, there is no equivalent to it in Europe, even worldwide.

In the future we plan to diverge to tailored courses. In 2021 we organized a custom SWIC for the United States Air Force, focusing in a limited time span on the topics that were of most use to them. We plan to continue on this route by providing, in addition to the regular SWIC that is now on point, one-day topical SWICs focussing on ionosphere, aviation or high-frequency communication. A one-day, specialized course may also attract interested trainees that are unable to free up multiple days in their busy work schedule.

Acknowledgements

This work was supported by the Solar-Terrestrial Centre of Excellence. We thank our partners of the Royal Netherlands Air Force (RNLAF) and the KNMI, for their help in setting up and continuously improving this course. The SWIC has benefited greatly from the contributions of its guest speakers and the guides of the site visits, but also from the generous feedback of all participants up to now.

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Design and implementation of space educational activities to motivate young students in Catalonia

Guillem Olivella[1], *Marcel Marin*[2]

Abstract

STEM education is a new interdisciplinary concept that fuses the learning objectives of sciences, technology, engineering and mathematics. After concluding that many undergraduate students are not interested in STEM disciplines and taking into account the admiration for space, a series of educational activities have been developed to increase their engagement in this field. The proposed project-based workshops are diverse: designing and launching High Altitude Balloons; building water rockets; protecting an egg from the impact with the ground after being dropped from a drone; designing and building paper gliders; 3D printing customzied quadcopters, etc.

One of the most impressive activities consisted of designing, manufacturing and launching a low-cost high-altitude balloon to take photographs of the stratosphere. To do so, a kit was developed and validated: this contains a GPS tracker, a camera, an EPS box, a parachute and a helium balloon. The selection of the components was done trying to minimize the operational cost and maximizing the reliability of the design; the final High Altitude balloon weights 350g and has reached altitudes around 27.000 - 30.000 m. The educational activity is a 3 to 4 days workshop in which the students go through the process of building their own HAB, launching it and eventually recovering it to obtain the photographs.

The activities have been implemented in multiple schools and high schools in Catalonia, and all of them have shown excellent results. After evaluating the reasons why the workshops were well-received, it was concluded that students were more implicated than in standard lectures because they went from a passive to an active mindset. Moreover, the workshops were designed to make them become curious and increase their eagerness to learn, while forcing them to think and to take important decisions that ultimately influence the final result, rather than observing and admiring somebody else's work.

Keywords
STEM, Space, Workshop, HAB

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Acronyms/Abbreviations

HAB	*High Altitude Balloon*
STEM	*Sciences, Technology, Engineering, and Mathematics*
UAV	*Unmanned Aerial Vehicle*

1. Introduction

STEM education is a new interdisciplinary concept that fuses the learning objectives of sciences, technology, engineering and mathematics. It is a new way of learning, usually related to the project-based methodology, which stimulates interest and creativity among students. STEM careers are growing more and more as a demand of high-technological future societies (IoT, Smart Cities, 5G…) [1]. The problem lies in the fact that STEM studies are usually not the priority among undergraduate students and this could result in a decrease in the life quality of future societies [2]. Moreover, there is an important gender gap when dealing with STEM disciplines: The majority of bachelor's degrees are obtained by women; however, STEM subjects are not attractive to them [3][4]. Increasing this interest in early phases of education such as high school can reduce the gender and social class gap [5].

On the other hand, in many countries, it is very common to divide the disciplines into mathematics, technology, engineering and sciences when killing the creativity among students and making the learner lose generality whilst being close-minded [6]. This can be improved by applying a project-based methodology - to increase creativity and interest - with a STEM framework. As can be seen, new ways of teaching need to be put on the table in this new era: the learning procedures need to adapt to the new world.

Most of the programs and activities that use space to motivate young students to increase their interest in STEM disciplines use an admiration-based methodology: They consist of showing examples of big achievements of difficult challenges (outreach strategies of Rosetta mission and Apollo program) [7]. Usually, in this kind of outreach strategies, the student does not have the opportunity to create anything. This is a logical approach since access to space is, in the majority of cases, expensive and technologically difficult. By doing so, most of the potential of space and its attractiveness to motivate high-school students to start STEM careers is lost because they adopt a passive attitude rather than an active one.

In order to solve this shortcoming, a non-profit organization called GoSTEM was created. This is a project born in the International Space University to motivate students from all over the world to pursue STEM careers. The goal of the organization is to find an educational project for each interested school, association, or group of students considering their needs and their desire to enter the world of space and STEM.

2. Workshops and activities

Currently, several workshops and project-based activities are being proposed by GoSTEM. These are:

1. "High-Altitude Balloon: photographs from the stratosphere".
2. "Saturn V: Fragile launch".
3. "Opportunity: Landing in an unknown planet".
4. "Wright Brothers' challenge".
5. "3D-printing your own drone".

All workshops are composed of the stages depicted in Figure 1.

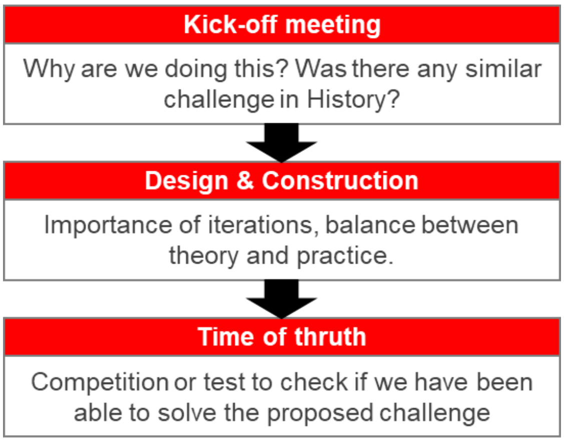

Figure 1. Workshops and activities architecture

Follows a small description of the activities and workshops. Note that all the workshops have been designed to be done with several students working simultaneously. In some cases, the motivation and capabilities among them vary and this may cause difficulties when trying to maintain a uniform flow when doing an activity. To solve this problem, all the workshops described hereunder have different layers of complexity and guidance. This allows the students to adapt to different rhythms and to feel comfortable within the educational activity.

2.1. High-Altitude Balloon: photographs from the stratosphere.

This is, without any doubt, the most impressive activity done by GoSTEM. The educational workshop consists of a 3-4 days project, whose ultimate goal is to take a photograph of the

Earth, from the stratosphere as the one shown in Figure 2.

Figure 2. Photograph of the Earth at 36.000m altitude (Taken by GoSTEM).

To do so, the students receive a kit designed by GoSTEM containing the following items: A sports camera, two independent GPS Trackers, all required components to do the platform for the High-Altitude Balloon, the parachute, and the weather balloon with helium [8].

Figure 3. GoSTEM High Altitude Balloon kit

2.1.1. Camera

To select the most appropriate camera for the HAB, five different properties were considered: weight, cost, image quality, temperature resistance, and battery duration. The final selection was an Apeman A80, which has an image resolution of 20 MP, a maximum visual angle of 170º, a minimum self-timer shooting mode of 2s, and a battery that has proved a duration of 120min @ -18ºC [9].

For this component, the students have to do a trade-off between the battery duration in low temperatures, image quality, and the rate at which the photographs are taken.

2.1.2. GPS Tracker

For the tracking system, 2 redundant devices are included in each kit. Both trackers are GPS-based but differ on the way of transmitting their position to the ground station: A SPOT Trace is used to transmit the position of the HAB via satellite (Iridium-based) [10]. An Invoxia GPS does the same function but transmits its position via the SigFox network [11].

2.1.3. Platform

The Platform is composed of three different components: an EPS Box (internal dimensions 160 mm x 95 mm x 35 mm), cross-linked polyethylene for the interior of the box, and methyl methacrylate to cover the hole for the camera.

The students are in charge of cutting, gluing, and preparing the platform to accommodate all other components.

2.1.4. Parachute

The parachute is built from scratch using nylon fabric. This is one of the most interesting designs that the students have to develop. From a basic equation that represents the static equilibrium between weight and drag, the students have to derive the parachute diameter from a given HAB mass and drag coefficient. Moreover, they have to do a trade-off to select the terminal velocity of the HAB. If the terminal velocity is too high, the components inside it such as the camera or GPS can brake down. On the other hand, if the terminal velocity is too low, the HAB can travel too much horizontally during its descent and this increases the probabilities of landing in remote areas.

2.1.5. Weather Balloon and Helium.

After many iterations, it was concluded that is was highly recommended to use an over-dimensioned weather balloon. This allows the HAB to ascent very quickly (which is favorable given the low battery durations in low stratospheric temperatures).

Moreover, online calculators such as the one presented by Habhub [12], are used to predict the flight of the HAB. Since these online tools require inputs in the form of parameters that describe the HAB, students are usually motivated to do tests and calculations to estimate properties such as the ascent and descent velocity.

2.2. Wright Brothers' challenge

This is one of the most complex activities proposed by GoSTEM. The challenge proposed to the students consists of designing and building a carboard airplane following all the design guidelines of a real airplane.

The concepts explained to the students include static and dynamic stability of an airplane, Lift,

DOI: 10.5821/conference-9788419184405.005

Drag, Center of Gravity, etc. This is presented in a simplified way that allows the students to understand the basic concepts without overwhelming them.
After going through structural and dimensional tests, the airplanes are thrown using a dedicated launch pad.
The structural tests consist of supporting the airplanes by their wingtips and hanging a mass from the airplane center of gravity.

Figure 4. Wright's Brother's challenge

2.3. Saturn V: Fragile launch & Opportunity: Landing in an unknown planet

These two activities are very similar and share the same architecture: a challenge is presented to the students consisting of designing, building, and testing a capsule capable of protecting an egg against its fall to the ground. For the first activity (Opportunity: Landing in an unknown planet), the capsule is launched with a water rocket and, with the second one (Saturn V: Fragile launch), the capsule is launched with a quadcopter UAV or by other analog means.
As all engineering challenges, a set of requirements constraints the design of the students:

- Maximum mass
- Maximum quantity of tokens used to buy materials to construct the capsule. *(Each student starts the activity with the same amount of tokens and the non-compliance of requirements supposes the removal of them)*
- Design envelope

This makes the students to work with a clear objective and the activity forces them to retrofit the design in order to meet the requirements.

Figure 5. Opportunity: capsule launch from UAV.

2.4. 3D-printing your own drone

The majority of educational activities consisting of building drones are limited to building a pre-designed UAV. GoSTEM has proposed, for this activity, the following: the students receive all electronics required to build a standard quadcopter, a set of 4 motors, and a flight controller. The challenge consists of designing and 3D-printing the frame (platform) of the quadcopter. The final drone contains a camera to transmit real-time images and a wifi-based comms system.
The activity also deals with concepts such as stability vs maneuverability by proposing different challenges to the students and making them adapt the design for each situation. An example of this is how the students have to adapt a drone prepared for an obstacle course to a drone capable of carrying a mass. The driver of the first design is maneuverability, hence, it has to be designed with short legs and low mass. The second one, on the other hand, has to have long legs to maximize stability.
The educational activity is complemented with simulators to practice how to fly a quadcopter.

3. Results and Discussions

In total, 698 students have participated in different activities, distributed as follows:

Table 1. Results [1]

Project	Students	
	M	F
"High-Altitude Balloon"	13	17
"Opportunity: landing in an…"	201	247
"Wright Brothers' challenge"	49	32
"Saturn V: Fragile launch"	68	55
"3D-printing your own drone"	10	6
TOTAL	**341**	**357**

DOI: 10.5821/conference-9788419184405.005

In summary, all the activities were a success: all the students had a great time developing their creations. As a reminder, the main objective was to motivate young students to engage in STEM disciplines by using the attractiveness of space. Their motivation during the activities was obvious since the vast majority of them were extremely engaged during all the workshops. This could directly imply a growth in the number of students engaged in STEM careers. After surveying all the participants, they declared that they increased their comprehension of the STEM concepts treated during the activity. Furthermore, they emphasized that the proposed workshops allowed them to have a first-hand experience with the theoretical concepts that the teachers explained to them in class.

In terms of gender equality, 51% of the participants were female students and no difference was appreciated between the motivation and performance between female and male students.

4. Conclusions

The educational project has proved to be an excellent platform to fulfill the objective of popularizing STEM disciplines.

The next steps would be to reach more and more schools and associations to continue motivating young students to engage in STEM disciplines.

As an example of this, two measures have already been implemented:

1. The creation of a website to present the project and spread it among all the schools in Catalonia:

   www.gostemspace.com

2. The creation of a summer camp that encompasses all GoSTEM workshops:

   www.spacecamps.cat

Acknowledgements

The team would like to aknowledge the International Space University and, in particular, Joan de Dalmau. We would also like to thank all the people that have contributed to the growth of GoSTEM such as: Professor Gonglin Sun, Jordi Mazón and Marc Boada.

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Mission analysis of nanosatellite constellations with OpenSatKit

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Abstract

CubeSat reliability is still considered an obstacle due to the sizeable fail rates generally attributed to the dead-on-arrival cases and early subsystem malfunctions. Thus, as CubeSats' primary purpose moves from technological demonstrations and university projects to missions where a significant risk of failure is not acceptable, an inexpensive method to emulate low Earth orbit constellations is being researched.

The results presented have been developed in the framework of the PLATHON research project, which intends to develop a hardware-in-the-loop emulation platform for nanosatellite constellations with optical inter-satellite communication and ground-to-satellite links. Consequently, a crucial aspect of this project is to have a sufficiently precise orbital propagator with real-time manoeuvring control and graphical representation.

NASA's OpenSatKit, a multi-faceted open-source platform with an inbuilt propagator known as 42, has been chosen to analyse the programme's feasibility in order to create a constellation testing bench. As an initial development of a software-in-the-loop application, the pre-processing of files has been automated; enhanced Attitude Determination and Control System manoeuvres have been added and configured through bidirectional socket interfaces, and the results format has been modified to be easily post-processed with MATLAB and Simulink.

Keywords

Constellations, Inter-Process Communication, Nanosatellites, Orbit Propagation

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Acronyms/Abbreviations

ACS	*Attitude Control System*
cFS	*core Flight System*
GNSS	*Global Navigation Satellite System*
GS	*Ground Station*
GUI	*Graphical User Interface*
HiTL	*Hardware in the Loop*
IoT	*Internet of Things*
IPC	*Inter-Process Communication*
LEO	*Low Earth Orbit*
NASA	*National Aeronautics and Space Administration*
NS3	*Network Simulator 3*
PLATHON	*Integrated Hardware in the loop simulation Platform of Optical communications in Nanosatellites*
SiTL	*Software in the Loop*
SSH	*Secure Shell Protocol*
TLE	*Two-Line Element*
ECEF	*Earth-centred, Earth-fixed*
ECI	*Earth-centred inertial*

1. Introduction

Since the beginning of the space age, satellite design philosophy was dominated by conservative designs built with highly reliable components to endure extreme environmental conditions. During the last two decades, the dawn of the CubeSats has changed this philosophy, enabling a whole world of new possibilities.

The deployment of monumental CubeSat constellations in low Earth orbit (LEO) is set to revolutionise the space sector by enabling faster and more economical innovation cycles. However, CubeSat reliability is still considered an obstacle due to the sizeable fail rates among universities and companies, generally attributed to the dead-on-arrival cases and subsystem malfunctions [1]. In recent years, increased flight experience is changing this trend, and future testing systems are set to considerably reduce the probability of any malfunction.

Mission Analysis is the design and analysis of satellite orbits such that the objectives of a space mission are achieved in the best possible way. Among the main tasks and outputs, this research has focused on ground station coverage, communication angles and distances between satellites, as well as eclipses and distance from the Sun, which are crucial to power subsystem manoeuvre strategies.

The results presented in this paper have been developed in the framework of the Integrated Hardware-in-the-loop (HiTL) emulation Platform of Optical Communications in Nanosatellites (PLATHON, from the Spanish acronym). This research project intends to develop a Hardware-in-the-loop emulation platform for nanosatellite constellations with optical inter-satellite communication and ground-to-satellite links.

Section 2 summarises the state of the art and programme selection, section 3 enumerates new programme contributions during all simulation stages, section 4 shows the results of the new features, and section 5 concludes with the current state of the project and potential improvements.

2. State of the art

In order to propagate orbits, there are open-source and private programmes that can perform the simulations with a wide range of detail depending on the project requirements. Among the available open-source options, the National Aeronautics and Space Administration's (NASA) OpenSatKit has been chosen because it offers HiTL capabilities and can be easily customised to interact with the project's models. Thus, as the programme is open-source, it is helpful for research and development purposes, and introduces students and professionals to the space sector.

2.1. OpenSatKit

OpenSatKit is a multi-faceted platform that combines three independent programmes [2]: Ball Aerospace Corporation's COSMOS command and control platform for embedded systems; NASA's core Flight System (cFS), a platform and project-independent, reusable software framework; and NASA's 42, a comprehensive, general-purpose simulation of attitude and trajectory dynamics and control which can be applied to numerous spacecraft composed of multiple rigid or flexible bodies [3].

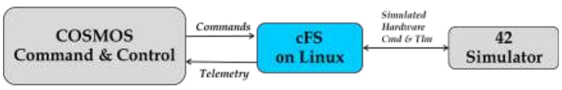

Figure 1. OpenSatKit platform connectivity [4]

This study aims to analyse the feasibility of NASA's 42 orbital propagator in the PLATHON project and its connectivity with OpenSatKit modules.

DOI: 10.5821/conference-9788419184405.006

2.2. PLATHON

Figure 2 portrays PLATHON's software applications, combining NASA's 42 and Network Simulator 3 (NS3), as well as with HiTL connections to the CubeSat test devices.

NS3 is a discrete-event network simulator containing precise communication channel models between nodes to calculate the optimal route between two points.

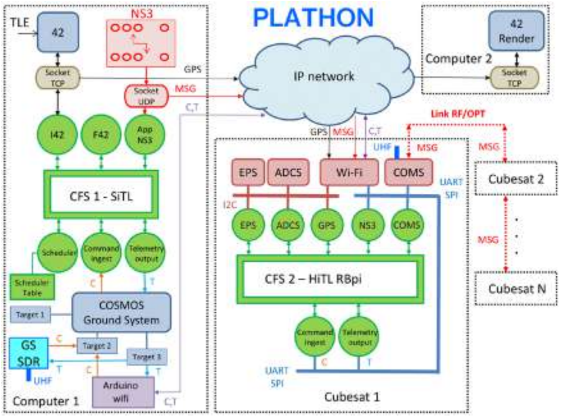

Figure 2. PLATHON project diagram

This prospective example considers a set of satellites that collect data from the Internet of Things (IoT) networks located across the world in areas inaccessible to the internet and relays the data to a connected ground station (GS) in an optimal way.

Since the communication system nodes are mobile, and their communication state changes with the satellite's time, position and attitude, it is necessary to calculate the previous possible routes at each point of the orbit.

For this purpose, it is necessary to simulate the mission with the OpenSatKit system and transfer the results to the NS3 so that it establishes the optimal routes for each position, taking into account all satellite positions as well as those from the IoT and GS, which will also be mobile due to Earth's rotational movement.

3. Programme contributions

Some programme modifications and new features are highlighted, and these are divided based on their relative position within the simulation.

3.1. Pre-processing

Due to the fact that 42's input variable system is based on structured text documents, where each file performs a specific function, it is necessary to automate the process for large satellite constellations. Thus, a MATLAB-based code has been developed to read database files and create the essential input files.

Furthermore, a capability to read two-line element sets (TLE), which is a data format encoding a list of orbital elements of an Earth-orbiting object for a given point in time, has been set to simulate current constellations with the latest available data. TLE constellation records are extracted from CelesTrak [5] and transferred to 42-readable document files within seconds.

3.2. 42 files and ACS

Initially, 42 is only set to save all spacecraft's dynamic and kinematic states, whilst most of the remaining properties are only kept for the first simulated body. Thus, the programme has been modified to be able to select and store the simulation data for every spacecraft. Depending on the magnitude of the constellation, a preselection of a pertinent memory allocation loop defines the maximum number of bodies to analyse. The concurrent number of active files has been modified for Linux OS versions as the files are created simultaneously at the end of the simulation.

Conditional on the purpose of the simulation, two 42 variants are defined; one for post-process data analysis and another for real-time communication with the Software in the Loop (SiTL) and HiTL capabilities

The simulator contains several basic attitude control subroutines, ranging from passive to active control. However, based on the Prototype control mode function, in which the satellite adjusts its attitude using a Proportional Derivative controller, new Attitude Control System (ACS) functions have been wholly reassembled to suit PLATHON's hardware models. The manoeuvres explored by these models are coarse and fine pointing with reactions wheels, as well as pointing and detumbling with magnetorquers.

Basic sensors and actuators are included. The truth value is tampered with noise and bias in the sensor models to simulate real-system distortion. At the same time, the maximum torque limits the actuator models according to the product specifications. In order to replicate the PLATHON's hardware currently under development, the laboratory specifications have been set to obtain reliable results.

The primary attitude control function is capable of determining the satellite's attitude with sun sensors, star trackers or gyroscopes, and adjusting it accordingly with a 3-axis stabilised system based on either reaction wheels or

DOI: 10.5821/conference-9788419184405.006

magnetorquers, depending on the manoeuvre speed requirements. The function has been tested with sun sensors to detect eclipse and to rotate so that solar rays impact the photovoltaic cells and not on the optic communication system, in order to prevent saturation. The system's node connectivity, possible states and phases are further explained in [6] and [7].

3.3. Inter-Process Communication

Once all the required modifications have been set for the use of the programme, it has been proceeded to analyse, modify and test Inter-Process Communication (IPC) capabilities. When hardware prototypes are tested on the air-bearing test bench [8], the satellite will not translate within the Global Navigation Satellite System (GNSS). Therefore, the IPC mechanism is required to use the position computed within 42 so that the simulation can be tested in a real-case scenario.

Regarding the whole emulator, 42 will be responsible for providing the orbit simulation variables. At the same time, other tasks will be delegated to external software for ACS and mission control, or to hardware sensors and actuators connected with the onboard CubeSat computer.

The system architecture comprises a leading 42 simulator, which interacts with the dependencies, N external standalone attitude control bidirectional applications, and an external 42 simulator that receives data and acts as a Graphical User Interface (GUI). Each external application simulates an individual CubeSat system. Figure 3 illustrates the system's architecture with two satellites:

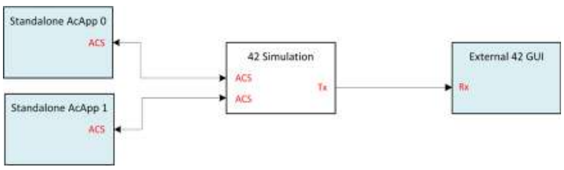

Figure 3. IPC system architecture

Each block can be located on a different device or combine several features on one computer. For the PLATHON project, the 42 Simulation and the Standalone ACS apps are based on the same server, while the graphical representation is in an external machine. However, everything can be controlled remotely from a unique device using Secure Shell Protocol (SSH) for convenience.

3.4. Post-processing

With all the available data saved into document files, a highly customisable MATLAB code extracts the formatted outputs and saves them into body-indexed matrices.

A 3D representation using Simulink has been designed based on MATLAB's Aerospace Toolbox for a limited number of satellites. The purpose of the model is to visually analyse attitude changes of 42 simulations, which can be saved into a high-speed video file.

As a result, it is unnecessary to rerun a previous simulation to view satellite manoeuvres. This saves computational time and allows the user to select a narrow interval of time at a specific simulation speed.

The required data comes from 42 output files except for the quaternions in the Earth-centred, Earth-fixed (ECEF) frame, as the programme only saves them in the Earth-centred inertial (ECI) frame. However, this approach was not designed for an expandable nmber of bodies. Thus, the visualisation of constellations is constrained to a low number of spacecraft, which is sufficient to validate the results among constellation subgroups or clusters.

4. Results and discussion

4.1. Constellation generation

Once the programme had been modified to fulfil the project's initial requirements, it was then tested and validated with custom design constellations, and currently operative ones such as Iridium NEXT, shown in Figures 4 and 5. This constellation covers the entire Earth with 66 active devices while another nine remain as a backup. This example was chosen because of its design in which each satellite is linked to the four closest satellites, enabling independent service from any local ground infrastructure.

Figure 4 illustrates the 3D Camera view at a particular time on 14 June 2021. The GUI allows for movement between satellites and shows local and global axes.

Figure 4. Iridium NEXT. 3D Camera View

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At the same time instant, the 2D map view of Figure 5 shows each satellite's position, current orbit, and field of view towards nadir.

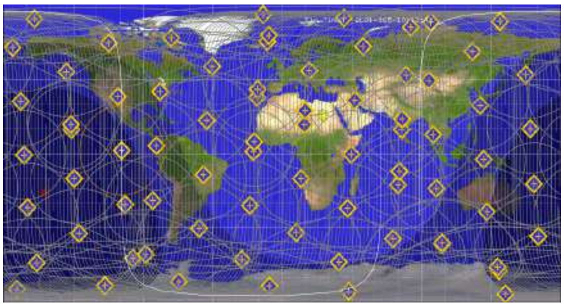

Figure 5. Iridium NEXT. 2D Map View

4.2. IPC and ACS manoeuvres

Regarding Inter-Process Communication, the current ACS app modification allows changing Euler angles at a specific time to simulate that two CubeSats rotate to point to each other and send data through optical communications.

This simulation serves as a demonstration of the IPC capabilities and as a proof of concept for the future PLATHON project architecture. It paves the way to a more elaborate simulation that recreates a full-on constellation when assembled with the cFS and NS3's node connectivity features currently under development.

Figure 6 represents two CubeSats orbiting in formation with their main body axis visible:

Figure 6. IPC Architecture – Initial attitude

At a specific time, both satellites receive a telecommand from their respective ACS applications to point to each other. The result is shown in Figure 7.

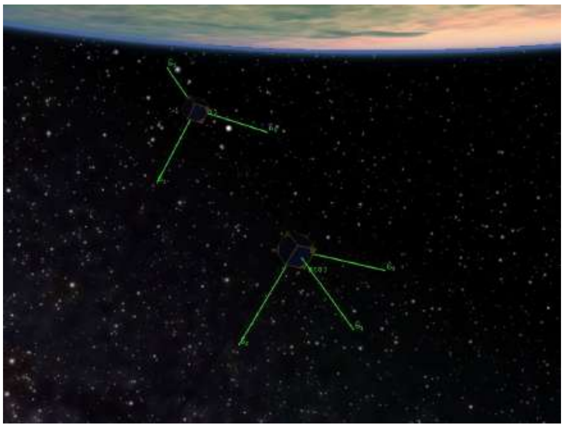

Figure 7. IPC Architecture – Modified attitude

The attitude modifications necessary to perform the rotations have been externally controlled from the main simulation. Each satellite takes into consideration the relative position of the other, and computes the rotations independently.

The visualisation is also being externally provided by another machine running 42 and relaying the data. The receiving device only represents the data as it comes through the socket interface.

4.3. MATLAB GUI

The MATLAB GUI offers an alternative approach that requires extensively less computational power, both in terms of CPU and GPU, once the results have been recorded.

Figure 8 shows the post-processing of the IPC architecture during the satellite pointing manoeuvre with Simulink 3D Animation.

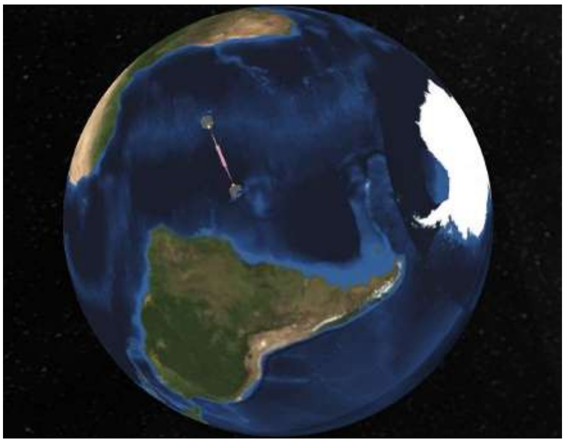

Figure 8. Simulink 3D Animation – IPC mode [9]

DOI: 10.5821/conference-9788419184405.006

5. Conclusions

The PLATHON project has selected 42 as the main propagator due to its connectivity with all the OpenSatKit modules. After analysing the whole system architecture, the connectivity between the programmes has been deemed feasible for the emulation of CubeSat constellation missions involving laser-based inter-satellite communication and ground-to-satellite links.

The pre-processing of input files has been automated to design custom constellations and download data from orbiting ones.

42 has been customised to PLATHON's mission, and it has been modified to be connected to the Inter-Process Communication network currently under development.

The post-processing of output files has been automated and combined with MATLAB features to save computational time and allow the user more manoeuvrability.

The results have paved the way for SiTL simulations, providing a basis for the subsequent software connections and hardware implementations, which may be performed in the following years to reach the next mission validation level with a complete HiTL emulation.

5.1. Future prospects

The PLATHON project requires extensive efforts to reach a fully functional, stable status.

42 propagator perturbation models, although precise for these analyses, will require more complexity to provide better approximations and higher accuracy during long simulations.

Similarly, the current 42 models for both sensors and actuators might be too simple to portray the fluctuating space environment. Considering that the GNSS position will be the only 42-dependant asset during the HiTL emulations, the model should be enhanced. The other sensors and actuators will be included within hardware connections.

Finally, integrating all the OpenSatKit modules through the IPC will be the logical step forward, principally combining the cFS with 42 and then with COSMOS.

Acknowledgements

The team would like to highlight the support of all of the PLATHON project individuals, both professors and students, who have contributed to the development of this paper.

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Design and methodology for a Remote Sensing course

Josep Sitjar Suñer[1]

Abstract

Remote sensing offers Geographic Information Systems specialists the possibility of integrating useful and powerful information into their analyses. As at least a basic knowledge of remote sensing principles and methodologies are desirable for anyone working in the geospatial industry, we include this competence as a mandatory subject in the curricula of our online master's degree in GIS analysis.

The topics of this remote sensing course have been selected based on our experience in the sector, but also with the support of tools like the body of knowledge developed by the GI2NK and EO4GEO projects. These applications can be very useful for anyone starting with the creation of new courses, as they take into consideration the recommendations of experts related to different sectors: from university to private companies, and also from the public sector.

The course is fundamentally based on practical work, but since it is introductory and most of the students are not familiar with the principles of remote sensing, it is essential for them to start understanding basic concepts such as electromagnetic radiation, electromagnetic spectrum, spectral signature, bands, etc. After that, they are prepared to start searching the best images for a specific project, perform image enhancements and corrections, compute indices and apply supervised and unsupervised classifications.

During the course, students are encouraged to use open-source software to develop the mandatory activities and the optional ones. Most of the tutorials are based on QuantumGIS and some of its main extensions to work with raster data and remote sensing images, but there are also tutorials based on GRASS Gis and SNAP. Nevertheless, students have total freedom to choose any available software (open-source or not) to perform the mandatory activities, and the tutor is open to resolving doubts about them.

Finally, the module is designed to practice with Copernicus and Landsat images. The use of these free catalogues offers the possibility to analyse phenomena from all over the world without cost, and it empowers students to carry out their own projects more economically. Also, the historical series of Landsat Images is very useful to evaluate changes over long periods of time.

Keywords
Remote sensing, GIS, e-learning, open-source, open data

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Acronyms/Abbreviations

BoK *Body of Knowledge*

CDT *Curriculum Design Tool*

GIS *Geographic Information System*

LST *Land Surface Temperature*

SCP *Semiautomatic Classification Plugin*

1. Introduction

The use of remote sensing data is very useful for Geographic Information Systems (GIS) specialists, as it provides powerful information for their analyses.

It is for that reason that the UNIGIS Girona master's degree in GIS includes a subject about remote sensing, in which students understand the basic principles of this discipline and also learn how to obtain, process, analyse and extract information from satellite datasets.

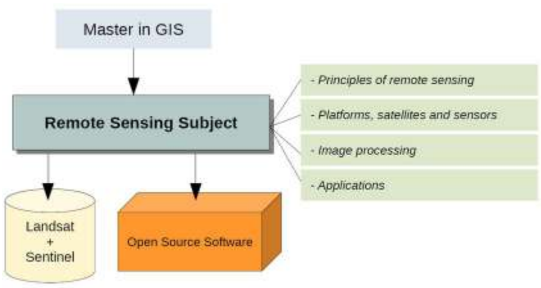

Figure 1. Remote sensing subject in the framework of a Master's degree in GIS.

Designing this kind of subject requires a knowledge of the needs of the sector, and tools like the Body of Knowledge (BoK) developed in the framework of the GiN2K and EO4GEO projects can be of great help.

Access to open datasets, like Copernicus or Landsat, are a very valuable resource for this course. Students can access these catalogues for free, and obtain images to analyse a great variety of study cases.

Open-source software is also a recommendation for students in order to visualize and analyse the images. During the course, they are provided with tutorials and guided activities about QGIS and the Semiautomatic Classification Plugin (SCP), SNAP and GRASS GIS.

2. Discussion

The methodology based on the learning-by-doing approach is adopted in all the subjects of the UNIGIS-Girona master's degree. And the remote sensing subject is not an exception in that sense.

Students must solve some practical activities that will help them to acquire the competences of the course.

In order to complete the mandatory activities, students have some resources at their disposal:

- Learning materials

- Self-study activities

- Webinars

- Lectures and online resources

Also the **forums** are a very valuable part of the learning methodology of the subject. Through these channels the tutor can answer student's questions, and also mentor them on how to complete the activities.

2.1 *Subject structure*

The remote sensing subject is structured in four different units.

The first one, **introduction to remote sensing**, is just an introduction to some basic concepts of remote sensing such as electromagnetic radiation, electromagnetic spectrum, spectral signature or bands. Since most of our students have never used processed remote sensing images, they need to be familiar with these basic concepts, which will help them later to complete the mandatory activities.

A questionnaire is used to verify if students have learnt these theoretical concepts.

The second unit, **platforms, satellites and sensors**, refers to the different types of available platforms and sensors, the missions which provide remote sensing images (Copernicus, Landsat, Spot, Ikonos, Aqua and Terra, etc.) and the different ways to obtain these data.

In this unit students are also introduced to the different types of resolutions: spatial, spectral, radiometric and temporal.

The third unit, **image processing**, introduces the steps to perform image processing. The unit also deals with the application of geometric and radiometric correction techniques and image enhancements.

Finally, the image processing unit shows how to apply the different techniques to analyse the images visually and statistically.

The last unit, **applications of remote sensing images**, shows the applications of remote sensing in different areas: forest, agriculture, oceans and water, ice, cartography, geology and land use. It is also the unit where students learn how to extract information from satellite data, applying indexes, classifications and algorithms to obtain Land Surface Temperature (LST) from thermal bands.

In order to evaluate the competences acquired by the students, they have to work on two different practical activities. Both of them try to emulate a real study case, and are designed to perform the following tasks:

- Search and download images from a public catalog.

- Apply an image correction process over the images.

- Create RGB band combinations.

- Calculate indexes, such as NDVI, NDWI, NBR.

- Apply cloud masks.

- Create image mosaics.

- Obtain LST from thermal bands.

- Execute a supervised classification process.

2.2 The software

The objective of a subject like this is to learn how to deal with remote sensing images and apply the correct methodologies in order to extract useful information from them, but not how to use a specific software, library or toolbox.

Nonetheless, it is obvious that students will perform the activities with a specific tool, and they need to be instructed on that.

Our first approach is to let the students to choose their preferred tools, although we offer some recommendations and materials (lectures, tutorials, manuals and self-study activities) related to specific software.

In that sense, our priority is to recommend the use of open-source tools. So, students are encouraged to use tools like QGIS with the SCP plugin, GRASS Gis and SNAP. With these technologies, they can complete all the mandatory activities, and we consider that are very useful for acquiring the mandatory competences of the subject.

For those students who choose other options, like ArcGis Pro, ENVI, Erdas, etc., we don't offer support materials, but if necessary we can give advice through the forums.

2.3 The data

Nowadays there are lots of missions providing remote sensing images.

It is in fact one of the main competences of the second unit of the course (**platforms, satellites and sensors)** to be familiar with some of these missions and know their main characteristics in order to choose the best one for a specific project.

As it would be completely impossible to design activities to work with data from all the available missions, we can select only some of them.

Due to its impact on the industry, historical series and open access, **Landsat** data are widely used during the course. Students can easily obtain the images from Landsat catalogues using applications like Earth Explorer [1] or through the SCP plugin. Also, Landsat data formats can be directly used by our recommended software solutions and are offered in different processing levels.

Data from the **Copernicus** programme are also used during the course, especially the images offered by the **Sentinel** missions. In the same way as with Landsat images, Sentinel data can be obtained for free through applications like Sentinel Open Access Hub [2] or also the SCP plugin.

In the case of Sentinel datasets, we mainly work with the images provided by the optical sensor on board Sentinel 2. But we've also prepared a non-mandatory activity where students can practice with the radar images provided by Sentinel 1.

2.4 EO4GEO

Our experience developing projects in the geospatial sector is fundamental for designing a programme for a subject like this. We can easily identify the skills that student must acquire in order to successfully join a team involved in the use and processing of remote sensing images.

However, beyond the experience, there are some tools that can be very useful in order to help in the design of such a programme.

EO4GEO[3] is a co-funded project of the Erasmus+ Programme of the European Union which aims to bridge the skills gap between the supply and demand of education and training in the space/geospatial sectors.

In the framework of EO4GEO, a set of tools based on the GIS&T body of knowledge [4] have been developed.

For example, the ‘**Bok Visualization and Search**’ [5] tool allows users to navigate and visualize the EO4GEO BoK in a graphical and textual way. Starting from higher level concepts representing areas of knowledge in the field, one can browse down to more detailed concepts. So, this tool is specially indicated to identify the knowledge areas and concepts that the subject should integrate.

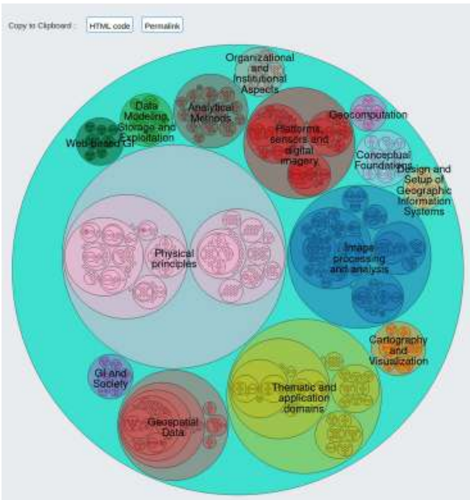

Figure 2. BoK Visualization and Search tool.

The ‘BoK Visualization and Search’ tool is public, and no registration is required.

The ‘**Curriculum Design Tool**’ [6] (CDT) allows users to create, edit and find educational offers in the field of Earth Observation and Geographic Information. The tool could be useful to define the remote sensing subject programme re-using descriptions of related BoK concepts and link specific EO/GI BoK concepts and skills.

3. Conclusions

Remote sensing is a very valuable source of information for GIS projects. So, from our point of view, a master’s degree in GIS must include a course about remote sensing.

A subject like this should guarantee that students have learnt the basic principles of remote sensing, and have also acquired competences in order to search and download remote sensing images, perform enhancements and corrections over them, and also extract information by applying some processes like RGB band combinations, index calculations, band maths or classifications.

Open-source tools like QGIS and the SCP plugin, GRASS or SNAP are good candidates to use during the course.

Despite the wide variety of providers, the open catalogues form Landsat and Sentinel are very useful for acquiring the skills of the course.

Finally, the GIS&T BoK and tools developed in the framework of projects like EO4GEO can help in the design of the course topics.

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CANSAT Competition 2020: Best technical development by OrbiSat team

David Hernando-Diaz[1]

Abstract

OrbiSat is a high school educational project that was part of the CANSAT SPAIN 2020 student competition organized by ESERO. This project has ranked first in the Catalonia Championship and second at the National Championship, winning the prize for the best technical development. OrbiSat has successfully fulfilled the objective of creating a mini satellite with the size of a soda can that was later launched by a rocket of the COSMIC Research UPC Students Association to analyze physical aspects of the air such as pressure, temperature, humidity, or the amount of UV solar radiation of a territory.

Thanks to the CanSat presented by this team, during the launch we were able to know the presence of up to 15 chemical elements in the air. Elements ranging from hydrogen and oxygen can indicate water in the atmosphere or other greenhouse gases such as CO2 or methane.

The launched rocket reached an approximate height of 532.7 ± 1.5 meters, with the sensors we were able to determine the apogee of the rocket and the subsequent release of the minisatellite and deployment of the parachute. We were also able to interrelate the altitude data with parameters such as humidity, UV radiation, presence of hydrogen, among others.

The CanSat presented by the OrbiSat team had a unique design never seen before in other CanSat competitions, solving problems such as high weight and overheating. This design made by AutoCAD was an open concept where the air can refrigerate the CPU and also the 3D printed concept saved 125 grams over a third of the maximum allowed. In addition, all the data collected was broadcast in real-time and received by a ground station every 0.25 seconds.

Before the launch, a simulation was completed estimating a 61 seconds flight, finally, the real flight was 59 seconds. The vast majority of the project was done during the COVID-19 pandemic, the consequence was new methodologies to carry on the project with a minimum time for the workshop and test phase that were supplied with simulations having a better performance than expected.

Keywords
CanSat, Educational Project, ESERO

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1. Introduction

CanSat is an initiative of the European Space Agency [1] that challenges students from all over Europe to build and launch a mini satellite the size of a "soda can" to a height of no more than one kilometer. The challenge for participants is to fit all the major subsystems found in a satellite: electric power, sensors, and the communications system. Everything must fit into the volume and shape of a soda can.

Subsequently, the CanSat will be launched, in our case by a rocket, to a height of no more than one kilometer. Although on other occasions, it is dropped from a platform, a drone, or a balloon. Once the CanSat parachute [2][3] deploys, the mission begins, and the satellite starts to perform scientific experiments as it descends and lands safely. After the flight, the teams must process the data and draw conclusions about the flight.

The experiments that the CanSat will perform while descending are divided into two parts firstly, the Primary Mission, mandatory for all teams and consisting of the constant emission from the satellite and reception from a ground station [4][5] of temperature and atmospheric pressure data at least once per second.

The Secondary Mission is free and is the one that differentiates CanSat from the other teams. However, the implementation of both in a different way led the OrbiSat team to win the technical achievement for the complexity and originality of the design, implementation, and integration.

In the case of the OrbiSat team, the Primary Mission mentioned above communicated with the ground station four times per second, allowing us that if one of the temperatures and atmospheric pressure data did not arrive or arrived damaged, it could be discarded without affecting the overall results. We also decided to extend it a little more by obtaining the humidity data and sending the satellite's GPS position through the antenna, which helped to locate it once it had fallen.

The OrbiSat team's secondary mission was to recreate a kind of probe satellite that would be launched on a planetary mission. As it descended through the atmosphere, it would collect data on gases that might be in the atmosphere of the hypothetical planet. It also collected information on UV radiation, and all were stored on two SD cards that served as a backup if one was damaged during the impact.

2. Prototype

2.1. Version 1

The CanSat structure presented here shows an open concept that has been entirely designed in AutoCAD, allowing us to save many resources since we were able to perform tests and simulations of practical space for the placement of the various experiments without the need for further printing.

2.1.1. Materials

The material used for the structure was Polylactic Acid, commonly known by its abbreviation (PLA). The properties of PLA [6] are interesting; the one we highlight is its melting temperature as it is relatively low, between 130 - 180 ºC making it an ideal material for 3D printing. In addition to the properties that this plastic has that perfectly adapt to our needs, it is a plastic obtained from fermented vegetable starch. In other words, it is a plastic that does not come from petroleum.

2.1.2. Prototype parts

This prototype CanSat (Figure 1), was divided into three parts. The lower part was where the battery and two SD cards would be housed. The middle part, a circular piece 3 millimeters thick, served as the lid of the lower part and the base of the upper part. Finally, the upper part was the structure that would house all the sensors, the Arduino UNO board, and the GPS antenna.

The lower part (Figure 2) has three protected areas; the first two on the starboard and port side of the CanSat are symmetrical and one more in the aft area. In addition to protecting batteries and SD memory cards, this is the place where this part connects to the rest of the CanSat's parts.

The upper part has three columns located at 120º and whose thickness is 10.6 millimeters. These columns allow having an interior space where all the sensors were located. Moreover, we would find another circular cover attached to the columns in the upper part. This cover has two holes, the first and central one where the eyebolt that would join the parachute with the CanSat would be located. The second hole was used to pass the cables from the lower part to the upper part.

The pieces of this first CanSat prototype were joined with polymer glue.

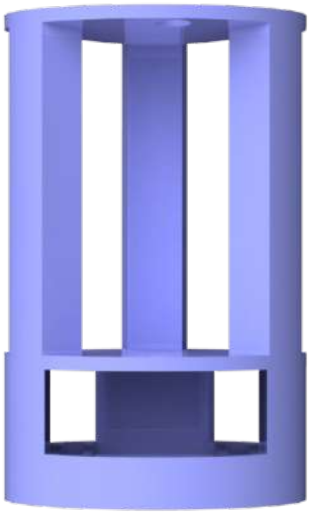

Figure 1. CanSat Prototype Version 1.

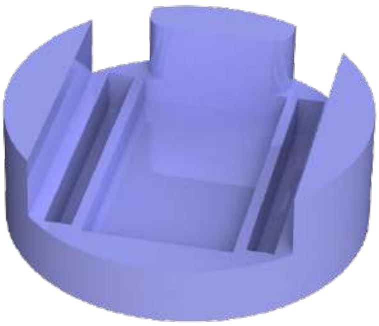

Figure 2. Lower part section CanSat Prototype Version 1.

2.1.3. 3D Printing

The 3D printing was carried out, leaving a square mesh inside the structure, which allowed saving weight, counting both the mesh and the outer layer, which was solid. As a result, we only used 30% of the material compared to making the whole figure solid.

2.2. Version 2

We did not have the opportunity to print this second prototype, although it would have allowed us to correct errors that we had detected after submitting the first prototype to some tests.

2.2.1. Materials

The materials used were the same as the first prototype: PLA plastic and polymeric glue.

2.2.2. Prototype parts

This second prototype (Figure 3) had two pieces, the first lower part formed by the lower part mentioned above and the circular piece that acted as a lid. The second part was very similar to the upper part mentioned before.

The lower part (Figure 4) in this prototype was going to be the sum of the lower part of the first prototype and the intermediate part, and it also includes three holes where the upper part would fit. It also contains four holes that have the sole purpose of being places to pass cables from the lower part to the upper part of the other way around. Unlike the previous prototype, the rear area is covered, allowing access to the interior area only through the front part protecting more components.

The upper area would be very similar to the one mentioned in the first prototype. The main changes would be some bars in the lower area of the three columns that would be inserted in the other piece of this prototype. In addition, we implemented changes to reduce the width of the columns and round off their inner edges. It would also include four holes in the upper part to allow different accesses, thus reducing the number of cables needed.

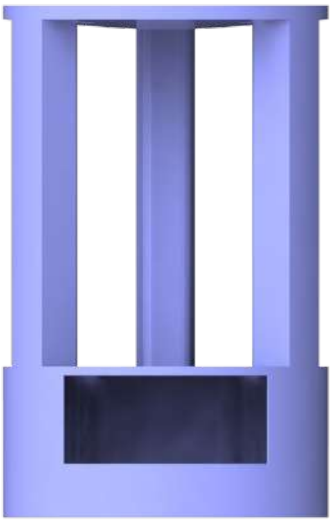

Figure 3. CanSat Prototype Version 2.

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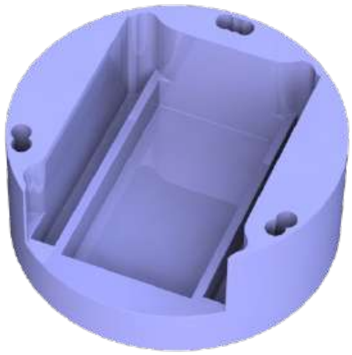

Figure 4. Lower part section CanSat Prototype Version 2.

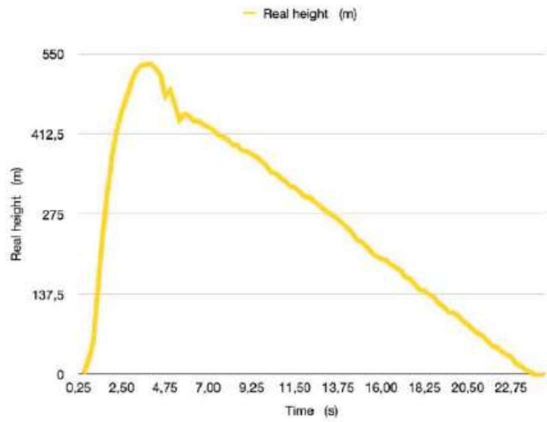

Figure 5. Height graph OrbiSat launch July 2020.

2.2.3. 3D Printing

The 3D printing would have been carried out following the method previously mentioned in the first prototype, although slight changes would have. The lower and upper parts would have a different mesh at this prototype. The lower part would have been printed with a mesh of 90%, while the upper part would have a mesh of 45%.

As a result, in addition to increasing the weight, we would not have had to insert ballast, thus occupying space, which would have allowed us to lower the center of gravity, thus improving stability during the descent. In addition, the CanSat would be positioned in the optimal way to open the parachute in a shorter time.

3. Results and discussion

The Primary Mission that the OrbiSat team planned worked perfectly, fulfilling all the requirements requested by ESERO Spain. The maximum height that the rocket reached was 532.7 ± 1.5 meters, which was later checked correctly by the organization.

In the height graph (Figure 5), it is possible to observe two peaks after the maximum point of the graph. The rocket itself created the first one when the warhead deployment. The rocket made a small charge explode to deploy the warhead, and since the satellite was still inside the rocket, it could detect that pressure spike. The parachute's opening caused the second one since it took 2 seconds to open from being fully folded.

On the other hand, the Secondary Mission was not so brilliant since we had the failure of the CO_2 sensor, and even having checked its correct operation the day before, it gave completely erroneous and meaningless data. Therefore, after analyzing the sensor data, we had no choice but to dismiss it and not take its information as relevant.

The rest of the sensors of the Secondary Mission worked perfectly and without problems.

As we had predicted, the structure ended up yielding at the weakest point. Once the competition was over and analyzing the debris, we could see that because we had to load ballast the day before the launch and that this ballast exceeded the allowed dimensions, we had to break a joint. Unfortunately, when we reassembled that joint, we did not clean well the surface of the old adhesive, and we added new adhesive on top of it, creating tiny air chambers as we feared that resulted in the breakage of the lower part of the CanSat.

As we thought that a slight possibility of break could occur at the lower part of the CanSat, we attached the battery to the main body of the CanSat. If the situation of that breakage occurred, the operation of the satellite would not be compromised, and it could continue operating without problems. So that contingency plan worked perfectly.

CanSat regulations require a minimum weight of 300 grams, but thanks to the 3D printing used and the design, our casing had such a low mass that we initially lacked 125 grams. This problem would have been solved with the second version. However, in a case closer to the reality of launching a satellite into orbit, every gram saved is money.

DOI: 10.5821/conference-9788419184405.008

4. Conclusions

After the various arguments exposed previously, we conclude that the first design we made was outstanding since it demonstrated its capabilities in the competition to achieve the second position. Moreover, it was a first test prototype of several that were expected to be manufactured but the pandemic forced to modify the plans with little time to act.

The second prototype would have solved the biggest problem we had during the competition, the breakage of part of our CanSat. However, it would have also helped to improve the aesthetics and possibly would have allowed us to be in the first position.

The open concept design avoided many problems and gave us many options in the days before the final. For example, after having some severe failures in the control boards, it allowed us to introduce an Arduino Uno board in the CanSat, something that other teams did not understand how to fit. Consequently, it has advantages when transferring it to other types of secondary missions other than ours. Also, this design has allowed us to have more accurate data, especially in temperature, since no heat produced by the CPU and gas sensors alter the measures.

Acknowledgements

I would like to thank the Santo Angel school for their support and sponsorship throughout the project. I would also like to thank the City Council of Gavà for sponsoring the national launch campaign in Granada and the whole ESERO Spain team for organizing the CanSat Spain 2020 competition with all the difficulties it entailed due to the pandemic.

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TOLOSAT project: Gravimetry and Communication

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Abstract

The use of Constellations for weather science, security and disaster monitoring is a major challenge for space application services. Satellite to satellite communication using existing constellations has not been extensively explored yet. It can improve the communication times for small-satellite missions which have limited access to ground stations. Thus, a mission to demonstrate the feasibility of this link is required.

Another element of interest in space application is Earth Observation, especially in the context of Climate Change. Gravimetry allows an understanding of mass transport in the Earth System through the remote sensing of the time variation of the Earth gravity field. CubeSats are low-cost small-scale and hence lower risk solutions to Earth Observation missions. University CubeSats have shown their success in demonstration and scientific missions, and have a great potential in providing students with practice and application on real space systems.

In this context, the student associations ASTRE and SUPAERO CubeSat Club have joined in a CubeSat program called TOLOSAT, with the hope of demonstrating such technologies. Gathering 70 students from Toulouse, the team was split into subsystems in accordance with the concurrent engineering principles. The work performed followed recommendations from experts from the French National Centre for Space Studies (CNES) and the industry.

The TOLOSAT payloads have to test and demonstrate new means of measuring gravity and addressing communication issues. Firstly, for the gravimetry mission, our approach relies solely on GNSS to compute the gravity field, avoiding expensive gravimeters. For the communication mission: the Iridium constellation will be used as an intermediate between the CubeSat and the ground station. Off-the-shelf components such as patch antennas are planned to prove their efficiency in orbit. This would improve the coverage and the communication window.

The preliminary design was completed. TOLOSAT was designed as a 3-unit nanosatellite, on a 97.4° inclined, 500km high orbit. Margins were also ensured to allow a third payload to be defined in the future, that will be used for finance and partnerships.

Detailed designs are still required, but the educational purposes have been fulfilled, in terms of discovery of the development of space missions as well as in the teamwork culture. The team is now moving on to a new phase, dedicated to a more detailed conception with an on-going focus on the introduction to students to technical - but not only - fields of knowledge applied to space systems.

Keywords

Gravimetry, Iridium, Students

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1. Introduction

This paper goes in detail over the TOLOSAT student project and its current state as of March 2022.

Section *2* details all main aspects of the system ranging from technical to financial progress. It is important to note that the project is separated into subsystem teams which each focus on one aspect or system of the project. In subsection *2.1* the two payload teams for Gravimetry and Iridium explain their methodological approach and expected results. The systems and mission analysis team's role are covered in subsection *2.2*, and subsection *2.3* separates the space segment in the work carried out by each of the six technical teams. Finally, the finance and partnership aspect of the mission is addressed by subsection *2.4*.

2. Results, progress and discussion

TOLOSAT students achieved the preliminary design. Our satellite was designed as a 3 unit nanosatellite, on a 97.4° inclined, 500km high orbit. Margins were also ensured to allow a possible third payload to be defined in the future.

2.1. TOLOSAT payloads

The TOLOSAT payloads have to test and demonstrate new means of measuring gravity and addressing communication issues.

2.1.1. Gravimetry payload

Our gravimetry mission relies solely on GNSS to compute the gravity field and draw a geoid (Figure 1.) (while satellites typically deduce the gravity field from their orbit using complex and expensive on-board gravimeters coupled with GNSS data [3]).

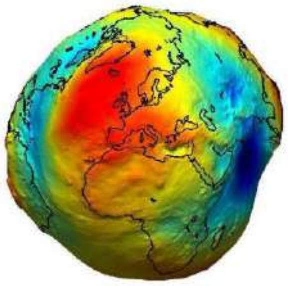

Figure 1. Earth's geoid as seen by European satellite GOCE (credit ESA) [1]

This does not require heavy equipment and was selected for the mission. This method was firstly described in detail by Ales Bezdek and al. [1]. Their work highlights that mapping the gravity field could be done without heavy and costly equipment, that is why we have based our studies on their research.

Here is a brief summary of the acceleration-based method:

The calculations are based on the fact that the geoïd is an equipotential. Thus, one has to solve a Laplace equation, Eq. 1:

$$\Delta V = \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} \quad (1)$$

It could be demonstrated that the solution of this equation is of the following form, which introduce Legendre polynom and Stokes coefficients, in Eq. 2 :

$$V(\theta,\lambda,r) = \frac{GM}{r}\sum_{n=0}^{\infty}(\frac{R}{r})^n \sum_{m=0}^{n}[C_{nm}cos(m\lambda) + S_{nm}sin(m\lambda)].P_{nm}(cos\theta) \quad (2)$$

This equation can be simplify in Eq. 3:

$$V(\theta,\lambda,r) = \sum_{n,m}[C_{nm}V^{(c)}(\theta,\lambda,r) + S_{nm}V^{(s)}(\theta,\lambda,r)] \quad (3)$$

This solution is a development in spherical harmonics. Thanks to the four main GNSS constellations (GPS, GLONASS, GALILEO and BEIDOU) the latitude, longitude and altitude of the satellite in the *Earth Center Earth Fixe (ECEF)* frame are known. After converting the position in the *East North Up (ENU) frame*, the position became $\rho(r,\theta,\lambda)$, where the parameters are respectively the altitude, latitude and longitude of the satellite.

Then, its acceleration can be computed by a numerical derivation thanks to a Golay filter. The acceleration is decomposed in a sum of contributions, in Eq. 4:

$$\frac{d^2\rho}{dt^2} = a_{grav} + a_{LS} + a_{tide} + a_{NG} + a_{REL} = a_{grav} + a_{other} \quad (4)$$

With:

- a_{LS} and a_{tide} the acceleration due to lunisolar perturbations and tides
- a_{NG} and a_{REL} the acceleration due to relativity and non gravitational forces

DOI: 10.5821/conference-9788419184405.009

By applying the third Newton's law, this acceleration can be linked to the gradient of the potential which is given by applying the nabla operator to Eq. 3. Eq. 5:

$$a_{grav}(\rho) = \nabla V(\rho) = \sum_{n,m}[C_{nm}\nabla V^{(c)}(\rho) + S_{nm}\nabla V^{(c)}(\rho)] \quad (5)$$

Then, the only things which remain unknown are the Stokes coefficients C_{nm} and S_{nm}. These coefficients can be determined by applying the least square methods to this last equation.

Then, all the terms of the spherical harmonic development in Eq. 2 are known and one has access to the local gravity potential.

2.1.2. Iridium payload

Nowadays communications with satellites are enabled by ground stations and limited by the rare passes of a satellite over an accessible ground station.

The TOLOSAT mission proposes a different type of protocol: exploit an existing telecommunication constellation (namely Iridium Next) in order to make a relay between the ground and the satellite. This additional passage may enable communication with the ground much more frequently: there are indeed up to 66 Iridium satellites and multiple Iridium ground stations.

Several aspects make the Iridium mission tricky.
First, the Iridium satellites' beams take the form of visibility cones that are designed so that the Earth's surface is entirely covered (Figure 2.)

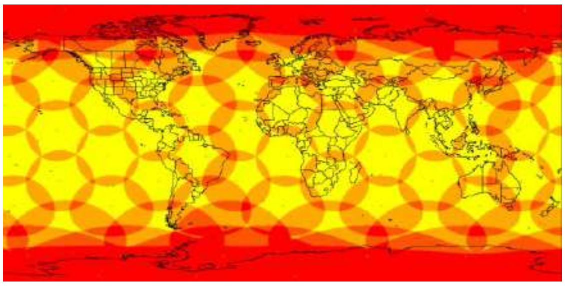

Figure 2. Coverage of Iridium Next Constellation on ground [2]

As the altitude rises, the coverage ensured by the cones decreases, which fixes an important constraint for our 500km high satellite:

- The satellite must be in the visibility cones.

Second, the existence of the Doppler effect further reduces the total time visibility of our nanosatellite. The Iridium antennas are indeed sensitive to the Doppler frequency shift. The modem algorithms hence imposed an additional requirement:

- The frequency shift caused by the Doppler effect should be limited to +/- 37.5 kHz.

According to certain sources (including specialists from aerospace industry), the time derivative of the Doppler effect (the Doppler rate) would also affect the communication. This has to be proven and backed by precise values.

These two constraints set a limit altitude of 650km and a minimum elevation angle of 24° for our satellite. For a 6 hours coverage simulation, we obtained the following estimations of Table 1:

Table 1. Table with visibility results for a 6 hours coverage simulation [1]

	Mean time session	Nb of sessions	Total time visibility
Only visibility	104s	31	214 min
With Doppler range	51,6s	39	134 min
With Doppler range and delta Doppler	63,5s	8	8 min

When it comes to hardware choices, the Iridium subsystem selected a L-band antenna (1621MHz) which has been subject to a link budget, and an Iridium modem which is in tested and operated thanks to a *PCB (Printer Circuit Board)* and driver software the subsystem developed.

2.2. Systems & mission analysis

The System engineering subsystem is in charge of creating and managing the complex architecture of the TOLOSAT project, seen as a whole system including the nanosatellite, the ground segment and the launcher.

This work requires the collection of data among all subsystems. The data is then formatted and well-structured through the *Valispace* browser, making sure there are no wrong assumptions

DOI: 10.5821/conference-9788419184405.009

between subsystems and the constraints defined in the System Technical Specification are respected. This is key when operating with large teams of students which are not always working on the same time slots. Furthermore work is under progress on validating the interfaces across the space segment.

The systems team's work also involves the monitoring of how the TOLOSAT project fulfills the on-going phase's objectives, by creating and updating the specific documentation required for each phase. Currently, the TOLOSAT project meets the methodological recommendations of the *Référentiel Normatif du CNES, RNC* to build a solid phase B documentation.

Mission analysis team on the other hand focuses on studying the implications of the orbit choice and its degradation on the mission.

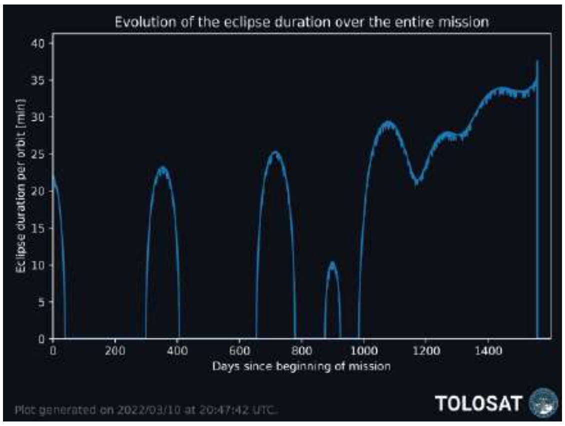

Figure 3. Evolution of eclipse duration over the entire mission [3]

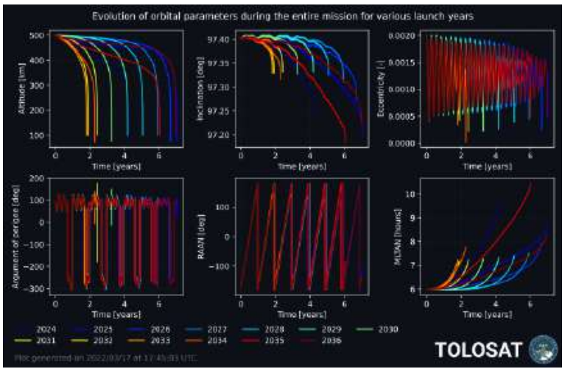

Figure 4. Evolution of orbital parameters during the entire mission for various launch years [4]

2.3. *Technical aspects of the space segment*

Currently, the TOLOSAT team focuses its efforts on the space segment, planning to elaborate its studies on the ground segment and the launch segment on further phases. Here are the main advances of the different subsystems.

2.3.1. *Structure and Thermal*

The Structure subsystem is in charge of designing a solid external structure and developing an internal structure that hosts the different components. Mass and volume budgets were done to make sure our satellite meets the requirements defined during our preliminary design. Our current budget shows that 1,5U is still available on-board, so that the implementation of a potential third payload would be possible. Currently, the Structure team is working on hosting and deploying our CubeSat's solar panels.

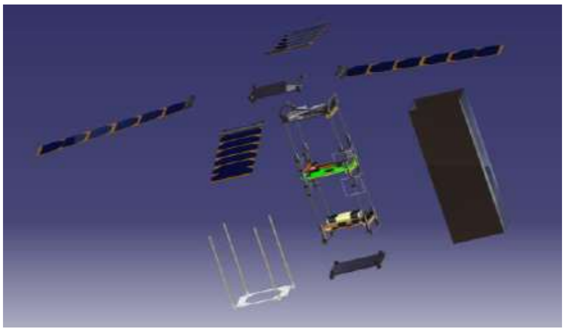

Figure 5. The phase A exploded view of the TOLOSAT nanosatellite [5]

Besides, the Thermal subsystem runs simulations to ensure our satellite handles the two extreme cases when the solar panels are oriented towards the sun: these two cases, the hot case and the cold case, are characterized by the thermal dissipation of components. We have observed that the temperatures of all the components stay within the limits.

2.3.2. *Power supply*

A budget is necessary to estimate the amount of electric power that each subsystem needs during the various operation modes of the CubeSat (safe, nominal, transmission, etc.). The eclipses are also to be considered because they deprive the solar panels of the sunlight for several minutes per orbit. Due to the orbit's features, the duration of such eclipses varies all over the mission duration.

Power subsystem is currently using a P31u card to ensure power supply and elaborate more and more accurate power budgets. The subsystem is also working on a *PCB (Printer Circuit Board)* to test the P31u.

2.3.3. Communications

Link budgets were established by the Communications subsystem, based on various parameters that have to be chosen eventually: the radio frequency, the ground and on-board antennas, the bitrate. Communications subsystem uses the same frequency for up-link and down-link, but is still working on its link budgets to choose between UHF frequency (30 MHz - 1000 MHz) and S-band frequency (2 GHz - 4 GHz). A choice is also to be made about bitrates, depending on whether the Gravimetry subsystem's data is treated on-board or at ground.

Our current link budgets demonstrate that the Communications subsystem gets enough electric power to compensate for the different physical sources of signal intensity losses.

2.3.4. On Board Computer

The On-Board Data Handling OBDH subsystem is in charge of storing the nanosatellite's data. This is currently done through the NINANO OBC card from Steel Electronics (a card that is required by the Nanolab Academy project of the CNES). The subsystem has also to choose a software architecture that manages memory, RAM, IO communication and software errors. Currently, the software *LVCUGEN* from CNES is used.

2.4. Finance and partnerships

Apart from the technical approach to conceiving a satellite, the last two subsystems created are dedicated to communication about the project, as well as finding partnerships and funding to support it. To do so, members of the 'Finance and partnerships' subsystem have been contacting several institutions (companies, schools, laboratories), resulting in the establishment of official partnerships. Indeed, TOLOSAT is now officially supported by five companies:

- Valispace offer us full access to their project management software;
- Syntony GNSS gift us a GNSS spatial receiver;
- Astreos Launch will provide us with some support regarding the budget, licensing and risk management of the project;
- Expleo and U-Space offer technical assistance to subsystems, on specific subjects.

Furthermore, our project having an educational purpose, it is important for us to establish sustainable relations with the universities our members belong to, and important institutions such as CNES and CSUT.

3. Conclusions

The TOLOSAT project has shown the feasibility of its mission through phase A. It has now to focus on detailed design and definition, but has already achieved its educational purposes in terms of discovery of the development of space missions as well as in the teamwork culture. The TOLOSAT team is starting a new phase, dedicated to a more detailed conception of the satellite. The project managers and the System engineering subsystem are currently working to provide clear and exhaustive phase B objectives to all the TOLOSAT subsystems.

During this phase, and as for all the project, TOLOSAT will remain true to its main objective by focusing on the introduction to students to technical - but not only - fields of knowledge applied to space systems.

Acknowledgements

We would like to thank our partners, who help TOLOSAT to better reach its objectives: CSUT, Valispace, Syntony GNSS, Astreos Launch, Expleo and U-Space.

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gLAB hands-on education on satellite navigation

Adrià Rovira-Garcia[1, 2], Deimos Ibáñez-Segura[1], Mowen Li[1], María Teresa Alonso[1], Jaume Sanz[1], José Miguel Juan[1], Guillermo González-Casado[1]

Abstract

The Global Navigation Satellite System (GNSS) allows computing the Position, Velocity and Time (PVT) of users equipped with appropriate hardware (i.e. an antenna and a receiver) and software. The latter estimates the PVT from the ranging measurements and ephemeris transmitted by the GNSS satellites in frequencies of the L band.

The research group of Astronomy and Geomatics (gAGE) at the Universitat Politecnica de Catalunya (UPC) has been developing the GNSS LABoratory (gLAB) tool suite since 2009, in the context of the European Space Agency (ESA) educational program on satellite navigation (EDUNAV). gLAB is a multi-purpose software capable of determining the PVT in several modes: stand-alone (e.g. as a smartphone or car navigator), differential (e.g. surveying equipment or precise farming), and augmented with integrity (e.g. civil aviation or safety of life applications).

gLAB has been designed for two main sets of users and functions. The first one is to educate University students and professionals in the art and science of GNSS data processing. This includes newcomers to the GNSS field that highly appreciate the Graphical User Interface (GUI), the default templates with the necessary configuration or the messages with warnings and errors. The second group of users are those with previous experience on GNSS. Those are interested into a high computation speed, high-accuracy positioning, batch processing and access to the intermediate computation steps.

In the present contribution, we present some examples in which gLAB serves as an education platform. The data sets are actual GNSS measurements collected by the publicly available International GNSS Service (IGS), together with other IGS products such as the satellite orbits and clocks broadcast in the navigation message. The proposed methodology and procedures are tailored to understand the effects of different error components in both the Signal in Space (SIS) and the position domain, by activating or deactivating different modeling terms in gLAB. The results illustrate some examples of how the PVT can be enhanced or deteriorated when using different processing strategies or propagation effects present in the GNSS signals traversing the atmosphere, among others.

We conclude that gLAB is a useful tool to learn GNSS data processing or to expand any prior knowledge.

Keywords
Global Navigation Satellite System (GNSS), open-source, International GNSS Service (IGS)

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Nomenclature

The mathematical symbols used in the present contribution are described in what follows:

ρ_i^j *Geometric distance, in meters, between the antennae of receiver "i" and satellite "j"*

c *Speed of light, in meters/second*

δT_i and δT^j *Clock offsets, in seconds, of receiver "i" and satellite "j"*

f_m *Signal frequency, in Hertz*

$\alpha_m = \frac{40.3 \cdot 10^{16}}{f_m^2}$ *Conversion factor from Total Electron Content Units to meters of delay at the frequency* f_m

$Trop_i^j$ *Slant tropospheric delay, in meters, between receiver "i" and satellite "j"*

$STEC_i^j$ *Slant ionospheric delay, in Total Electron Content Units, between receiver "i" and satellite "j"*

DCB_i and DCB^j *Hardware delays, in meters, of receiver "i" and satellite "j"*

ε_i^j *Noise, in meters, of the GNSS signal between receiver "i" and satellite "j"*

Acronyms

APC	*Antenna Phase Center*
CA	*Coarse Acquisition*
DCB	*Differential Code Bias*
ESA	*European Space Agency*
FOC	*Full Operational Capability*
gAGE	*group of Astronomy and Geomatics*
gLAB	*GNSS LABoratory*
GNSS	*Global Navigation Satellite System*
GUI	*Graphical User Interface*
ICA	*Ionospheric Correction Algorithm*
IGS	*International GNSS Service*
ITU	*International Telecommunication Union*
PVT	*Position, Velocity and Time*
SBAS	*Satellite Based Augmentation System*
STEC	*Slant Total Electron Content*
SIS	*Signal in Space*
SPS	*Standard Positioning Service*
TECU	*Total Electron Content Unit*
UPC	*Universitat Politecnica de Catalunya*

1. Introduction

The origin of navigation dates back to ancient times, when sailors computed the position and course with the use of Astronomic, Cartographic and Geometry references. The principles and techniques to guide vessels from a given origin to a destination remained unchanged for several millennials. However, with the advent of space activities following the first artificial satellite launch Sputnik in 1957, the navigation has been revolutionised.

Global Navigation Satellite System (GNSS) [1] [2] comprises the space and ground segments that allow users equipped with appropriate hardware and software to compute its Position, Velocity and Time (PVT), see Figure 1. The space segment is composed by a constellation of space vehicles at an almost circular orbit of about 20,000 km in height [3].

Three constellations have already declared their Full Operational Capability (FOC). Namely, the Global Positioning System (GPS, US Air Force), completed in 1994; the Global Navigation Satellite System (GLONASS, Russian Federal Space Agency) completed in 1995 (and restored in 2011); BeiDou Navigation Satellite System (BDS, China National Space Administration) commissioned in 2020. The fourth constellation is being completed: the Galileo (European Commission). Together, these four GNSS constellations account for more than 100 satellites.

Each GNSS monitors the satellites by means of a worldwide network of few tens of permanent stations with ground antennas. Such control segment maintains the GNSS satellites healthy and performing nominally. The status of each GNSS constellation can be monitored in real-time at the websites [5]-[8].

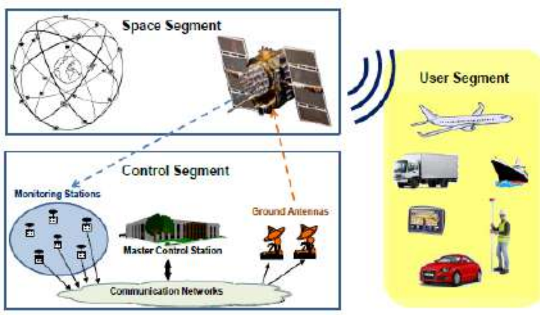

Figure 1. GNSS Architecture

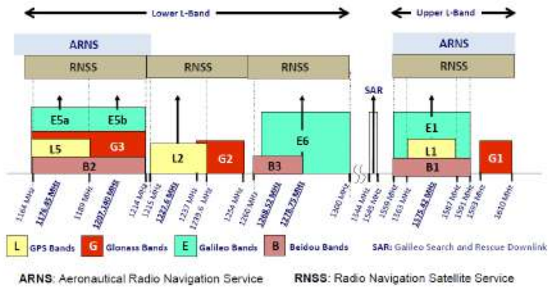

Figure 2. GPS (L), Glonass (G), Galileo (E) and Beidou (B) frequency bands.

The present contribution focusses on the third segment, composed by users of the GNSS. Currently, there are more than 5 billion GNSS devices in use across the world, a number expected to double by 2031 [9]. The GNSS receiver acquires and demodulates radio-navigating signals at the frequencies of the L band, i.e. around 1.2 GHz. Those frequencies are allocated by the International Telecommunication Union (ITU) [10] and are depicted in Figure 2.

The receiver then generates the code and carrier-phase measurements (i.e. the so-called observables). These measurements are used to estimate the PVT of the GNSS receiver by means of Weighted Least Squares (WLS) or the Kalman filter [11], among other techniques. Currently, several software packages exist that are capable of processing GNSS data in an automatic manner.

The GNSS LABoratory tool (gLAB) is an advanced educational multi-purpose software used for processing and analysing GNSS data [12][13]. Since 2009, gLAB has been developed by the research group of Astronomy and Geomatics (gAGE) at the Universitat Politecnica de Catalunya (UPC), in the context of several contracts with the European Space Agency (ESA).
gLAB is open-source and allows to fully control its internal processing through its many configuration options. This is a great advantage with respect to proprietary GNSS data processing programs produced by receiver manufacturers, or other entities, which do not allow any modification and hence, from the user/scientific point of view, are black boxes.

The remaining of the present contribution is organised as follows. Section 2 addresses the basic GNSS measurement equation. Section 3 presents the data used. Section 4 analyses in detail the effects of considering/neglecting some modelling terms. Last section concludes the paper summarizing the results.

2. Methodology

Equation 1 presents the fundamental modelling of the code pseudorange measurements, in meters, whose terms are defined in the Nomenclature section.

$$P_i^j = \rho_i^j + c(\delta T_i - \delta T^j) + Trop_i^j$$
$$+\alpha_m \cdot STEC_i^j + DCB_i + DCB^j + \varepsilon_i^j \qquad (1)$$

where the GNSS signal has propagated from the antenna of the emitting satellite to the antenna of the receiver. Without the loss of generality, but for clarity purposes, we restrict our analysis to the signals of the GPS constellation, at the frequency f_1 and for the civilian Coarse Acquisition (CA) pseudorange measurement.

The geometric distance ρ_i^j is the square root between the coordinates of the receiver (X_i, Y_i, Z_i) and those of the satellite (X^j, Y^j, Z^j). Fortunately, we can linearize ρ_i^j using a Taylor expansion and apply linear Algebra procedures to solve for the user position, its velocity, and its time offset δT_i with respect to GNSS time. The interested reader is pointed to [1]-[4] for further details.

gLAB implements different options to account the different model terms in Eq.1. For instance, the one defined in the Standard Positioning Service (SPS) of GPS [14], which is embedded in most of the mass-market receivers that we use in our everyday life. Figure 3 depicts the gLAB Graphical User Interface (GUI) modelling options, stored as pre-configured templates.

Hence, the gLAB user can use this baseline configuration effortless. It is worth to note, that these options can be modified to meet most of GNSS data processing needs, or, as we will see in the next section, the default options can be modified to get hands-on education on satellite navigation.

Figure 3. Modelling tab of gLAB GUI with default options selected for the SPS.

The gLAB GUI was designed having in mind newcomers to the GNSS field, such as our students at UPC, other Universities or professional courses where we teach GNSS. Every option displays information, so that the user can get familiar with the options that is selecting. In addition, it triggers warnings and errors to avoid any miss-configuration of the tool. Finally, it is worth to mention a second group of users with previous experience on GNSS, such as professionals and companies. Those are interested into the high computation speed offered by gLAB, its high-accuracy positioning capabilities in batch processing and access to the intermediate computation steps.

3. Data Set

GNSS data can be obtained free of charge from the International GNSS Service (IGS) [15][16]. Figure 4 depicts the status of the extensive permanent network of stations belonging to IGS and available from [17]. Any user can download GNSS measurements, satellite positions (i.e. ephemerides), and Earth rotation parameters, among other products.

As an example, we gathered data from a permanent station named Cachoeira Paulista (i.e. “CHPI” according to the IGS naming convention). The receiver is located in the south of Brazil, at a geographical longitude of -22.7º and latitude of -45.0º. We processed 24 h of data belonging to January 1st 2004, a year within the maximum of the 23rd Solar Cycle. The latitude and date of the experiment are chosen so that the ionospheric delay on the GNSS measurements is greatest.

Figure 4. IGS network status on March 2022. The green circles depict operating stations, whereas red triangles indicate stations whose data is not available.

4. Results

This section presents some examples of processing computed with the gLAB tool. The approach is tailored to understand the effect of error components in both the Signal in Space (SIS) domain and in the position domain. In order to address quantitatively and qualitative such effects, we follow the procedure of activating or deactivating some SPS modelling terms in gLAB.

Figure 5 depicts the delay occurred at the ionosphere, i.e. the upper layer of the atmosphere comprised from 60 to more than 2000 km of altitude. The electromagnetic energy from the Sun produces photoionization, which produces free electrons that interact (i.e. delaying) with the GNSS signals propagating from the GPS satellites to the receiver at CHPI.

In order to correct this delay, the SPS employs the Klobuchar model [18] as Ionospheric Correction Algorithm (ICA). The Klobuchar ICA uses eight coefficients transmitted in the navigation message that are updated every day. The Klobuchar can correct the ionospheric delay with Root Mean Square (RMS) errors between 50 to 60%.

We now turn our attention to the navigation performance. Since we are using data collected at a permanent ground station, we know its coordinates with an accuracy of few centimetres. Therefore, we can infer the navigation error of SPS modelling in Eq. 1, by computing the difference from the estimated coordinates of CHPI and those already known. For clarity purposes we will separate such differences (i.e. errors) in the vertical and horizontal planes.

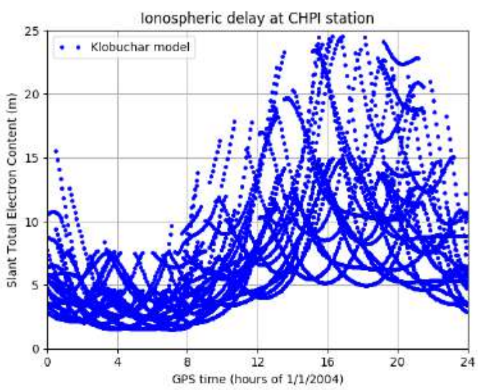

Figure 5. Ionospheric Slant Total Electron Content at permanent IGS station CHPI, modelled by Klobuchar.

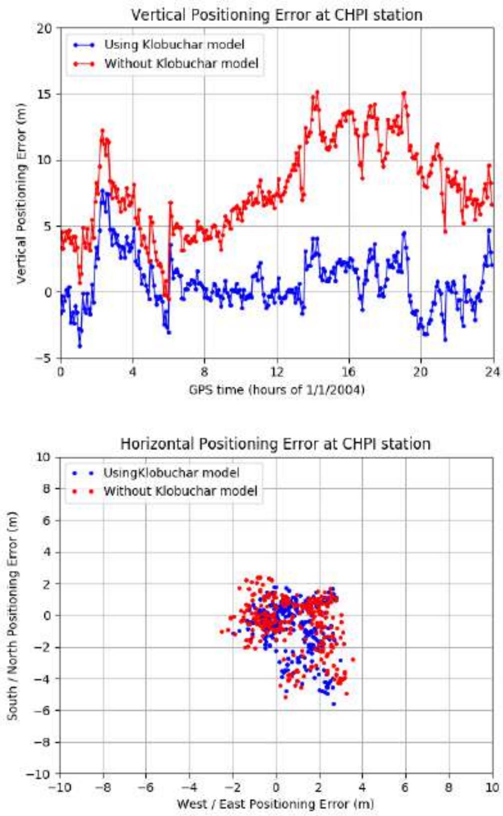

Figure 6. Vertical (top) and Horizontal (bottom) errors obtained with (blue) and without (red) Klobuchar model.

Figure 6 depicts the effect of correctly modelling the ionospheric delay on the user coordinates. For this purpose, the process is executed twice. In the first run (whose results are depicted in blue colour), we apply the full SPS modelling, with all terms of Eq.1 included. In the second run (depicted in red colour), we intentionally disconnect the ionospheric model, maintaining all other processing options from the SPS unchanged.

We can observe that the vertical component of the error is degraded by a factor three when the ionospheric delay is not corrected. As it can be seen, the vertical position error is linked to the ionospheric delay modelling previously depicted in Figure 5. The bottom plot depicts the horizontal component of the error, by plotting the North vs the East error. In this case, we do not appreciate a degradation of the error.

The reason for such asymmetry in the vertical and horizontal is an example of question posed to the students using gLAB in the laboratory sessions. The analysis of the results raises interesting questions and discussions that link the observed results with the theoretical aspects seen in the lectures.

5. Conclusions

gLAB is a useful tool to learn about GNSS data processing or to expand any prior knowledge. Using actual data sets collected by the publicly available IGS network, we give an example of a straightforward procedure tailored to understand and question the effects of different error components in both SIS domain and the The gLAB tool suite can be downloaded together with different Books and Tutorials on GNSS Data Processing from our website gage.upc.edu.

Acknowledgements

The present work was supported in part by the by project RTI2018-094295-B-I00 from the Agencia Española de Investigación of the Spanish Ministry of Science, Innovation and Universities MCIN/AEI 10.13039/50110001103, which is co-founded by the FEDER program. The authors acknowledge the use of data and products provided by the International GNSS Service.

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Analysis of planetary spacecraft images with SPICE

Teresa Peña[1], Manel Soria[2], Paula Betriu[2], Enrique García-Melendo[2]

Abstract

Spacecraft images are an invaluable source of information in Planetary Science. However, they must be processed and the initial stage is to navigate them, i.e., determine the longitude and latitude coordinates of each pixel on the image plane. The main goal of the present work is to develop an open-source tool to do so. It will be independent of proprietary software and implemented in a widely used language (Java, Python). It will be able to analyse planetary images taken by different spacecraft, such as New Horizons, Cassini or Voyager, with minimal user intervention. Here we present the first steps of the process illustrating the techniques to navigate an image of an ellipsoidal body, obtained from mission kernels using NASA Jet Propulsion Laboratory SPICE library, considering that the attitude and position of the spacecraft are available; correct the camera attitude information; determine the image resolution for each pixel; and combine different images of a body to generate mosaics with high resolution.

Keywords

Planetary Science, Planetary Image Processing, SPICE, Open Software

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Nomenclature

CCD	*Couple-Charged Device*
FOV	*Field of View*
SPICE	*Spacecraft Planet Instrument C-matrix Events [4].*

1. Introduction

Spacecraft images are an invaluable source of information in Planetary Science. To mention just one example, in atmospheric science they can be used to measure wind velocities and track the evolution of storms [1,2]. The first step to process the planetary images is usually to *navigate* them [3] i.e., determine the longitude and latitude coordinates of each pixel on the image plane. In order to do so, accurate information about the position of the spacecraft and the attitude of the optical instrument are crucial. These data are usually presented in the form of *kernel* files generated by the mission and processed with the SPICE library [4]. However, attitude kernels (C-kernels) are sometimes not available at all (Voyager) or not entirely accurate (Cassini [5]).

Many researchers have put their efforts on finding the way to process the images with very precise data sets. In [6] a photogrammetric control network to generate accurate mosaics of Jupiter's moon Europa is developed. In [3], the authors present a software package called PLIA (The Planetary Laboratory for Image Analysis) to navigate and process images from different missions. The present work is aimed to eventually develop an open-source tool for planetary image analysis that does not rely on proprietary software (such as IDL or MATLAB), minimizes the need of human intervention in the navigation process, provides an estimation of the navigation error for each image and can be used to process images of different missions.

Here, as a first step towards the aforementioned goals, we present algorithms to (a) Navigate an image of an ellipsoidal body, assuming that the exact attitude and position of the vehicle are available; (b) Correct the camera attitude information; (c) Obtain the image resolution for each pixel; and (d) Combine different images of the same body in a mosaic to obtain a full projection, choosing the best resolution available for each region.

2. Image projection from known spacecraft position and instrument attitude

Assuming that the attitude of the camera and the position of the spacecraft are perfectly known, the navigation of the images could be performed with the algorithm outlined in this section. An example of an image where little correction is needed is presented in Figure 2.

2.1. Projection of a point in the image plane

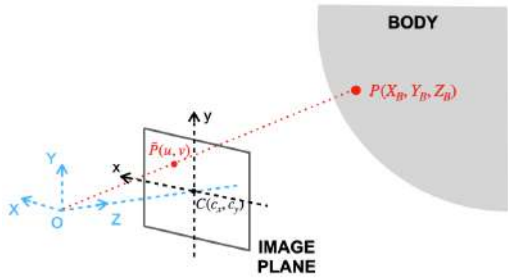

Figure 1. Projection of a surface point in the image plane

Consider a point on the body surface (Figure 1), expressed in its fixed frame, $P(X_B, Y_B, Z_B)$, The rotation matrix from the body frame to the instrument frame, at the instant of the image, can be obtained from the kernel data with the SPICE function *cspice_pxform.* Afterwards, the rotated vector is translated to the location of the instrument by determining the relative position of the frame with SPICE function *cpsice_spkpos*.

Once the position of $P(X_B, Y_B, Z_B)$ is expressed in the frame of the instrument as $P(X_I, Y_I, Z_I)$, it is projected on the image plane and converted into pixels, using the intrinsic matrix of the camera [7]:

$$K = \begin{bmatrix} \pm\frac{F}{\rho} & 0 & c_x \\ 0 & \pm\frac{F}{\rho} & c_y \\ 0 & 0 & 1 \end{bmatrix} \qquad (1)$$

where F is the focal length of the camera, ρ the size of the pixels and c_x and c_y the coordinates of the optical centre of the FOV (point C in Figure 1). The homogeneous coordinates of $\tilde{P}(u', v', w')$ can be expressed as:

$$\begin{bmatrix} u' \\ v' \\ w' \end{bmatrix} = K \cdot \begin{bmatrix} X_I \\ Y_I \\ Z_I \end{bmatrix} \qquad (2)$$

and finally converted to Cartesian with:

$$u = \frac{u'}{w'} \qquad v = \frac{v'}{w'} \qquad (3)$$

in order to obtain the coordinates of $\tilde{P}$, the projection of P.

2.2. *Image navigation*

The navigation of the image is carried out scanning each pixel of the CDD to determine if there is a surface point of the planet projected on it and visible from the spacecraft. To do so, the intersection points between the ellipsoid and a line of sight, which emanates from the centre of the instrument O (Figure 1), goes through the pixel $\tilde{P}$ considered and continues to infinite, has to be obtained.

The equation to determine the intersection between the line of sight and the ellipsoid can be expressed as:

$$(S + \lambda L - C)^T A (S + \lambda L - C) = 1 \qquad (4)$$

where S is the position of the spacecraft, the scalar λ (the unknown) is the distance between the center of the instrument frame O and the body, C is the center of the body, A is a parametrization matrix described below and L is a unitary vector defining the line of sight of each pixel. All the magnitudes are expressed in the reference frame J2000 (equivalent to the *International Celestial Reference Frame* [8]). L is the vector of the line of sight expressed in the frame of the camera. Regarding the matrix A, defined in the principal axes of the ellipsoid and composed of the equatorial r_e and polar r_p radii of the body, it is:

$$A = \begin{bmatrix} \frac{1}{r_e^2} & 0 & 0 \\ 0 & \frac{1}{r_e^2} & 0 \\ 0 & 0 & \frac{1}{r_p^2} \end{bmatrix} \qquad (5)$$

Eq. 4 is expressed as a second-degree equation, whose discriminant Δ is solved. When its value is null or positive, the line of sight intersects the ellipsoid in one or two points, respectively. The smaller value of λ is the one referring to the point in the near-face of the body. Then, the surface points of the ellipsoid are calculated and converted from J2000 to the body-fixed frame by means of a rotation and a translation as described in sub-section 2.1.

Apart from imposing that the intersection point must be on the edge or inside the body, it is also necessary that it is illuminated to be seen from the spacecraft and shown in the image. Function *cspice_illumin* from the SPICE library is used with this purpose.

Once the previous requirements are verified, the longitude and latitude associated to the surface point projected in each pixel are computed. These values can be obtained with two SPICE functions, *cspice_reclat* or *cspice_recpgr*, depending on the system that wants to be used to express the lon/lat values, the planetocentric or the planetographic one.

2.3. *Image projection*

In order to obtain the projected image, the intensity associated with each lon/lat is needed.

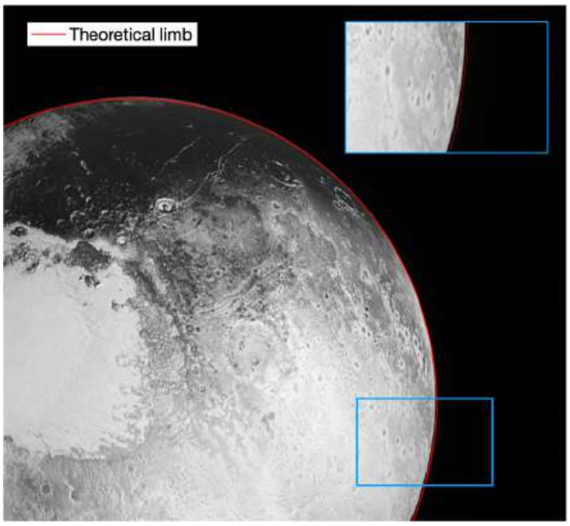

Figure 2. Theoretical limb of Pluto in New Horizon's image 299147481 [9]. The difference between the limbs position predicted with the mission kernels and the image can be seen more clearly in the zoomed area.

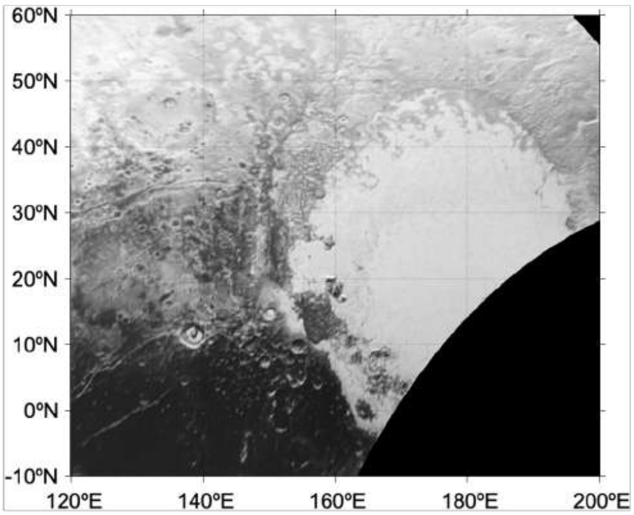

Figure 3. Image projection of Pluto from New Horizon's image 299147481 [9] generated from Figure 2.

To compute it, we use an interpolation algorithm based on the triangulation of the intensity data obtained from the original image.

In order to consider that the intensity of a pixel obtained from the interpolation is valid, the surface point associated to it has to be (a) inside the FOV of the camera and (b) in the near face of the planet or moon. The first condition is verified by computing the location of the pixel in the image plane and, for the second, the angle between the position vector of the surface point and the one that has its origin in this point and its end in the spacecraft is computed. If this angle is smaller than 90º, the point is located in the near-side of the body and the interpolated intensity of the pixel is maintained.

If one of the previous two conditions is not fulfilled, the interpolated intensity is changed into a specific value, such as 0, so in the image the pixel under consideration is displayed in black.

To increase the quality of the projection, image processing techniques are used and, more specifically, sharpening and contrast adjustment. The final result can be seen in Figure 3.

3. Attitude correction from known planetary limb position

If the attitude of the camera is not perfectly known, the image navigation provides wrong results that lead to unreal image projections or mosaics. In fact, even the projection of Figure 3, where the kernel is quite accurate, does not coincide perfectly with that provided in [10], since the longitude is slightly different.

The inaccuracies in the data are manifested as a displacement of the position of the body with respect to the one that can be seen in the image. In order to correct this mismatch, the procedure that is proposed here consists of determining the rotation around the axes of the instrument (with the attitude provided by SPICE) necessary to make coincide the positions of the body.

3.1. Limb points on the image

The aim of this work is to provide procedures that can be used with the majority of images in which all or a part of the limb of the body is displayed. However, when trying to generate the limb of the planet or moon directly from the original image, there are factors that make it very complicated to do it with completely automatic methods that do not require the intervention of the user, such as the presence of rings in the images of Saturn or the dark zones of Pluto in the images taken by New Horizons.

Because of this, here we propose a method characterized by the generation of a limb defined by as many points as desired, which follow the limb that can be seen in the image and are computed in the same way. Thus, is the user who chooses the zones in which the limb points should be located and the algorithm computes the exact pixel. To do so, it first determines the average intensity of the pixels of the background and those of the planet. Then, the mean of these two values is calculated to know the intensity that the pixel where the limb point will be located should have.

3.2. Theoretical limb position

As the points of the limb from the image are expressed in pixels, the limb generated with the SPICE data (i.e., the theoretical limb) also has to be expressed in this units in order to be compared.

The theoretical limb is defined in the body-fixed frame by the main parameters of a conic (i.e., center and major and minor semi-axes), obtained from SPICE function *cspice_edlimb.* From them and the parametric expression of an ellipse in 3-D, an arbitrary number of points that are part of the conic can be generated and afterwards converted into pixels to be shown in the image. To do so, a rotation and translation of their position vector from the body-fixed frame to that of the instrument is performed as described in previous sections.

3.3. Correction procedure

To correct the mismatch between the limbs of the body, the frame of the instrument is rotated causing a variation in the position of the theoretical limb. To do this, the rotation matrix that makes coincide almost perfectly both limbs has to be found.

This matrix is defined by the angles of Euler (α, β, γ) and is applied to the coordinates of each point of the conic expressed in the frame of the instrument:

$$\begin{bmatrix} X_{I'} \\ Y_{I'} \\ Z_{I'} \end{bmatrix} = R_z(\gamma) R_y(\beta) R_x(\alpha) \begin{bmatrix} X_I \\ Y_I \\ Z_I \end{bmatrix} \qquad (6)$$

To find the combination of angles that generates the best fitting, an iterative minimization procedure is used. The parameter to minimize is D, the sum of the distances d_i between each limb point p_i and its projection on the theoretical limb conic t_i.

$$D = min[\sum(\|p_i - t_i\|)] \quad (7)$$

The minimization starts with arbitrary angles, such as a tenth of the angular field of view of the camera, and after a few iterations the error is notably reduced, provided that the number of limb points is sufficient. Once the right Euler angles have been obtained, they are used to generate the corresponding rotation matrix.

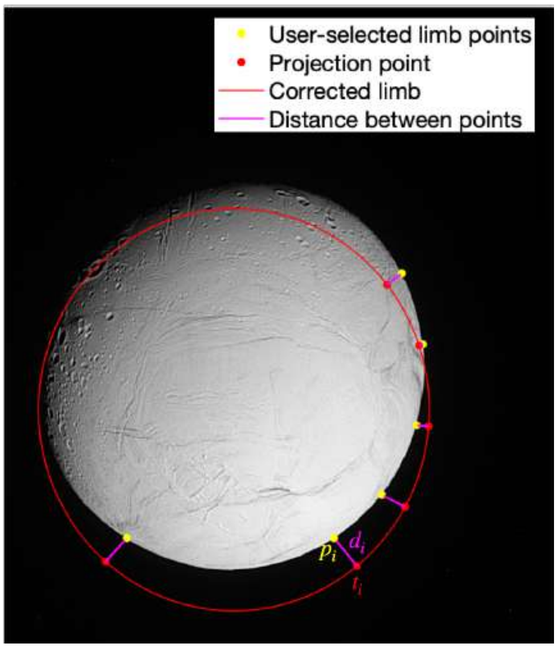

Figure 4. Iteration of the minimization in Cassini's image N1516169656 of Enceladus [9].

3.4. *Application of the correction to the image navigation*

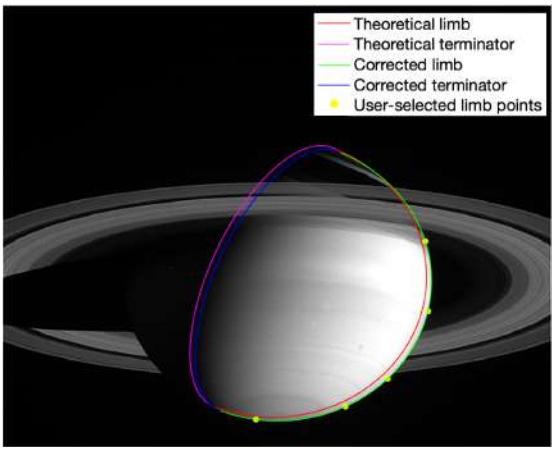

Figure 5. Comparison of the theoretical and corrected limbs and terminators of Saturn in Cassini's image 1461406214 [9].

When the rotation matrix that corrects the attitude of the spacecraft has been computed, it has to be applied to the image navigation procedure and, more specifically, to the pointing vector (L in Eq. 4) used to defined the position of each pixel of the CCD.

In the case presented in Figure 5, the Euler angles are (0.0024°, -0.0032°, 0.0352°) and the total distance or error between limbs is 0.814 pixels.

4. Generation of image mosaics

An image mosaic can be defined as the union of multiple image projections, in such a way that the range of longitude and latitude displayed is wider than the one that could be shown in each individual image projection. For each pixel, the image with best resolution is selected.

The resolution in pixels/meter is computed as the square root of the surface that covers each pixel, which is defined by the mean vertical and horizontal distances between the pixel whose resolution wants to be determined and the adjacent pixels in each direction. As the pixels are associated to a longitude and latitude, Vincenty's formula [11] is used to compute the geodesic distance between two pixels on the surface of an ellipsoidal body.

As with the intensity of the pixels in the image projection, the resolution is also interpolated to obtain the correct value associated to the lon/lat of the pixels. The interpolation algorithm is based, as well, on the triangulation of the resolution data obtained from the original image.

Once the intensity of the pixels and its resolution for each image have been filtered, the data of the image mosaic can be generated by selecting, from the multiple images, the pixels with a higher resolution.

5. Results & Discussion

To illustrate the procedure described in this article, the image mosaic of Figure 6 is presented. Here each image has been represented with a different color for clarity.

6. Conclusions

The results provided confirm that the first steps of the work that will end in the development of an open-source tool for planetary image analysis have been completed.

We are now able to navigate images obtaining accurate longitudes and latitudes, by means of a correction procedure based on an estimation of the camera kernel error.

However, there are still a few aspects that should be addressed in the near future: (a) the Newtonian light time correction and stellar aberration correction; (b) the analysis of images in which the *kernel* files are not available, such as those of Voyager 1 and 2; (c) the treatment of images without limb; (d) the estimation of the error in the image projection due to inaccuracies in the attitude of the instrument or the selection of limb points; and (e) the estimation and correction of the spacecraft position when multiple stars and a body are visible in the image.

The final algorithm will be implemented in a widely available and portable language such as Java or Python.

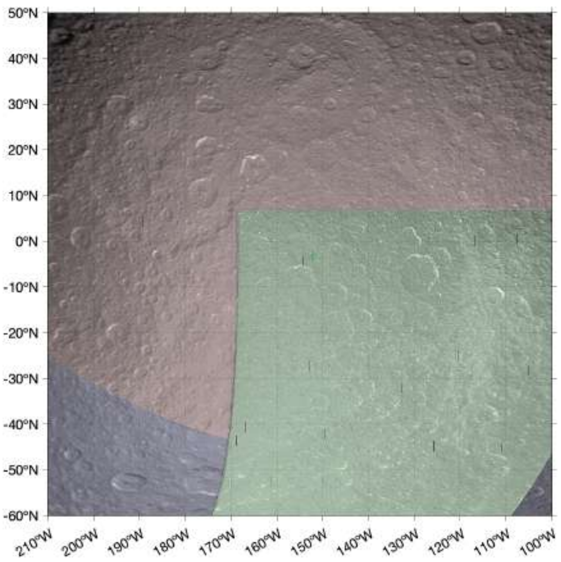

Figure 6. Colored image mosaic of Rhea from Cassini's images N1511700504, N1511717371 and N1499997169 [9].

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SDR Helix Antenna Deployment Experiment (SHADE) on board BEXUS

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Abstract

In the field of space travel, space communications has always presented a slew of obstacles and hurdles that must be overcome in order to complete a successful mission. Space limits inside a satellite or spaceship, vast distances between satellites and ground stations, and a phenomenon known as "Faraday Rotation" in the ionosphere are only a few of the most typical issues. Satellite antennas must be small, compact, efficient, and circularly polarized as a result of the aforementioned issues. The helix antenna is an excellent answer for all of the requirements. In this work we develop a deployment and pointing mechanism of a helix antenna operated with software defined radio algorithms. The features of helix antennas are exceptional, and they are especially suitable for satellite communication. Three coaxial cylinders, two stepper motors, one pulley, and one thread make up a deployment-pointing mechanism. The mechanism deploys the antenna along its longitudinal axis and turns it horizontally towards the ground station. During the flight, the antenna is deployed and retracted. Under different positioning situations, the GPS, an altimeter, and a compass calculate the gondola's position in order to rotate the antenna towards the Ground Station and close the communication link. The antenna's rotation mechanism is triggered by the integrated attitude determination and control system algorithms in order to correct the pointing and orientation towards the Ground Station. The antenna uses software defined radio algorithms to achieve weight and volume reductions while maintaining high efficiency and reconfigurability. The experiment includes a high-definition camera that provides real-time information on the antenna's orientation and condition. SHADE's flight on the BEXUS 28/29 balloon resulted in effective deployment and transmission, as well as the ability to receive and decode transmitted packets. The rotating mechanism met the pointing requirements, and all of the sensor's data was correctly saved to our system. Throughout the trip, there were no signs of thermal risk.

Keywords

Antenna Deployment, Helix Antenna, REXUS/BEXUS, Software Defined Radio, Stratospheric Balloon

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Acronyms/Abbreviations:

ADCS	*Attitude Determination & Control System*
AUTH	*Aristotle University of Thessaloniki*
BER	*Bit Error Rate*
DMCS	*Deployment Mechanism Control System*
FEM	*Finite Element Method*
GHz	*Giga-Hertz*
GMSK	*Gaussian Minimum Shift Keying*
GNSS	*Global Navigation Satellite System*
GS	*Ground Station*
HCS	*Heating Control System*
HPBW	*Half Power Beam Width*
LNA	*Low Noise Amplifier*
OBCS	*Observation Control System*
PA	*Power Amplifier*
RX	*Receiver*
SDR	*Software Defined Radio*
SHADE	*SDR Helix Antenna Deployment Experiment*
SSC	*Swedish Space Corporation*
TT&C	*Telemetry Tracking and Command*
TX	*Transmitter*
TXCS	*Transmission Control System*

1. Introduction

In space telecommunication systems, closing long distance links and Faraday rotation are major challenges faced by engineers. Stratospheric balloons and other high-altitude platforms regularly use monopoles to communicate with the ground station, as their omnidirectional properties nullify any need for beam steering. Nevertheless, monopoles have low gain and linear polarization that could be easily affected by Faraday rotation; therefore, they require high power consumption to establish a link. Helix antennas could offer a solution to these issues, with their good gain/cost trade-off and circular polarization that they provide. Even though they are widely used in aerospace communication systems, the geometry of this antenna type, resembling a relatively long and wide spring, often violates the volume restrictions set in space applications.

In addition, following a present tendency in research and industry to replace conventional communication circuits with software cores, Software Defined Radio (SDR) technologies are gradually established in the space sector. SDR offers accurate signal processing applications without unnecessary physical components in small sized modules.

SDR Helix Antenna Deployment Experiment (SHADE) is an SDR operated helix antenna with a spring-based deployment mechanism and a Ground-Station-Tracking automation system. A helix antenna, protected by a teflon cover, is operated by an SDR module that transmits data to the ground station. To compensate for the narrow beamwidth, an automation system has been developed in order to ensure that the antenna will always point at the ground station and maintain Telemetry Tracking and Command (TT&C) applications. Moreover, a deployment mechanism has been implemented which exploits the antenna's spring characteristics ensuring a reduced size for the system.

The experiment's potential was recognized by REXUS/BEXUS programme [1], [2] and SHADE was designed, implemented and had a successful flight on board a stratospheric balloon.

The structure of the present paper is firstly the Introduction, secondly the Mechanical Design followed by the Thermal Design; after that is the section of the Electronics and Software and then the last technical section, the Telecommunications section. The final sections include the Testing and Verification and Conclusion, on which the lessons learned are described, acknowledgments and references are also cited.

2. Mechanical Design

The Mechanical Design aimed to satisfy the following requirements. 1) The antenna's deployment 2) the antenna's controlled rotation 3) the overall fixation of the experiment on the gondola 4) BEXUS space and weight limitations 5) the safety of the experiment's assembly during the "cut-the-rope" phase. To accomplish these requirements, the mechanical design consisted of 1) the Antenna's Casing, which contained the helix antenna, 2) the External Box, which contained the rotational mechanism and the motors for deployment and rotation respectively 3) the Electronics Box and 4) the fixation of a camera to monitor the operation of the experiment. The degrees of freedom of the experiment and its major parts are presented in Figure 1.

To satisfy the requirements: 1) the natural length of the helix antenna was chosen to be longer than the length of the deployed case, so the spring's tension would result to the complete deployment of the case. The antenna's casing consisted of three co-axial cylinders, made by Teflon, which is an electromagnetic neutral material, has a low shrinking ratio at low temperatures and it has a low friction coefficient (solid lubricant) to facilitate deployment.

The clearance tolerances were carefully designed to achieve the translational movement. JS7 group has been chosen for the internal surface of the external cylinders and g6 for the external surface of the internal cylinders. Continuing, the deployment was controlled by a thread, tighten on the edge of the smallest cylinder. From the other side the thread was tighten to a pulley controlled by an electric stepper motor. An intermediate pulley was used to minimize the friction of the thread while entering the antenna's casing (Fig. 2a). Dyneema fine SK78[3] has been chosen as thread's material since its tensile strength exceeded the stress requirements.

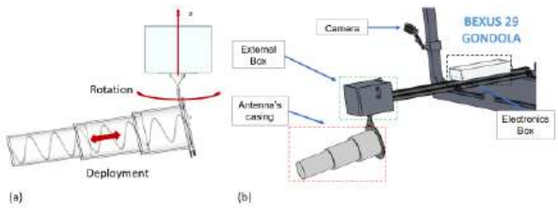

Figure 1. a) Degrees of Freedom of the experiment b) the experiment's assembly on the BEXUS Gondola.

2) The external box (Fig. 2c) contained the rotational mechanism that consisted of a spur gear-pinion mechanism with a transmission ratio of 2.6, the hollowed axis supported by two bearings, paved the passage of the thread and power supply cables to the antenna and assured the rotation of the antenna. In addition, it contained the stepper motor responsible for the rotation (assembled to the pinion) and a stepper motor that controlled the deployment of the antenna (assembled to the pulley). The external box has been fabricated by aluminum profiled rods and aluminum plates for simple assembly and quick access to the internal components. The Electronics Box was made by folded aluminum plates, and it contained all the electronic components. It was fixed on the main aluminum profile with bolts with T type nuts.

3) The fixation of the experiment (Fig. 2b) on the gondola has been designed on a profiled aluminum rod that connected the External Box with the Electronics Box. It was fixed on the gondola's trails using corner connectors and rubber bumpers, which secured the experiment of any resulted shocks (especially during the cutting the rope phase and the landing).

4) To assure the safety of the experiment and avoid material failures that could lead to any falling part, various numerical Finite Element Method (FEM) simulations have been conducted for stress and modal analysis. Furthermore, to increase the safety, all the external parts were tied to the gondola's main skeleton with Dyneema rope SK75.

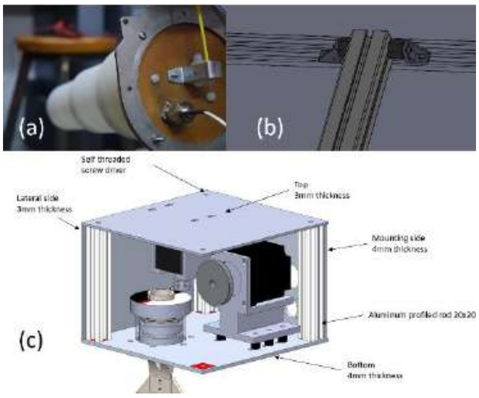

Figure 2. a) Pulley in the base of antenna casing b) Fixation with rubber bumpers on gondola's trails c) Structure and internal components of external box.

3. Thermal Design

During the flight, the experiment was expected to be exposed in harsh atmospheric conditions, which could potentially damage the sensitive electronic parts. To avoid any malfunctions of the components, both the internal and the external part of the experiment were insulated. The thickness and the material of the insulation were determined based on calculations and data retrieved from multiple simulations, using a plethora of parameters.

Due to the differences in the density of the atmosphere, the main source of heat transfer was not the same for the entirety of the flight. Therefore, to acquire more accurate results, the flight was divided in two phases, the floating and the ascending phase, which were studied and simulated separately. It is important to note that during the ascending phase the main heat transfer sources are conduction and convection. Contrastingly during the floating phase due to the lower atmospheric density, convection can be omitted and heat transfer via radiation becomes more significant.

For the thermal calculations, both the enclosure inside the gondola and the external, were considered black bodies and the heat dissipated from each electronic component was computed as 10% of its power consumption.

Both the internal and the external box were insulated externally with a layer of 30mm thick extruded polystyrene, which was ultimately selected due to its low thermal conductivity factor as well as it being a rather lightweight material. The aluminum box outside the gondola containing the stepper motors was further insulated internally using a 10mm thick layer of expanded polyethylene, while flexible heaters were attached on the motors to ensure that they would constantly operate within their operating temperature limits.

4. Electronics & Software

From the electronics' perspective, SHADE was divided in the subsystems shown in Table 1. Each subsystem was implemented as an independent prototype and got tested. Subsequently, the design of the PCBs took place in order to merge the experiment into one main circuit.

Table 1. Subsystems and components

Deployment Mechanism Control System (DMCS)	Stepper Motor, Stepper Driver, Altimeter
Attitude Determination Control System (ADCS)	GPS, Magnetometer, Stepper Motor, Stepper Driver, IMU
Power Control System (PCS)	DC-DC converters
Observation Control System (OBCS)	Camera
Transmission Control System (TXCS)	SDR module, Bandpass Filter, Amplifier
Heat Control System (HCS)	Temperature Sensor, Heaters

The system was designed with the "Fault-Tolerance" principles to make sure that it will be functional in case of a subsystem's failure. Every subsystem operates as an isolated process, in order to be decoupled from other subsystems and to constrain possible unexpected errors/malfunctions within the boundaries of a single process. For the communication between our experiment and the control station, TCP/IP protocol was used over a radio link, connecting the gondola and the ground station, and was provided by SSC. Furthermore, to enhance control of each subsystem, two modes of operation were implemented: manual mode which was based on remotely executed commands, and automatic mode. In the event of a loss of connectivity, the application runs in automated mode, ensuring that the various activities are completed in the proper order. The software modules/scripts were deployed on a raspberry Pi. Also a second raspberry pi was used for the camera-related operations, such as heavy computational processes of image capturing. Last but not least, the system logged all the data from the sensors and transmitted them to the GS for visualization and post-processing purposes. Below is a brief description of every subsystem.

The ADCS is responsible for the antenna's positioning and rotation. The antenna had to aim towards SHADE's GS during flight time, for solid communication to take place ensuring the success of the experiment. In order to fulfill this requirement, special algorithms were designed that took into consideration data from a compass, a GNSS RX, and gave as output the rotation of the stepper motor, that was responsible for the bearing/pointing of the antenna.

The DMCS is responsible for the deployment and the retrieval of the antenna, either automatically (based on altitude data) or manually. The TXCS is responsible for transmitting data to the SHADE's and SSC's GS. The HCS is responsible for the control of the temperature of the external box, based on temperature data and using a cluster heater. Finally, the OBCS is responsible for camera-related operations, such as image capturing.

The flow of SHADE experiment can be described as follows. The antenna gets deployed either automatically (above an altitude or a specific time), or manually (by command). Following a confirmation of successful deployment, ADCS is actuated and TXCS starts to transmit data to the SHADE's and SSC's GS. In case of unsuccessful deployment, the antenna is retrieved and redeployed until success. The antenna is retrieved, either below a certain altitude or by command, after having interrupted the ADCS. During the experiment, HCS continuously adjusts the external box's temperature. At the same time, OBCS captures the experiment flow providing visual control from SSC GS.

5. Telecommunications

Present SHADE Telecommunications subsystem was designed to provide an effective communication interface for high altitude platforms. It consists of a flight segment and a ground segment. The flight segment is responsible of transmitting the data collected through the flight. The ground segment receives and processes the data sent from the flight segment. The basic telecom subsystems are presented below:

5.1. Helix Antenna

The helix antenna was chosen due to its use in a variety of space applications offering suitable electromagnetic characteristics; relatively high gain, wide bandwidth and circular polarization [4], [5]. The system was operated at 1.43GHz and the transmitting and receiving antennas were designed and manufactured by the team to match the specific frequency band. Specifically, the TX helix antenna made of Stainless Steel 302 with 7 turns, to achieve a Gain of 11 dBi and a HPBW of 36 deg. The S11 parameter of the antenna should be less than -15dB at 1.43GHz proving the suitability of the material for its chosen application, exploiting both its spring elasticity and its electromagnetic conductivity.

5.2. Flight Segment

Being powered by the Raspberry Pi, an SDR module computed with GNU Radio algorithms generated the TX data and channeled them through a Power Amplifier and a 1.4GHz filter to the TX helix antenna. The ADCS system ensured constant pointing of the antenna towards the ground segment regardless of the rotation of the BEXUS gondola. The output power of the SDR module was -10dBm which strengthened with the 25dBm Gain of the PA and the antenna gain, provided the required power for the signal to reach the ground segment for approximately two hours of flight.

5.3. Ground Segment

To complete the designed telecommunication system, the ground segment consisted of a copper helix antenna with three turns in order to have a wider receiving angle, followed by an LNA and the respective 1.4GHz filter. Continuously the received signal was split to feed both the custom RX SDR module and a digital spectrum analyzer for maximization of the experiment's results.

5.4. Digital Signal Processing

The transmitting and receiving algorithms and techniques were implemented using GNU Radio. A GMSK scheme was selected to modulate the generated data, as its differential nature ensured TX/RX clock synchronization, while a packet encoder and decoder were used to lower the BER. The algorithms were translated into Python source code files and were executed within the SDR modules.

6. Test and verification

A series of 22 tests were run to ensure that the experiment was working as planned. At first, each component was put through testing on its own. After the assembly and integration was completed, the experiment was tested in a thermal and vacuum chamber in full operational mode. The most important tests are examined in subsections 1, 2, and 3.

6.1. Thermal Test

To simulate the thermal conditions of stratosphere the experiment was placed in a thermal chamber capable of reaching temperatures close to -70°C. The experiment presented normal functionality through the whole thermal test (~2.5 hours). Both motors remained fully functional during the whole test while reaching a temperature steady state at -22.5°C, proving there will be no issue of freezing. Furthermore, the electronics box reached a steady state at -30°C with the amplifier being at -12°C and the raspberry at -20°C.

6.2. Vacuum Test

To test the experiment under the low pressure conditions of the stratosphere, the experiment was placed in a vacuum chamber capable of lowering the pressure close to 50 mbar. The experiment presented full functionality during the whole test. No mechanical or electrical failure were observed. Temperature of all components stayed in nominal levels and no malfunctions were observed.

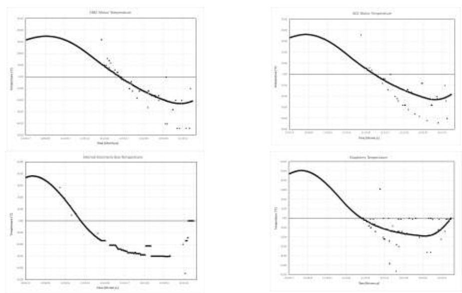

Figure 3. Thermal test results

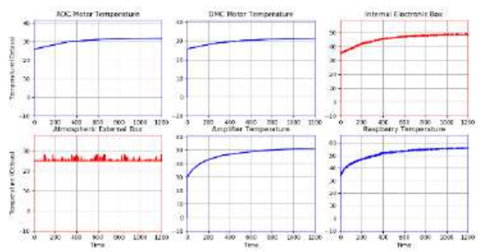

Figure 4. Vacuum test results

6.3. Antenna propagation test

At first, the helix antenna was placed in an anechoic chamber to measure its basic characteristics. The calculated gain of the antenna was 11dbi and the Half Power Beam Width (HPBW) of the antenna was 36deg. The measured S11 was 18dB at 1.4 GHz.

To simulate the link between the helix antenna and the ground station, an analog test scenario was created. The helix antenna was placed on a tripod 3.3 meters away from a log-periodic antenna with known characteristics. Both antennas were connected to SDR modules and a test file was sent. The receiving SDR managed to receive the file without any errors.

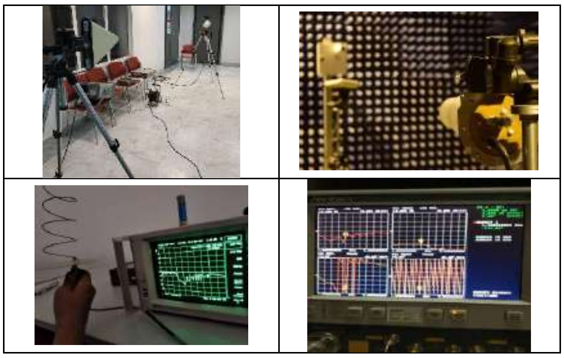

Figure 5. Antenna propagation test set-up and results.

7. Launch Campaign.

SHADE was launched successfully with BEXUS 29 gondola and recovered intact. Communication with the experiment was achieved and all measurements during the flight stayed within predicted threshold. The operation of the experiment was nominal; the deployment of the antenna was successful and no re-tries were needed. After that, image and text data were transmitted to the SHADE's GS and successfully decoded. The pointing system acted as expected, since throughout the whole flight time (until communication was lost) the communication dropouts were almost non-existent. However, an incident occurred when the gondola was above the 12km; the GPS signal was lost. After further investigation was conducted, the source of the problem was the permissions of the GNSS module. As it turned out, military permission is required to use GNSS modules after the altitude of 12 km. Because of that, after the incident the ADC System was operating on manual mode.

8. Results and discussion

The manufactured model was tested in full operating mode on BEXUS 29 stratospheric balloon, meeting all requirements. The maximum point-to-point distance, where communication was still nominal, was 138 km. After that point the signal power started to drop below the desired levels and communication was therefore lost. In an overall approach the experiment fulfilled the predefined requirements and laid the foundations for its use on space applications. In the year covering its development from concept to launch at the ESRANGE Space Center, SHADE offered collaboration between students from different backgrounds, practical application of theoretical knowledge and overall a valuable educational opportunity with multiple lessons learnt.

9. Conclusion.

In this work we designed, constructed and tested a deployable helix antenna operated by SDR. The system is intended to be used in small satellites and high-altitude platforms. Future plans include further research on the deployment mechanism, miniaturization of the model and product design.

Figure 6. SHADE on stratosphere

Acknowledgements

This work was supported by Aristotle University of Thessaloniki (AUTH), AUTH research committee, BETA CAE Systems, Hellenic Aerospace Industry, Swedish Space Corporation (SSC), German Aerospace Center (DLR), Swedish National Space Agency (SNSA), European Space Agency (ESA) and Center of Applied Space Technology and Microgravity (ZARM)

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The advanced Master of Space Studies at KU Leuven and Ghent University: Trends and tendencies in the program demographics

Hugues Sana[1], *Clio Gielen*[2]

Abstract

Organized by KU Leuven and Ghent University, two leading Belgian universities, the Master of Space Studies is an interdisciplinary post-master program that aims to equip students with the skills they need to initiate a career in the space sector. Beyond the deepening of their initial expertise, the program exposes the participating students to a broad range of topics, from human science (space law and policy, international organizations, project management, …), to technical science (space missions, spacecraft and payload engineering, satellite telecommunications, ...), and exact sciences (Earth and Space observations, medical sciences, human explorations, …) with the aim to provide the students with a broad overview of the interdisciplinary expertise required by many space projects. Initiated in the late 2000s, the program has served as a gateway into the space sector for over 100 students since its creation.

After a brief introduction to the program, we present a programmatic analysis, based on quantitative and qualitative surveys of students and alumni. We present the demographic, career tracks and current professional situations of students in the last 10 years, allowing us to identify trends that affects tertiary education to space sector. We conclude by briefly highlighting other ongoing space education activities, from the Belgian antenna of ESERO to the involvement of students in CubeSpec, a 6U CubeSat platform selected as ESA in-flight demonstrator to enable low-cost versatile spectroscopy of astronomical targets.

Keywords
Tertiary interdisciplinary post-master education

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Acronyms/Abbreviations

MSS	*Master of Space Studies*
STE(A)M	*Science, Technology, (Arts) and Mathematics*

1. Introduction

Together with the depths of our oceans and the mystery of our brain, space symbolizes the next frontier of knowledge and human exploration. Space is a place of wonder and of discovery. Because of this, space has been and remains today one of the most inspiring topics to promote the fields of Science, Technology and Mathematics (STEM) among the next generations of girls and boys and to attract them to much needed STEM careers in our technology-driven society.

The inspiration potential of space reaches out beyond STEM and is nowadays regularly associated with Arts in STE(A)M events that touch an even wider and more diverse public. The recently organized Big Bang festival ("KNAL" in Dutch [1]) in Leuven, Belgium, is a concrete example of such a STE(A)M endeavor. Organized around the theme of the Big Bang to celebrate the contribution of the Belgian physicist Georges Lemaître, the KNAL festival was a city-wide festival organized over a three-month period in the fall and winter of 2021 and has guided almost 100000 visitors through exhibits, concerts, conferences and public events that mixed arts, science and technology.

Aside from providing a gathering theme able to touch a very large public, space is of course a crucial sector for our modern societies. Its importance has been growing in the last 50 years and now occupies a central place that directly or indirectly impacts an estimated 60% of our modern economic activities [2]. From a scientific point of view, space provides us with unmatched laboratory conditions and a unique perch to observe the cosmos. Downwards observations from space allow us to collect crucial information for understanding our planet, forecasting our weather, monitoring human activities, hence providing key support to our modern economies. Spaceborne facilities are indeed important assets with undeniably large geo-strategical and geo-political impact.

From this brief sketch of the landscape, it is obvious that operating in space is a globalized and complex activity that lays at the crossroad of science, technology, management, economics, law and politics, to mention but a handful.

In this paper, we first introduce the KU Leuven and Ghent University Master of Space Studies (MSS), an interdisciplinary post-master tertiary education program organized in Flanders, Belgium. In a second part of this paper, we look back to the statistics of the program, tracing our alumni through social media and assessing their professional occupation to identify trends and themes relevant for the space education sector. Finally, we present other high-profile educational activities at KU Leuven.

2. The Master of Space Studies (MSS)

Space activities occur in a broad interdisciplinary landscape. This means that the space sector needs skilled experts that can operate in an interdisciplinary environment. Unfortunately, there are usually two main roadblocks. On the one hand, there are very few initial training programs that directly prepare the students to enter the space sector. On the other hand, most new graduates have typically specialized in only one of the fields related to space and lack a much-needed interdisciplinary perspective.

In this context, the KU Leuven and Ghent University set up, in 2009, an advanced master program to help prepare new generations of students to start successful careers in the space sector as well as to provide industries, regional, (inter-) national and (inter-) governmental agencies and organizations with new talents that have a broad view of the space sector. To reach these objectives, the program acts at two levels: a broadening of the skills of the student by exposing them to a diversity of fields related to space and a deepening of the background specialization of the students, applied to the space sector.

The resulting Master of Space Studies (MSS, [3,4]) is a post-master English-taught interdisciplinary program of purely academic nature. It is organized jointly by KU Leuven and Ghent University, two leading Belgian universities, and involves lectures organized by the faculties of Sciences, Engineering, Laws and Economics. The program is unique in Belgium, and beyond, by its breadth and nature. The MSS is internationally oriented, interdisciplinary, interfaculty, and interuniversity.

As an advanced post-master program, applicants must have successfully completed an initial master's program in either the

COMMON CORE COURSES (29 ECTS)

Introduction to **(a)** *Law, Policy, Business and Management* **or (b)** *Exact Sciences and Technology***
Space Law, Policy, Business and Management
Fundamental Science from Space
Engineering Design of Space Missions and Spacecraft Components
Earth Observation
Questions in Space Studies

SPECIALISED, PROFILE-ORIENTED COURSES* (16 ECTS)

Space Law, Policy, Business and Management	Space Sciences	Space Technologies and Applications
The Law of International Organisations	Advanced Topics in Life Sciences in Space	Spacecraft Technology and Space Environment
Introduction to Management and Strategy	Astrophysics from Space	Robotics
Advanced Topics in Space Law, Policy, Business and Management	Space Weather	Reliability of Space Systems
Space Organisations	Synchrotron Radiation	Satellite and Space Communications

MASTER THESIS PROJECT (15 ECTS)

Figure 1. MSS program structure. (*) Students can also include courses from other master programs at KU Leuven or Ghent University. (**) Depending of the profile of the student: students with an initial master in Science or Technology have to follow (a) while students with a Humanities background will follow (b).

humanities and social sciences, exact sciences and technology, or biomedical sciences. The initial trainings of the influx students are very diverse but share a common thread: that the students demonstrate a strong interest in the space sector and that they are able to project their future self in a topic relevant to space.

In some more detail, the MSS is a 60 ECTS program, taken up as a 1-year full-time or a 2-year part-time program (Figure 1). The mandatory common core of 29 ECTS acquaint the students with the different aspects that together form the foundation of space-related activities. Mandatory courses cover law & policy, space missions and satellite technology, sciences aspects and earth observations

Depending on their background and interests, the students then deepen their existing knowledge through more domain-specific optional courses, for a total of 16 ECTS. These courses cover the domains of (i) Space Law, Policy, Business and Management, (ii) Space Sciences – which is very broad and covers topics ranging from space weather to radiation physics, to life science – (iii) Space Technology and Applications. Students can furthermore choose courses from other master programs at KU Leuven and Ghent University, as long as they are appropriate for their master thesis or their future professional project.

The master thesis is the final part of the interdisciplinary program, in which the acquired knowledge and interdisciplinary skills are applied to a complex and concrete project. The master thesis is a four months project mostly performed in the second semester during which the student is embedded in a research team at KU Leuven or Ghent University, or at an external institute, organisation or private partner, under the supervision of an academic promotor.

Thanks to the interuniversity effort of the program, students get embedded in the academic research expertise of two internationally-ranked Belgian universities. Furthermore, the program benefits from high-profile lecturers, including Frank De Winne, one of two Belgian astronauts, or Prof. Sarah Baatout, head of the Radiobiology Unit of the Belgian Nuclear Research Centre; as well as several international experts speaking in the yearly lecture series of the KU Leuven Centre for Global Governance Studies.

Finally, extracurricular initiatives are taken to bring the students in contact with actors in the different fields of space studies. Each year student excursions are organised, including visits to the European Astronaut Center in Cologne, Germany and the European Space Research and Research and Technology Centre (ESTEC) of ESA in Noordwijk (NL) and the Belgian Nuclear Research Center (SCK-Cen). Whenever relevant, students are given the opportunity to take part in a variety of national and international events. Recent

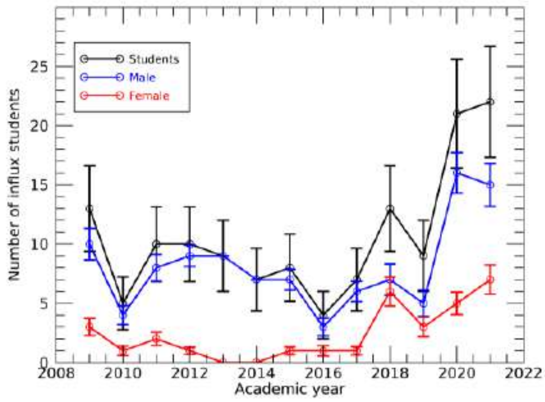

Figure 2. Number of students registered in the program per academic year. Poisson errorbars have been included.

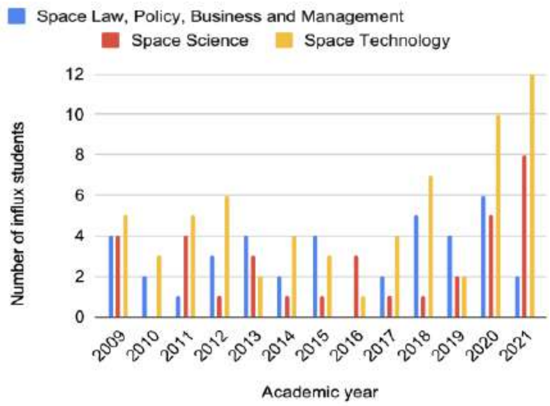

Figure 3. Distribution of students among the three specialization profiles of the MSS.

examples encompass the ESA Young Laywers' Symposium, the Luxembourg NewSpace Europe Conference or the Belgian Switch to Space event, allowing students to expand the local expertise, interact with industry leaders, policymakers and research experts, grow their network and explore new career opportunities.

3. Programmatic analysis

The MSS program is nearing the end of its 13th academic year and has graduated over 100 students since it was first offered in 2009-2010. This provides us an interesting sample of alumni specifically trained to enter the space sector. In this section, we investigate the demographics of the program, including attendance, gender balance and the distribution of students among the main study profiles. In a second step, we use social media and personal contacts to trace the current professional occupations of the program's alumni to identify the sector (space- vs. non-space-related) and subsectors (academia, (inter)governmental agencies, industry) in which they are working. Finally, we use the results of interviews from alumni to shed some additional perspectives offered by young professional on the space education.

3.1. MSS demographics

Students' influx: Figure 2 displays the number of students that have entered the program for each academic year. With an influx rate of less than 10 students per year in the first few years, the influx rate has more than doubled in the last couple of years with currently no less than 29 students registered for the academic year 2021-2022 (22 new students and 7 students spreading the 60-ECTS program over two years). As the reader will notice, Poisson error bars that are appropriate for counting statistics have been overlaid in Figure 2. Of course, one exactly knows the number of registered students each year, so one may wonder "*Why error bars?*". As data scientists would explain, considering the number (N_i) of registered students each year (i) as the realization of a random variable (X_N) allows us to investigate whether the observed year-to-year variations can be explained by statistical fluctuations due to random sampling of a constant parent population or whether significant time-depending trends can be identified.

For example, the 2012 and 2018 peaks in Figure 2 are by no mean significant, nor is the 2010 valley. Yet, the increase observed of the last couple of years cannot be explained by statistical fluctuations around a constant average (null hypothesis rejected at 99.9%-confidence). This suggests that an external factor came into played to modify the landscape in which students choose their orientation. While the number of students in tertiary education in Belgium grows over the years, this cannot be invoked to explain a short-term increase by a factor of more than 2.5. As an alternative explanation, one may note that the increase coincides with the first academic year after the start of the COVID crisis. One may therefore wonder whether (some) graduating students felt that the job-market would be difficult and have therefore chosen to pursue a complementary (post-master) education to increase their attractivity on the markets while weathering the crisis. Interactions with the students revealed however a different message in which they put forward their long-lasting interest for space, the perceived attractivity of the sector and the larger media attention to space-related news. Time will certainly help to differentiate between the latter two hypothesis.

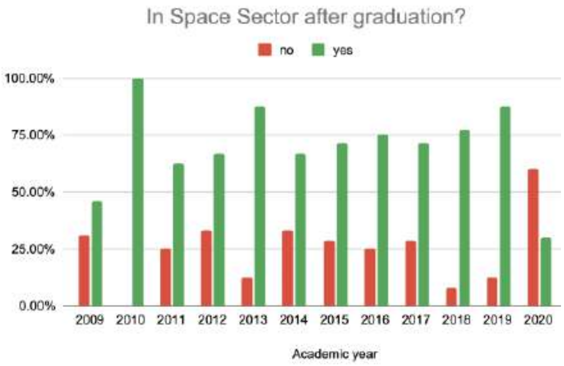

Figure 4: Fraction of MSS students with a space-related professional occupation immediately after graduating from the MSS

Gender balance: A similar analysis can be done with respect to the gender of the students' population. From 2009 to 2017, the fraction of female students was on average of 14% while, since 2018, its average now reaches 32%. The post-2017 fraction of female students cannot be explained by statistical fluctuation around the pre-2017 rate and should therefore be considered as significant (null hypothesis rejected at the 95%-confidence). The beginning of the trend precedes the start of the COVID crisis, and we might hope that this will be a long-lasting trend to improve the influx of women in a sector that has long standing gender imbalance (as other STEM-related sectors do).

Specialization profiles: Figure 3 displays the distributions of students across the three MSS specialization profiles. Averages are 28%, 25% and 47% for the Law & Humanities, Science and Technology profiles, respectively. Our analysis reveals no statistically significant trends albeit smaller sample sizes may limit our sensitivity.

Internationalization: A last trend of interest is the larger internationalization of the program, with an influx from abroad that has doubled, from an average of 11% from 2009 to 2017 to an average of 22% in the last 5 years, despite a drop to pre-pandemic level in 2020.

3.2. *Professional occupation*

One of the aims of the MSS is to help preparing the students to start a career in the space sector. A possible metric of success is thus to investigate the first professional occupation of the MSS alumni immediately after graduating. Figure 4 reveals that a consistent fraction off about 70% to 75% of the MSS students find a job in the space sector after graduation, but for 2020 (possible impact of the pandemic?). The retention rate however decreases over the years and drops below 50% at the 10-year

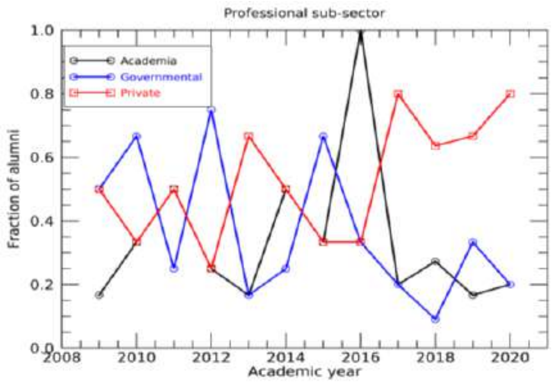

Figure 5: Distribution, as a function of their graduation year, of the professional sub-sectors (see legend) in which MSS alumni working in the space sector are working. Errorbars have been neglected for clarity but are of 15 to 20%.

horizon. Discussion with a subset of the alumni that have left the space sector indicates that this is rather the result of new opportunities and professional developments, or personal circumsances, rather than a lack of options within the space sector itself.

Among alumni working in the space sector, one may wonder which sub-sectors they are working in. Figure 5 reveals a good mix of alumni working in academia (e.g., researchers and PhD students at universities and research centers), governmental agencies (e.g., ESA, national agencies) or the industry. While the error bars are large given the limited sample size, the clear rise of the private sector share (mostly from within Belgium) in the last four or five years seem to suggest a more dynamic Belgian job market and a growing number of private opportunities in the space sector.

3.3. *Testimonials*

The quality of the MSS program is regularly monitored through surveys and interviews of our alumni and of representative of the workforce. Below, we report on a small subset of quotes that illustrate the perception of students and workforce alike.

(Alumni) "*When I found out this Advanced Master existed, I immediately applied. We had all sorts of subjects. Can you imagine what it must have been like for an engineer to have Space Law or Life Sciences in Space? The diversity was exactly what I loved about the Master*."

(Alumni) "*Another aspect of the 1-year experience that changed my life was the networking. Because we were so few in the class, we became a tight group. Together, we*

DOI: 10.5821/conference-9788419184405.013

organised many trips to different kinds of events."

(Alumni) "*The diverse company visits allowed me to really get to know the industry. Thanks to this master, I found out what I wanted to do in life. I became […]. As you can probably imagine, I would never have known this job even existed without this awesome program*."

(Workforce) **"***There are only limited real multidisciplinary spaces studies programs available, globally, and the quality of this program is, arguably, amongst the highest if not the highest in academic quality pur sang."*

(Workforce) *"The program is really tailored to where your interests lie while at the same time giving all students the same basis to build on.*"

4. Other space-education activities at KU Leuven

KU Leuven hosts ESERO Belgium [5], the Belgian antenna of the European Space Education Resources Office which we do not develop her further for the sake of place. We rather focus on a less known CubeSpec project [6-8]. CubeSpec is a KU Leuven-led in-orbit demonstration mission that have been selected by the ESA GSTP technology program with a preliminary launch date in 2023. The goal of the mission is to enable low-cost astronomical spectroscopy from a 6-unit CubeSat using an innovative optical design and pointing mechanism. While the mission aims are scientific and technological in nature, CubeSpec offers significant educational opportunities with several master thesis projects organized so far around various aspects of the mission development.

5. Conclusions

In this paper, we have reported on the advanced Master of Space Studies (MSS), an interdisciplinary post-master tertiary education program organized jointly by KU Leuven and Ghent University. The inspection of the students demographics and the professional occupation of the MSS' alumni since its creation has allowed us to identify a number of interesting trend that we summarize below:

Student demographics

- Increase in registered students in the last 2 years
- Increase in gender diversity and fraction international students since 2018

Professional markets

- About 75% of MSS alumni start a professional career in the space sector, about 2/3 of which remain in the sector 10 years after graduation
- The private sector seems to be hiring a larger fraction of our alumni in the last 4 years, correlating well with its increase role in the space sector.

These trends need to be consolidated over the next few years by further monitoring of the students' population and their professional tracks, but also by a comparison with similar statistics from other branches of STEM education.

Appendix: Admission requirements [3,4]

As an advanced master's program, applicants are required to have successfully completed an initial master's program before starting the MSS. The initial training can be very diverse (e.g., Law, Business, Economics, Physics, Astronomy, Management, Engineering, Design, Psychology, Biochemistry, Medicine, …). All applicants must further present a CV and a two-page motivation letter describing the importance of the program for their professional expectations, especially in view of their previous master education. A TOEFL English proficiency test is also required.

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Design and optimization of a rocket structure following the requirements for the European Rocketry Challenge (EUROC) to be fabricated using additive manufacturing

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Abstract

Amateur rocket structures are usually made of composite materials, wood or aluminium, their internal geometries and interfaces are usually restricted by the available manufacturing techniques. However, with the appearance of the additive manufacturing sector new possibilities arise for the design of the structures and its complexity.

In this paper a PA-12 and glass fibre composite structure for the Phobos rocket is designed which the UPC Space Program aims to use to participate in the European Rocketry challenge. The Phobos rocket structure is designed and optimized to be fabricated using additive manufacturing by Hewlett-Packard. The structure is designed using a lattice approach to obtain a PA-12 skeleton which is then reinforced with a skin of glass fibre composite.

Moreover, to obtain the desired structure an optimization methodology is set using a design loop in which the critical section of the rocket is parametrically optimized to reach the equivalent traditional structure performance. The structure is optimized in the size of the lattice geometry and in the thickness of the skin as parameters. To do so, the critical load during the flight of the rocket is identified and translated to the Nastran environment to run a parametric optimization of the structural model. The optimized geometry is then extended to the rest of the rocket to obtain the overall optimized structure. In addition, several analyses are conducted to validate the structure behaviour for the different load cases. Finally, both the optimized critical case and the overall optimized structure are compared to traditional design structures to obtain conclusive results about the use and limitations of the available additive technology and its materials.

Keywords
Rocketry, Students, Design, Optimization, Structure

Nomenclature

T	*Glass fiber thickness*
N	*Number of triangles per perimeter*
BF	*Buckling factor (number of times over the critical buckling load)*

Acronyms/Abbreviations

EuRoC	*European Rocketry Challenge*
ESEIAAT	*UPC Escola Superior d'Enginyeries Industrial, Aeroespacial i Audiovisual de Terrassa*
UPCSP	*UPC Space Program*
HP	*Hewlett-Packard*

1. Introduction

This paper is based on the final master's thesis which has the objective to design an optimized rocket structure which aligns with the requirements of the Ares mission inside the UPCSP [1] (UPC Space Program) frame. The Ares mission aims to participate in the EuRoC [2] (European Rocketry Challenge) competition, which takes place in Portugal using a new rocket called Phobos. The Phobos rocket design might use additive manufacturing technologies to improve several aspects of the rocket structure. The final master's thesis aims to optimize the rocket structure minimizing weight and comparing it to a traditional design giving justification for the use of additive manufacture techniques in the final rocket.

2. State-of-the-art

ESEIAAT [3] (UPC Escola Superior d'Enginyeries Industrial, Aeroespacial i Audiovisual de Terrassa) has always been involved in amateur rocketry with different student associations. UPCSP has been developing several amateur rockets since 2016.

Traditionally, these rockets are made of glass fibre, aluminium, carbon fibre and wood, with either self-made engines or commercial ones. However, with new technologies such as additive manufacturing those designs may be able to be improved.

Moreover, a lattice structure is sought to be used in the solution explained in this paper, several solutions can be found in the industry such as the ATG Europe [4], which provides composite structure solutions for rockets or satellites or the United Launch Alliance [5] which uses a lattice structure milled from aluminium sheets for its fairings.

3. Methodology

3.1. Work structure

The workflow for the thesis is the following:

- First a critical case with a critical section of the rocket will be set.
- A traditional critical section will be analysed and used as target for the optimized critical section.
- The optimization process will be conducted to reach the performance of the traditional design critical section.
- Both designs will be extended to the whole rocket.
- Several analyses will be conducted and both rocket designs will be compared.

3.2. Critical load case

The critical load case used for the dimensioning of the design is the buckling failure mechanism. A thin-walled elongated cylindrical rocket structure could collapse under the loads provided by the simulation department of the Ares mission inside the UPCSP. According to their simulations, the maximum loads occur during the ignition stage of the launch which correspond to an axial load of 3000 N. This value will be the dimensioning loads of the design.

It is worth to mention that due to the small engine and short burn time of the rocket (around two seconds) no thermal loads are considered in this study. The thermal isolation of the engine paired with the thick aluminium wall of its mount are enough to not let heat reach the structure considering the short burning time.

3.3. Critical section of the rocket

To size the structure and optimize correctly the most critical section of the rocket structure is selected to be the payload bay, which corresponds to a cylinder of 14 cm in diameter and 90 cm of longitude. Is the most critical section due to:

- Being the longest empty section of the rocket.
- Being the section needing more empty space inside for the payload.

DOI: 10.5821/conference-9788419184405.014

3.4. Design and Analysis methodology

Two design methodologies will be followed. The traditional design with typical materials already used by the UPCSP and the optimized design which incorporates additive manufacturing and its corresponding materials.

3.4.1. Traditional design

The traditional design has the characteristic of having a thick skin on the walls of the rocket. This skin typically withstands all loads on the rocket structure, and it is often oversized for manufacturing purposes. The typical values from past UPCSP rockets are:

- Three layers or two of glass fibre with a 1:1 ratio in mass to epoxy resin. Applied by hand lay-up.
- Interior parts made of wood or 3D printed PLA polymer.
- Interfaces between skin and interior geometries glued or joined by bolts.

3.4.2. Optimized design

The optimized design will be built of one skin of glass fibre and an internal structure based on a lattice distribution made of triangles. The internal structure will be additive manufactured.

The optimization procedure for the structure will be the following:

- Model with *N* triangles.
- Parametric optimization of the thickness of the glass fibre skin, the width, and the height of the beams of the triangles.
- Linear buckling analysis on the optimized structure.
- Comparison with the traditional design.
- Iteration loop to match the performance of the traditional design.
- Final *N* triangle optimized critical section model.

The triangles in which the structure is formed are the following:

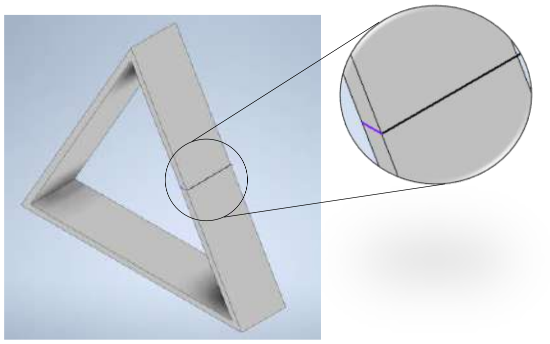

Figure 2. Base triangle of the structure, in purple the width of the beam and in black its height.

Several examples of similar functioning structures can be found in the references such as the Lattice structure of a satellite designed by *ATG Europe* [4].

Once the critical optimized section design is obtained the lattice structure will be extended to the whole rocket to obtain the optimized rocket design. Additionally, a thin skin wall joined to the lattice structure on its exterior will be designed to facilitate the hand-layup of the composite material.

3.4.3. Analysis methodology

The analysis is conducted using Beta Cae Systems Ansa [5] as a pre-processor, MSC Nastran [6] as a solver and Beta Cae Systems Meta [7] as a post-processor.

Two sets of analysis will be conducted for the designs:

- Analysis for the critical section and optimization of the critical section.
- Analysis for the general traditional rocket design and the optimized rocket design.

The different analysis under which both rocket designs will be submitted are:

- Strength analysis: In which the static-strength failure mechanism is simulated.
- Modal analysis: In which the dynamic failure mechanism is simulated.
- Linear buckling: To simulate part of the buckling failure mechanism.
- Non-Linear buckling: To simulate the non-linear part of the buckling failure mechanism.

DOI: 10.5821/conference-9788419184405.014

For the optimized design to be considered usable all the analyses results must be on par with the traditional ones, which will be used as a target for the performance of the optimized structure.

Moreover, a local deformation will be introduced into both critical section models to understand the structural behaviour in front of possible irregularities in the hand lay-up or manufacturing process, this deformation will be induced into the model displacing the mesh elements.

3.5. Materials

There are two types of materials used in this design.

3.5.1. Composite materials

The composite materials used in this analysis are a glass fibre and epoxy composite. For its modelling the rule of mixtures [8] is applied.

$$E_c = fE_f + (1-f)E_m \quad (1)$$

Where:

$$f = \frac{V_f}{V_f + V_m} \quad (2)$$

In Eq. 2. V_f and V_m are the volume fraction of fibre and matrix respectively. In Eq. 1. The Young Modulus is calculated using the Young modulus of both materials and the volume fraction f of Eq. 2. In a similar way the density, compressible and tensile strength and poisson number are also calculated.

The glass fibre used by UPCSP is a E-glass V-twill of 165 grams per square meter [9] and the Epoxy resin for hand-layup laminates [10]. The volume fraction used for the design is of 67% of fibre and 33% of matrix.

3.5.2. Other materials

For the traditional design the other materials to be modelled are:

- Aluminium 3003 with its mechanical properties [11].
- PA12 with its mechanical properties provided by HP (Hewlett-Packard) [12].
- PLA, used for common 3D printing [13].

4. Results and Discussion

The results will comprise of the most relevant results and comparisons between the following analysis:

- Traditional two-layered critical section and different N triangle optimized critical sections to obtain the best optimized critical section.
- General comparison between the traditional and optimized final critical sections.
- 4 mm deep local deformation at half length of the critical section between both cases.
- Traditional design rocket and optimized design rocket linear buckling, non-linear buckling, modal analysis, static analysis, and masses comparison.

The optimization process was set with a target critical lineal buckling load of 30 KN, which corresponds to the critical load of the traditional design for two glass fibre layers (Factor of security of 10 over the design load).

When comparing the results to the traditional section for a linear buckling analysis is obtained:

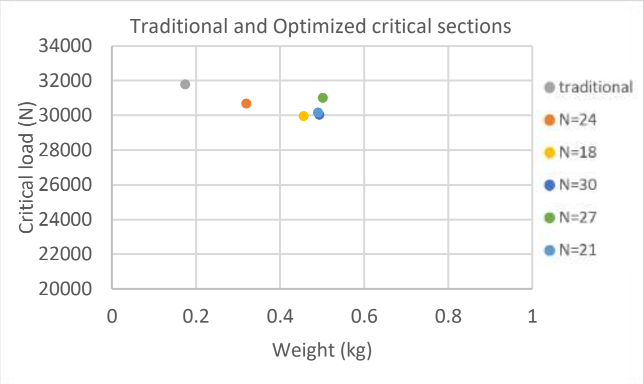

Figure 3. Comparison between the two-layers traditional design and the optimization process of the critical section.

For the critical section in Figure 2 the optimization process shows a reduction of mass maintaining the same critical load ending up on the 24-triangle configuration with a total mass of 0.32 Kg which will be the used configuration for the general optimized rocket.

Figure 4. N=24 triangle configurations for the optimized design.

4.1.1. Traditional and optimized critical section comparison

For both the traditional two-layer design and the 24 triangles optimized design are compared.

Table 1. Comparison between final optimized critical section and two-layer traditional critical section

	T (mm)	Triangles (Width x height, mm)	Mass (Kg)	Max. Lineal Load (N)
Traditional	0.50	-	0.17	3.18E+04
Optimized	0.25	3.1x1	0.32	3.03E+04

4.1.2. Global and local deformations

The 4 mm deformation is induced in the model at half length of the critical section displacing mesh elements:

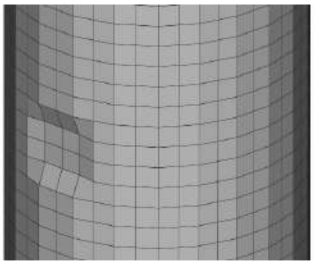

Figure 5. Displaced elements on the mesh with a depth of 4 mm.

For both cases a non-lineal buckling analysis is launched obtaining:

Table 2. Comparison between Traditional and Optimized critical sections with a 4 mm deep deformation under non-linear buckling analysis.

Model	Max. Non-lineal load (N)
Traditional Crit. Sect.	13200
Opt. Crit. Sect.	17400

4.2. General rocket model

The two-layer traditional design rocket and a N=24 Optimized design are compared under several analysis.

Figure 6. CAD model of the optimized rocket design

4.2.1. Linear buckling analysis

Table 3. Comparison between traditional and optimized rocket designs under linear buckling analysis.

	Traditional design	Optimized design
BF (Buckling factor)	6,744	13,076

4.2.2. Non-Linear buckling analysis

Table 4. Comparison between traditional and optimized rocket designs under non-linear buckling analysis.

	Traditional design	Optimized design
Max. Von Misses stress (MPa)	11.9	0.7
Max. Disp. (mm)	0.2431	0.0121

4.2.3. Modal analysis

Table 5. Comparison between traditional and optimized rocket designs under modal analysis.

	Traditional design	Optimized design
First mode (Hz)	50.00	32.63

4.2.4. Static analysis

Table 6. Comparison between traditional and optimized rocket designs under static analysis.

	Traditional design	Optimized design
Max. Von Misses stress (MPa)	25.7	21.0
Max. Disp. (mm)	0.3428	0.3276

4.2.5. Masses

Table 7. Comparison between traditional and optimized rocket designs masses.

	Traditional design	Optimized design
Total mass (Kg)	11.13	11.96

5. Conclusions

There are several sets of conclusions which can be extracted from the design of the rocket discussed in this paper.

The optimized critical section did not reach the performance of the traditional one. Weighting more and making it unfeasible to reach due to the low Young modulus of the PA12. The optimized design however is better at withstanding local deformations, making it less prone to failure under irregularities even though that both designs struggle to withstand them as expected.

From both final rocket designs several points must be raised. First the optimized rocket behaves with a much higher BF than the traditional one, this could be explained due to the increased thickness of the wall because of the beams of PA12.

The non-linear buckling analysis results are not conclusive enough to extract significant conclusions. However, both designs withstand the maximum load.

The modal analysis shows a variation in the values. These values will be used for the UPCSP team to ensure that no excitation frequency matches the first mode of the design.

The static analysis is similar in both designs, showing that both could withstand the maximum loads. Additionally, the optimized design has lower deformations.

Finally, the mass difference is greatly reduced in the context of the whole rocket, making it almost similar for both designs.

Besides the analysis the conclusions can be extended to the Ares mission inside the UPCSP. It must be considered that several manufacturing issues arise from the hand-layup of the composite material. The already existing strength of the skeleton of the optimized design creates an easier work environment. It is not possible to hand-layup one single layer of glass fibre properly, thus making all designs oversized.

The additive manufacturing approach allows for complex geometries to appear in the design. When updating the optimized rocket with the interior interfaces for the payload, electronics, etc. the additive manufacturing allows for much convenient solutions. A standardized manufacturing procedure allow the rocket to reach higher quality standards than hand made parts, which increase the reliability and safety of the mission.

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The "Effect of Marangoni convection on heat transfer in Phase Change Materials" experiment, from a student project to the International Space Station

Pablo Salgado Sánchez[1], *Jose Miguel Ezquerro*[2], *Dan Gligor*[2], *Úrsula Martínez*[2], *Jose Fernández*[2], *Ignacio Tinao*[2]

Abstract

This manuscript summarizes the educational and scientific outcome of the Research-based learning activities performed in the bachelor's, master's, and doctorate programmes in aerospace engineering at the Technical University of Madrid. The activities are related to the line of research in Phase Change Materials in microgravity developed at the Spanish User Support and Operations Centre. The principal scientific results obtained during these years are outlined, drawing particular attention to those related to the "Thermocapillary Effects in Phase Change Materials in Microgravity" experiment and the "Effect of Marangoni convection on heat transfer in Phase Change Materials" project. The outcomes of this research are discussed from an educational perspective. Since 2016, we observe an increased interest from students to participate in research activities, which has had direct positive impact on the production of scientific results.

Keywords

Active learning, ISS, Marangoni in PCMs, Microgravity experiments, Research-based learning

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Acronyms/Abbreviations

B/Md	*Bachelor/Master's degree*
ECTS	*European Credit Transfer System*
ESA	*European Space Agency*
E-USOC	*Spanish User Support and Operations Centre*
ISS	*International Space Station*
MarPCM	*Effect of Marangoni convection on heat transfer in Phase Change Materials*
PCM	*Phase Change Material*
RBL	*Research-based learning*
TEPiM	*Thermocapillary Effects in Phase Change Materials in Microgravity*
UPM	*Universidad Politécnica de Madrid*

1. Introduction

In recent years, universities are evolving toward teaching and learning methods based on active learning [1]. Among these methodologies, challenge-based learning is an excellent example of a widely implemented approach in engineering education, with positive results in the development of generic competencies and soft skills, and in the student's motivation and satisfaction [2],[3]. With a similar educational impact, research-based learning (RBL) [4] aims to connect students with research techniques and methodologies that allow them to develop competencies and analysis, reflection, and argumentation skills.

In the context of RBL, the Spanish User Support and Operations Centre (E-USOC), as part of the Aerospace Science and Operations research group at Universidad Politécnica de Madrid (UPM), has integrated progressively the participation of students in its microgravity research activities, as a way of implementing RBL in tertiary education.

Since its early stages, the line of research in Phase Change Materials (PCMs) and thermal control has counted on with a large student's contribution. Indeed, it was born in 2016 from the student's project "Thermocapillary Effects in Phase Change Materials in microgravity" (TEPiM) [5], and has progressively grown to the point that, a related experiment proposal, is now part of the European Space Agency (ESA) planned experiments that will be executed on board the International Space Station (ISS) in the near future [6].

Motivated in no small part by the worsening environmental problems created by modern society, the use of PCMs as thermal energy storage systems has seized lot of attention in the last few decades. PCMs, characterized by their ability to store and release large amounts of energy in the form of latent heat, are an attractive alternative to improve efficiency and reduce energy waste [7].

Space exploration is a special area of application, for which organic materials like alkanes are a suitable PCM selection, due to their moderate melting temperature and large heat of fusion. Their performance, however, is generally limited by low thermal conductivity. Recently, the thermocapillary effect has been proposed as an enhancement strategy with great potential for microgravity applications [8]. During the phase change, the presence of air or another gas in contact with the liquid phase of the PCM supports thermocapillary convection and provides an additional mechanism for heat transport that improves the performance of the PCM device.

Since 2016, our research activities have focused on the analysis of thermocapillary effects in PCMs in microgravity. The TEPiM experiment furthered our current understanding of PCM melting in microgravity and motivated further efforts. From an experimental research perspective, we highlight the need of microgravity: if thermocapillary convection occurs in a PCM device on ground, it interacts with, or can be even masked, by natural convection, fact that complicates quantifying the contributions of each effect to the heat transfer rate. The final goal is to design more efficient thermal control systems based on PCMs for future space missions.

In this manuscript, we provide an overview of the scientific results and related RBL activities performed. The manuscript is structured as follows. In Sec. 2, a brief review of the TEPiM experiment is given. In Sec. 3, we describe the future "Effect of Marangoni convection on heat transfer in Phase Change Materials" (MarPCM) experiment. In Secs. 4 and 5, the RBL activities performed during these years and associated results are summarized and discussed. Final conclusions are offered in Sec. 6.

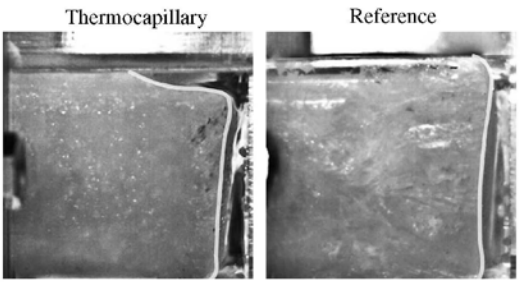

Figure 1. Comparison between thermocapillary and reference cell experiments. Adapted from Ezquerro *et al.* [9].

2. From a student project…: The Thermocapillary Effects in Phase Change Materials in Microgravity experiment

As a first effort to understand the possibility of using the thermocapillary effect as a heat transfer enhancer in microgravity, the research group presented the TEPiM experiment to the call for proposal of the 2016 ESA "Fly your Thesis!" programme, sponsored by the ESA Education Office — the educational division of ESA. The experiment, along with other three projects, was selected [5] to fly onboard the A310 ZERO-G aircraft in the 65th ESA parabolic flight campaign, November 2016.

TEPiM was designed, manufactured, and executed by students, and represents the first set of microgravity experiments on the melting of PCMs with thermocapillary flows.

2.1. The TEPiM experiment

The experiment proposed to study the heat transfer characteristics of PCMs designed with a free surface in reduced gravity. The principal objective was to measure the influence of the associated thermocapillary convection to the solid/liquid phase change [8].

The setup consisted of different pairs of thermocapillary, and reference cells filled with n-octadecane, an organic PCM from the alkanes family. The thermocapillary cells had an air layer on top that supports thermocapillary flows during melting, while the reference counterparts only contained PCM.

Experiments were performed during the repeated microgravity periods of the flight, with an approximate duration of 20 s. During melting, the thermocapillary-driven flow in the liquid phase of the PCM improved the heat transfer rate near the PCM-air interface. The advance of the solid/liquid front was accelerated (locally) in the thermocapillary cells compared to the reference counterparts; see Figure 1 [8],[9].

Overall, TEPiM demonstrated the potential of the thermocapillary effect to enhance heat transport in microgravity [8]–[10] and motivated further research. Note, however, that these results were constrained by the short microgravity timescale of parabolic flights; experiments over larger microgravity periods were needed to definitely evaluate the PCM design and provide data to validate theoretical and numerical models.

3. … to the International Space Station: The Effect of Marangoni convection on heat transfer in Phase Change Materials experiment

Since 2016, we have conducted extensive numerical research [11]–[16]. Results mainly focus on rectangular geometries and n-octadecane. Different studies show that thermocapillary effects depend essentially on container geometry, typified by the aspect ratio Γ, and the applied temperature difference, quantified by the Marangoni number (Ma).

The main conclusions of these works can be outlined as follows:

- Depending on Γ and Ma: (i) heat transport can be enhanced up to a factor of 20 [11], (ii) oscillatory flow can appear [12] in a complex pattern selection scenario [15].
- The performance of the PCM device can be further improved using liquid bridge [14] or trapezoidal [16] geometries.

From an experimental perspective, the MarPCM experiment was recently approved by ESA for its future execution onboard the ISS. This project is the result of a collaboration between UPM, with the E-USOC leading the project, and the universities Mondragon Unibersitatea and Universitat Rovira i Virgili.

3.1. The MarPCM experiment

The experiment will study the effectiveness of thermocapillary flows to improve the heat transfer rate of PCMs and make more efficient use of their energy storage capacity in microgravity. As in TEPiM, the proposed PCM design incorporates a free surface to support thermocapillary convection.

DOI: 10.5821/conference-9788419184405.015

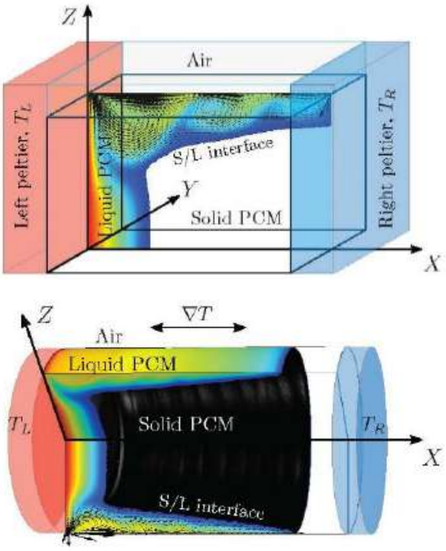

Figure 2. Sketches of the cuboidal and cylindrical (liquid bridge) cells.

Different PCM samples will be subjected to repeated melting/solidification cycles, by applying controlled temperature gradients, and will be held in containers having two different geometries: cuboidal and cylindrical (liquid bridge); see Figure 2. Each of these containers will be designed to passively maintain the PCM/air interface, except for one of the cuboidal cells, which will be filled completely with PCM and will provide a reference measurement of the heat transfer driven solely by conduction.

The phase change evolution will be diagnosed using an optical setup (cameras and illumination) and temperature measurements inside the PCM samples. A quantitative evaluation of the melting/solidification performance between different experiments will be made by comparing the evolution of the solid/liquid interface over time.

Based on simulations, we anticipate that thermocapillary flows will increase the heat transfer rate by a significant factor, depending on the physical properties of the PCM, geometry, and applied temperatures [11]–[14]. Additionally, we expect to observe interesting dynamics related to oscillatory flow. As commented above, different modes can appear [12]–[15], induced by the interaction between the evolving solid/liquid front and the thermocapillary flow.

As will be discussed below, the project has already counted with a large participation of students in different tasks ranging from numerical modelling to the design, manufacturing, and execution of ground experiments.

4. Research-based learning activities and scientific results

At UPM, these research activities are integrated in the curricula of the bachelor's degree (Bd) and master's degree (Md) in aerospace engineering, as well as in the doctorate (PhD) programme in aerospace engineering, as one of the offered lines of research.

At Bd level, RBL is implemented in the context of internships at E-USOC (12 European Credit Transfer System, ECTS) and associated final Bd projects (12 ECTS). Since 2016, 7 projects have been successfully defended, obtaining the maximum grading and excellent evaluations from the tribunals.

At Md level, RBL is analogously introduced as internships (12 ECTS) and associated final Md projects (18 ECTS). Since 2016, 3 projects have been successfully defended with the maximum grading. Currently, another 2 projects related to PCMs are being developed with an expected defence date in July.

At PhD level, 2 theses were recently approved and will be developed in upcoming years. The PhD projects are related to the design and development of the MarPCM ground prototype and associated numerical modelling.

From all these RBL activities, different scientific results have been produced. Since 2016, students have already contributed to 4 oral lectures in 3 international congresses:

- 26th ELGRA Biennial Symposium and General Assembly.
- 71st International Astronautical Congress: Cyberspace Edition.
- 43rd COSPAR Scientific Assembly.

Another 3 abstracts for oral presentations have been recently submitted and are currently under review.

In addition, a total of 9 scientific articles have been published in prestigious journals with the participating students (underlined in the References section) as leading authors in most cases. Another 2 articles have been recently submitted and are currently under review.

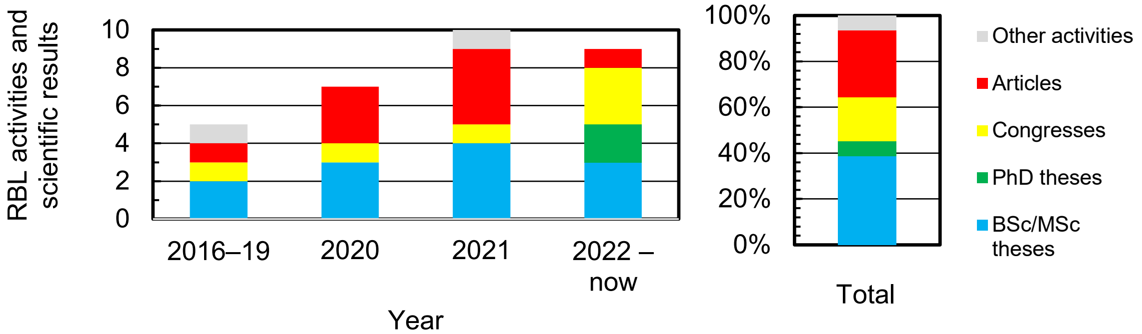

Figure 3. RBL activities and scientific results with student's participation since 2016.

Apart from curricular activities and associated results, we have further participated in other two RBL experiences: the 2019 UPM's science week and the 2021 ESA/ELGRA Gravity-related research summer school [17].

5. Discussion

A summary of the RBL activities and results is illustrated in Figure 3. Since in 2016, there have been an increasing number of activities and associated scientific contributions.

First, one may notice that the total number of final B/Md projects have increased year by year. Each academic course, students showing their interest in doing their projects at E-USOC are put in contact with former students so that they can share their experience. We attribute this increased interest to the overall positive evaluation of the internships at E-USOC.

As a direct consequence, the production of scientific results has grown notably. Since the very beginning of their internships, students are aware of the possibility of publishing their results in prestigious journals, fact that boosts their motivation. In line with this, students usually show their interest in extending their collaboration in subsequent academic years. As a clear example of this, the 2 theses mentioned above are related to PhD candidates who have continued their collaborations since their Bd projects.

From a training perspective, these RBL activities allow the students to integrate into E-USOC activities and participate in a real research experience that extends from the preliminary design of an experiment to its execution. It is not only about learning by doing research from a theoretical perspective, but also about acquiring a global vision of experimental research in microgravity and the complex requirements derived from carrying out experiments in parabolic flights or a unique platform like the ISS.

This experience is very motivating for the students, helping to promote their technological and scientific vocation and to value research in the development of new space technology. In addition, thanks to these activities, students develop transversal skills such as teamwork, oral and written communication in English or time management, among others.

6. Conclusions

This manuscript has summarized the educational and scientific outcomes of the RBL activities performed at E-USOC, within the scope of the Bd, Md and the PhD programmes in aerospace engineering at UPM. The activities are mainly related to the line of research in PCMs in microgravity. The principal scientific results are outlined, drawing particular attention to the TEPiM and MarPCM projects. From an educational perspective, we observe an increased interest from students to participate in research activities, which has had a direct positive impact on the production of scientific results.

Acknowledgements

This work was supported by the Ministerio de Ciencia e Innovación under Project No. PID2020-115086GB-C31, and by the E-USOC, Center for Computational Simulation. We thank the ESA Education Office, ELGRA and Novespace for the funding and contributions during the TEPiM project. We thank the E. T. S. de Ingeniería Aeronáutica y del Espacio and the Aerospace Science and Operations research group. Finally, we also want to thank the students that have participated in the RBL experiences.

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An investigation into cold weld adhesion for spacecraft repair after a space debris impact using space education based sub-orbital sounding rocket platform.

Mark Wylie[1], *Leonardo Barilaro* [2]

Abstract

It has been observed that similar metallic materials, when in contact and undergoing relative displacements, can fuse or weld. In standard atmospheric conditions it is not common but in the space environment the inability of the surface interfaces to re-oxide after abrasive contact is hindered, atomic diffusion of the metal occurs, and this can lead to fusion. Oscillatory motion and Hertzian contact stress between the two surfaces plays a major role in the strength of the cold welded joint. It has been shown that the action of a low fretting load can almost double the adhesion force under cyclic loading even in terrestrial atmospheric conditions. In space, cold welding was first identified in the 1960’s as an adverse reaction. It has been attributed to anomalies and failures of deployable mechanisms. Other research has alluded to the potential of this phenomena for use in spacecraft repair in space. Examples where this may hold promise is repair of a spacecraft hull breach after hypervelocity impacts due to micrometeoroids or orbital debris. This research proposes an investigation into cold welding for use in spacecraft hull repair. The research intends to qualify an experimental apparatus to TRL 4 using a sub-orbital sounding rocket platform. A joint research effort between the Aerospace, Mechanical and Electronic Department at I.T. Carlow, Ireland, the Department of Aviation at Malta College of Arts, Science, and Technology, Malta is underway. The project aims at developing a test apparatus to apply a number of custom patches to simulated hypervelocity spacecraft hull breaches and investigate the adhesion properties during re-entry for a range of mechanical application conditions. A number of chambers may be tested and monitored using pressure transducers. After Phase 1 (terrestrial development and validation using a vacuum chamber), there will be an application to education based space programmes such as the one offered by the European Space Agency (REXUS). The core of the activity will be the design and testing of the experimental payload, simulating hull breaches, deployment the repair patch and monitoring of its performance during re-entry (Phase 2). The recovery of the payload will allow further metallurgical analysis of the cold welded joint (Phase 3). A conceptual 3-D model of the payload has been developed and is presented here. The data acquired from the sub-orbital flight experiment will test the validity of the hypothesis for use of cold welding for spacecraft hull repair but will also detail the development and implementation of mock hypervelocity impacts to rocket skin for the purposes of simulating hull breaches in the space environment.

Keywords
Cold welding adhesion, Hypervelocity impacts, Space debris, Spacecraft repair, Sub-orbital flight

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Acronyms/Abbreviations

CPU Central Processing Unit

DRAMA Debris Risk Assessment and Mitigation Analysis

EM Engineering Model

ESA European Space Agency

EVA Extra Vehicular Activity

FM Flight Model

HGA High Gain Antenna

HVI Hypervelocity impact

ISS International Space Station

LEO Low Earth Orbit

LGG Light-Gas Gun

LVDT Linear Variable Differential Transformer

MASTER Meteoroid And Space debris Terrestrial Environment Reference

MCAST Malta College of Arts, Science and Technology

MRS Mini Research Module

MMOD Micrometeoroids and Orbital Debris

NASA National Aeronautics and Space Administration

ODEM Orbital Debris Engineering Models

RSC Rocket and Space Corporation

SSEA Symposium on Space Educational Activities

1. Introduction

Orbital artificial habitat satellites such as the International Space Station (ISS) have experienced loss of atmosphere due to perforation of the spacecraft hull. This can occur from engineering failures, manufacturing defects or Hypervelocity Impacts (HVIs) from space debris and micrometeoroids [1]. The frequency of the space debris impacts can be predicted using Orbital Debris Engineering Models (ODEM currently v 3.1). The Metroid impact flux can be estimated using NASAs ODPO SSP-30425 specification or European Space Agency's (ESAs) Meteoroid And Space debris Terrestrial Environment Reference (MASTER-8) and DRAMA (Debris Risk Assessment and Mitigation Analysis) [2]. One estimation based on early models predict that in a 30-year period more than 35,000 secondary debris particle impacts will occur to the ISS and will be at energy levels high enough to perforate the solar arrays [1].

By the end of 2020, the ISS has carried out 26 collision avoidance manoeuvres to escape impact with space debris [3]. If a collision is unavoidable, the ISS is equipped with a bumper structure known as a Whipple/Advanced Stuffed Whipple plate and this is designed to absorb the impact energy. However, secondary ejecta and collision with unprotected areas can, and do, lead to perforation of the ISS hull. If there is a hull perforation, the ISS benefits from its Low Earth Orbit (LEO) and ease of access to resupply any lost oxygen. Longer manned missions, also susceptible to hull perforations, do not have this option and it is a necessary precaution to consider how hulls would be repaired in space. There is a paucity of detailed information in the literature on how these leaks/perforations are repaired and no standards published but recently a description of a successful repair of 2.0 mm diameter hole in the Soyuz crew vehicle which was docked to the Mini Research Module (MRM-1) or Rassvet module was released [4]. It was stated that the perforation was repaired by using a medical gauze soaked in epoxy [5]. The adhesive is known as Germetall-1 and packaged as the GERMETIC leak repair kit. This repair kit includes Germetall-1 and Anaterm-1u sealant [6]. The most recent loss in atmosphere was identified in the Zvezda Service Module in 2020. A 22 mm long crack was detected in the module. It was reported that the leak was causing a pressure drop of 1 mm of mercury every 8 hours [7]. The crack was repaired using an undisclosed sealant. It is obvious that there is a conscious effort towards finding a viable solution. It is proposed to investigate the intentional cold welding of metals for spacecraft hull repair during a sub-orbital flight and monitor the performance of such repair during re-entry. This will also involve characterising and replicating perforations from HVIs. The aim of this project is to use an education-based sounding rocket platform and student team to investigate this phenomenon. The goal is to form a pan-European collaboration between third-level institutes and award an MSc in Space Systems Engineering. Project Team Lead, Materials Engineer, Mechanical Engineer, Aerospace Engineer and Electronics/ Communications Engineer are some of the student positions required. 5-10 team members are required. With that said, there are both educational and technical objectives for the proposed programme. This includes the identification of educational space-based opportunities through programme outreach. Recruitment of a student team and application to an education-based sounding rocket

DOI: 10.5821/conference-9788419184405.016

programme. As part of the technical objectives, an Engineering Model (EM) (Phase 1) along with HVIs perforations will be developed for terrestrial experimentation and validation. It is envisaged that the experiments will examine several material candidates, surface finishes and a range of impact forces and interactions (fretting and galling). The Flight Model (FM) (Phase 2) will re-design this experimental set up within the confines of a sounding rocket module. It will require the high vacuum conditions, re-entry pressurisation and acceleration forces/temperatures to validate the experiments. The micro-gravity environment in this phase may also play a role in the evolution of the joint adhesion. The experiment will introduce mock hull perforations and the experiment will operate autonomously during the flight profile. Further metallurgical analysis of the retrieved samples will form Phase 3 of this research.

2. HVIs and Cold Weld Adhesion

2.1. HVI effects

In hypervelocity impacts, the projectile velocity exceeds the speed of sound within the target material. The resulting shock wave that propagates across the material is reflected by the surfaces of the target, and reverses its direction of travel. The superimposition of progressing and reflected waves can lead to local stress levels that exceed the material's strength, thus causing cracks and/or the separation of spalls at significant velocities. With decreasing target thickness, the effects range from cratering, via internal cracks, to spall detachment, and finally to clear hole perforations. It has been shown that MMOD impacts on spacecraft, according to the debris' dimensions can generate [8]:

- Small surface pits due to micrometre-size impactors;
- Clear hole penetrations for millimetre-size objects;
- Mission-critical damage for projectiles larger than 1 cm

Any impact of a 10 cm catalogue object on a spacecraft or orbital stage will most likely imply a catastrophic disintegration of the target. This destructive energy is a consequence of high impact velocities. The effects of hypervelocity impacts are a function of projectile and target material, impact velocity, incident angle and the mass and shape of the projectile. At low velocities, plastic deformation normally prevails. With increasing velocities, the impactor will leave a crater on the target. Beyond 4 km/s, depending on the materials, an impact will lead to a complete break-up and melting of the projectile, and an ejection of crater material to a depth of typically two to five times the diameter of the projectile. Usually when the impact risk from meteoroids and orbital debris is assessed the main concern is usually structural damage. In this context, the proposed research targets the preliminary assessment of a repair to a damaged spacecraft hull shields. For this purpose, a range of mock hull perforation configurations will be evaluated and tested. An example perforation hole created by an Aluminium sphere projectile of 2.3 mm diameter at a speed of 4.8 km/s is shown in Figure 1 [9].

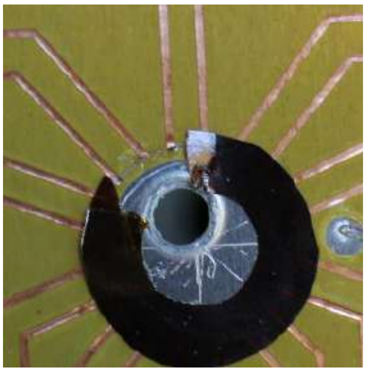


Figure 1. HVI impact example on an Aluminium plate.

2.2. Cold weld adhesion

Cold welding is the fusion of two metals at low temperature. Theoretically, adhesion of two metal samples of the same material will occur in contact providing the surfaces were smooth (microscopic scale), free from contaminants and the crystal lattice of the opposing surfaces have the same orientation [10]. There are two schools of thought on the mechanisms behind this phenomena and they are based on the film theory and energy barrier theory (mismatch of crystal lattice and recrystallization theory). In space, the absence of atmosphere provides necessary conditions favourable for cold weld adhesion. Furthermore, evaporation of lubricants in high vacuum and intimate contact of metal, causing disruption of the oxide film will further promote this fusion. In 1966 NASA published a state-of-the-art survey in the field of metal-to-metal adhesion or cold welding in space. This investigation examined both positive and negative effects of cold welding in space citing that it may be used someday to fabricate or repair structures in space [10].

This was followed in 1969, when NASA initiated a cold welding program to determine the proper test environment for qualifying spacecraft mechanisms. This research investigated the effects of cycles, and lubricated versus non-lubricated contact. In 1989, it was proffered that cold welding was shown to be a credible cause of the failure of the Galileo High Gain Antenna (HGA) to deploy [11]. The bond strength of cold welding in high vacuum has been shown to be significant, at least an adhesion strength equal to the load applied [12]. Adhesion forces in the vicinity of 10s of Newtons are reported and, in certain conditions, as high as 100 N under high vacuum launch environment using silver mating pairs [13]. Other soft metals, such as Indium, are excellent candidates for deliberate fusion as they have been shown to readily fuse in atmospheric conditions [14]. In general, along with metal surface conditions, the adhesion force is a function of the relative motion and magnitude of the applied contact force. In a study carried out by ESA in 2009 on the effects of fretting and metal adhesion, the maximum adhesion force (9.5 N) was found to be 2.5 times the applied load (4 N) [15].

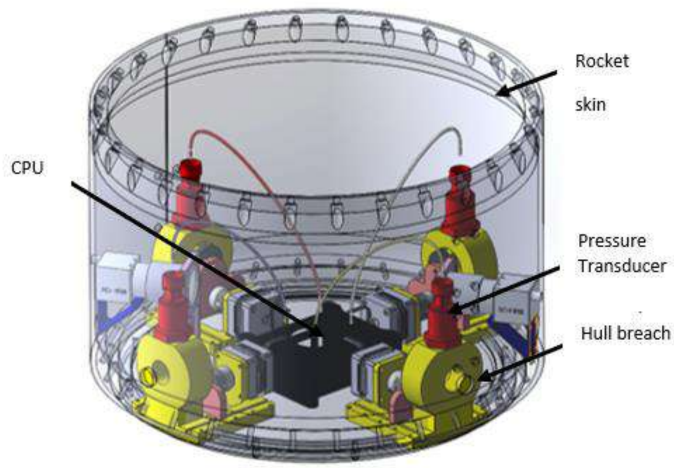
3. Operational framework

In November 2021, Institute of Technology Carlow, Ireland, initiated a collaboration with the Malta College of Arts, Science, and Technology (MCAST), which is currently developing the first hypervelocity impact facility of Malta. This joint research effort aims at attracting and involving post and undergraduate graduate students to a space based project while boosting the competences of these research centres. The two Institutions also initiated a collaboration with Luleå University of Technology, in Sweden. The focus is on studying the payload integration of the previously described experiment on a rocket for a sub-orbital flight. The space research centre of this University has world-class facilities and partners with Esrange, a rocket range and research centre located near Kiruna in northern Sweden. Currently a Memorandum of Understanding is being finalised.

4. Results

4.1. Preliminary design

A conceptual design of an experimental layout has begun. This includes four Aluminum alloy chambers (7075-T651), hermitically sealed and mounted to the rocket skin at the location of a simulated hull breach. Space qualified bonding agent, such as Kryptos may be used to form the seal. Each unit will investigate a set of experimental parameters established through Phase 1 testing. This may include, material type, surface finish and surface contact conditions. At apogee the experiment will commence. Signals from either ground station (SOD/SOE) or timers will initiate the experiment after Yo-Yo stabilisation. A breach in the rocket skin is introduced to each chamber and the material samples will be actuated by stepper motors or piezoelectric actuators. The performance of the sealed chamber will be monitored using welded stainless steel temperature compensated differential pressure transducers located in each chamber and will be monitored during re-entry. Some chambers may be pressurized prior to re-entry to examine the joint integrity in space (against a vacuum alone). A PC104 embedded CPU will be used to acquire the data. It will be stored locally, and an onboard Service Module (SM) and transmitter will be used to transit live data to ground station (sensors and housekeeping). Load cells or Linear Variable Differential Transformer (LVDT) may be used to verify the position of the sealing patch and the applied and reaction forces. Video data may also be acquired and stored locally as a means of anomaly detection. A preliminary outline and design of the experiment has been created. A potential configuration for multiple test chambers is offered but not fixed. It is intended for use as a guide or template for students to develop further into a proposal for a space-based educational research program. The preliminary design of the test rig is shown in Figure 2. This experiment is designed within 356 mm diameter and 237.5 mm in height, a standard REXUS sounding rocket module. Expected mass (excluding rocket skin and baseplate) is less than 4.5 kg.



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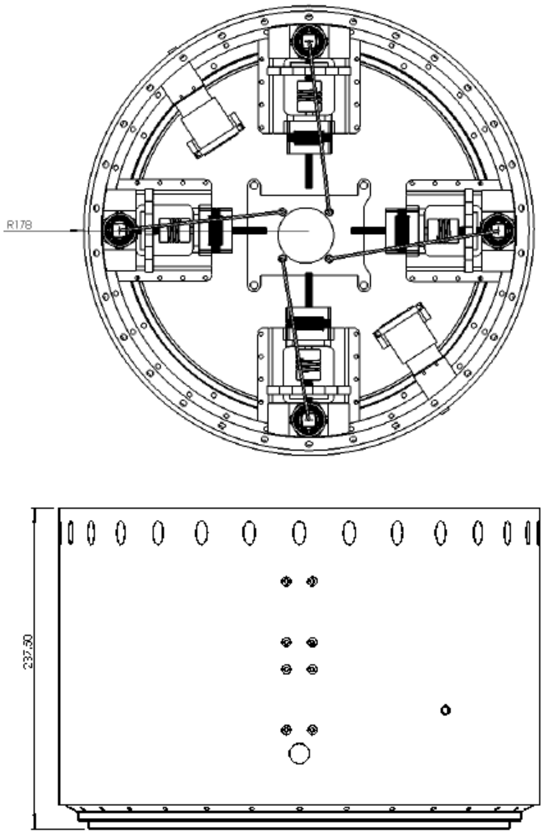

Figure 2. Conceptual design of sounding rocket experiment (mm).

This paper also details the basis of the technical objectives required for the student experiment. The general theme of the research is presented but the intention is that the student team will develop this project in more detail.

5. Conclusions

This publication forms the first collaborative effort towards achieving the academic objectives. It is designed as an impetus for students to develop this programme. There are a number of funded student positions available. Expressions of interest can be emailed to either of the authors before November 1st 2022. This effort was conceived as a means to combine expertise and resources from multiple third-level institutes with limited space flight heritage, to bolster their space research capabilities and to promote European collaborations.

Acknowledgements

The authors would like to thank Institute of Technology Carlow and Malta College of Arts, Science & Technology for their support with this research. We would also like to thank LTU for providing their guidance and expertise.

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Supporting an ISS experiment as PhD students: a case study of the PARTICLE VIBRATION project

Georgie Crewdson[1]*, Alessio Boaro[1], Monica Kerr[1], Marcello Lappa[1]

Abstract

This paper provides an insight into the involvement of two PhD students in the PARTICLE VIBRATION project, a multiphase fluid experiment, also known as, “Thermovibrationally-driven Particle self-Assembly and Ordering mechanisms in Low grAvity” (T-PAOLA) to be launched on the International Space Station by the end of 2022. The project aims to identify self-organization phenomena in dispersed phase flows when vibrations are applied to the system. It will therefore underpin the development of new contactless particle manipulations and materials processing strategies. In this short paper, the work of two PhD candidates, working within the T-PAOLA project framework, is discussed. In doing so, the various research activities undertaken are highlighted, both experimental and numerical, as is the peripheral or supporting research being undertaken by both students in order to expand the scope of the project and identify new lines of enquiry regarding convection-based control mechanisms.

Keywords

Microgravity, Thermovibrational convection, Particle aggregation, ISS experiment, T-PAOLA project

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Acronyms/Abbreviations

ESA	*European Space Agency*
E-USOC	*Spanish User Support and Operations Centre*
MSG	*Microgravity Science Glovebox*
ISS	*International Space Station*
SODI	*Selectable Optical Diagnostic Instrument*
T-PAOLA	*Thermovibrationally-driven Particle self-Assembly and Ordering mechanisms in Low grAvity*
TVC	*Thermovibrational Convection*

1. Introduction

Working on a space experiment to be launched on the International Space Station (ISS) is the dream of many mechanical and aerospace engineering students. These opportunities are however difficult to come-by as the level of expertise required to undertake such projects is significant, and often beyond the skills of postgraduate students. Although significant efforts have been made by organizations such as ESA Academy to make altered gravity and space platforms more accessible to students, contributing effectively to projects of such a kind and scale remains a challenge. The T-PAOLA project (Thermovibrationally-driven Particle self-Assembly and Ordering mechanisms in Low grAvity, the corresponding NASA/ESA opsnom being "Particle Vibration"), however, has enabled two PhD students from the University of Strathclyde to immerse themselves in a concrete space experiment, leading to significant benefits for both the students and the project itself. In the following, first the scientific context of the experiment [1]–[4], the structure of the research team and the other stakeholders (space agencies and payload developer) are introduced. Then, the specific activities undertaken by the students to directly support the project are described, followed by a more general presentation of their respective research interests and results. These align with the general goals of any microgravity-related project, namely, a meaningful extension of current state of knowledge through the execution of a well-defined series of space experiment and the definition of other experiments to be executed in the future to fill the remaining gaps (see e.g. refs [5], [6]).

2. Scientific objective and team

2.1. Scientific objective

The T-PAOLA project consists of performing multiphase fluid dynamic experiments onboard the ISS. These experiments will investigate how a set of particles dispersed in a Newtonian liquid can accumulate and form well-ordered structures. Indeed, on earth, the behaviour of particle-fluid mixtures is constrained due to gravity leading to flotation or sedimentation of the particles. Once gravity is removed, the dispersed particles are not forced to separate and exploring self-assembly principles becomes possible. By studying these surprising phenomena under microgravity conditions, T-PAOLA aims to pave the way to innovative applications in chemistry, physics, biomaterials, inorganic material science and eventually nanotechnologies.
The flow that facilitates this particle aggregation is known as thermovibrational convection (TVC). This type of convection is a variant of standard buoyancy convection where steady gravitational acceleration is replaced with vibrations (see Figure 1). When subjected to TVC, the patterning behaviour of the fluid becomes dependent on not only the magnitude of the imposed temperature gradient but also on the frequency and amplitude of the considered vibrations and the direction of these with respect to the temperature gradient

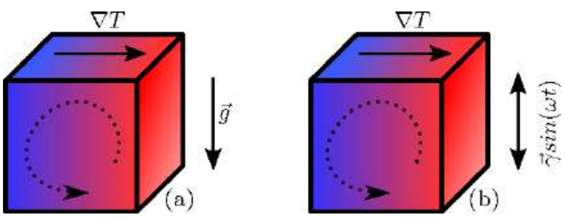

Figure 1: Mathematical model for (a) thermogravitational convection and (b) thermovibrational convection.

When particles are added to the mix, in microgravity conditions (where the only driving force present is due to vibrations), many different patterning behaviours are possible when the space of parameters of TVC is explored (frequency and amplitude of the vibrations). The properties of the particles also contribute to the structure formations, where both the size, density and concentration of particles affect the final structures. An example of possible patterning configurations is depicted in Figure 2 (adapted from Ref [7]).

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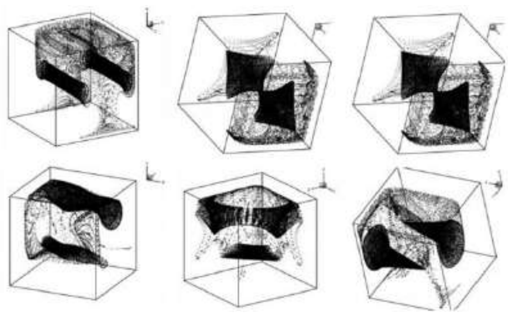

Figure 2: Example of particle aggregate structures varying in shape due to varying different thermo-vibrational conditions.

To keep the ISS experiment as simple as possible and owing to the fact that the project utilises the existing ISS hardware Selectable Optical Diagnostics Instrument (SODI) in combination with the Microgravity Science Glovebox (MSG), only the vibrational frequency, amplitude and temperature difference across the cavity are varied and the direction of vibrations is set in a perpendicular manner to the temperature gradient (as shown in Figure 1).

However, keeping with the aim of expanding the project scope, the involved PhD students (first and second author of the present paper, hereafter simply referred to as GC and AB, respectively) have also considered situations in which the temperature gradient has a different orientation and/or the liquid also possesses elastic properties (non-Newtonian fluids).

2.2. Team composition

A notable aspect of the project is the composition of the team responsible for the successful completion and continuation of the Particle Vibration project. The team is composed of two sub-teams. The science team (based at the University of Strathclyde) includes the principal investigator (fourth author, ML), a research associate (third author, MK) and the two aforementioned PhD students. The team is responsible for providing the exact scientific requirements for the series of experiments to be conducted on board the ISS and for expanding the project scope by pushing its boundaries further. The technical team includes the relevant personnel of the company in charge of manufacturing the experiment hardware (QinetiQ), the ESA project coordinator, the ESA Payload Integration Manager and the User Support and Operations Centre (E-USOC) in charge of commanding remotely the payload and developing the related procedures. In Figure 3 we schematise the composition of both teams.

Figure 3: **Composition of the Science and the Industry team.**

3. Discussion

3.1. Project activities and team integration

In this section the various activities undertaken by GC and AB, and directly related to the T-PAOLA space experiment, are discussed.

3.1.1. Experimental activities (GC)

We begin this section with discussing the plethora of experimental activities undertaken GC. For brevity we focus on the two most relevant tasks. Firstly, GC attended a weeklong activity where QinetiQ had been contracted to carry out the “cell filling procedure”, where the quartz cells to be used on the ISS are filled with both the fluid and the particles. During the filling procedure, many foreseen (and unforeseen) obstacles where tackled. These obstacles provided an insight into the difficulty of monitoring and performing the high-precision tasks required for the success of the experiment. The second critical experimental procedure to be carried out was the degassing of the fluid in preparation for the experiment (shown in Figure 4), which was supervised by MK. The related rationale/challenges can be described as follows.

Under atmospheric pressure a small amount of “air” is trapped in the fluid. When the fluid is placed under vacuum, this air is forced out of the fluid creating unwanted air bubbles in the fluid cell. Of course, this can make any particle formations impossible, therefore the fluid must be purged of all residual air before it is inserted in the cell with the particles. This activity involves the use of both compressed gases and liquid nitrogen that required GC taking short

DOI: 10.5821/conference-9788419184405.017

courses, hence developing her skill set, as well as contributing to developing bespoke experimental protocols.

Figure 4: Nitrogen gas is bubbled through the ethanol to displace any remaining oxygen.

3.1.2. Data downlink and post processing (AB)

In addition to the fundamental experimental activities, another crucial part of the project has been the treatment of the experimental data (signals and images) produced initially during ground testing. A proper description of these aspects requires the introduction of some details about the control parameters of the experiment (as developed in the following).

As stated in the introduction, TVC arises inside a differentially heated cavity when vibrations are applied. After selecting the properties of the fluid and the particles, four other control parameters remain, namely, the temperature at the top and bottom of the cell, the frequency of the vibrations and their amplitude. In addition, the applied temperature has to be varied sinusoidally in certain stages of the experiment in order to re-disperse the particles (after particle structures are formed for a given combination of the parameters, initial conditions with a uniform distribution of particles must be established for the execution of the next experiment dealing with a different combination of them).

In Autumn 2021 ground tests were carried out by the aforementioned E-USOC with two-fold purpose to 1) assess the consistency of the payload software (experiment “scripts”) with the specifications provided by the scientific team and 2) verify the ability of the hardware to support adequately the ranges of temperature and vibrational frequencies specified through such a set of requirements.

Here, the support of AB was fundamental. He developed a robust algorithm capable of automatically checking the results of the tests against the requirements in terms of duration of every step and amplitude and frequency of both vibrations and temperature. Moreover, the algorithm was also able to classify the pictures recorded during each run and split them into different subgroups according to the specific step of the experiment in which they had been generated. As an example, Figure 5 shows part the algorithm output for a generic run.

This procedure revealed an inconsistency between the image numbering and the recorded signals, which was timely communicated to the E-USOC and fixed accordingly. Moreover, the processed data proved that the hardware could maintain the required thermal modulations.

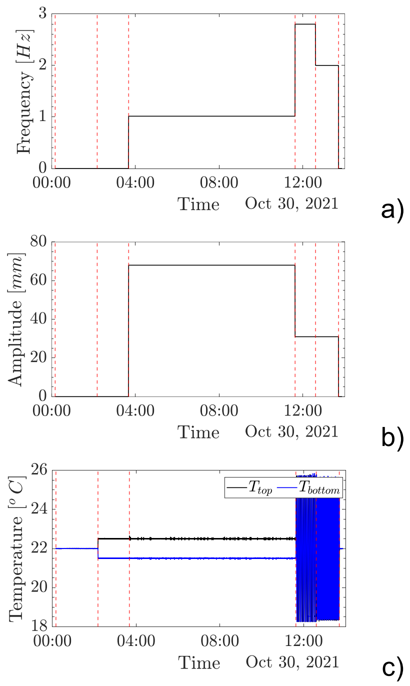

Figure 5: Output of the algorithm. The vertical dashed lines indicate the start of a new step. a) Frequency and b) Amplitude of the vibrations, and c) temperature of the primary cell.

3.2. Expansion of project scope through peripheral research

We now turn to the specific topics of the students PhD theses and show how their activities are contributing to the legacy of the Particle Vibration project not only from a technical point of view, but also in terms of scientific outcomes.

DOI: 10.5821/conference-9788419184405.017

3.2.1. Novel particle control mechanisms (GC)

T-PAOLA focuses on the case where vibrations are perpendicular to the temperature gradient. As part of her PhD GC has also investigated the case where the vibrations are parallel to the temperature gradient. In this case high frequency vibrations tend to “kill” convection therefore limiting the range of parameters that can be explored (as high frequency regimes are therefore excluded from the study). Preliminary research has revealed that highly ordered, time dependent particle structures can yet be achieved under TVC if vibrations with moderate frequency are considered, as shown in Figure 6. In addition to the direction of vibrations, the details of the thermal boundary conditions can also be altered to change the behaviour of the TVC and the ensuing particle accumulation structures.

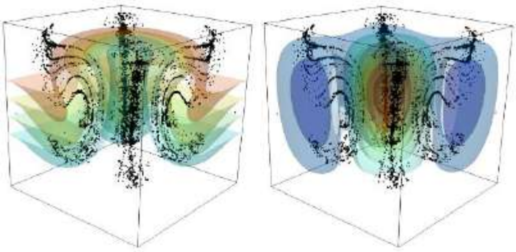

Figure 6: Temperature and velocity fields (left and right respectively), for a 3D cavity seeded with particles where the vibrations are parallel to the temperature gradient.

Figure 7 shows that when the temperature at the top and bottom walls is set in a non-uniform manner and the vibrations are set in the horizontal plane, a plethora of particle structures become possible.

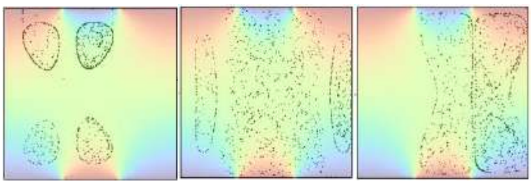

Figure 7: Possbile (2D) particle accumulation structures when a non-uniform heating configuration is considered and vibrations are set in the horizontal plane.The flowfield is colored by temperature.

The variations of structure types seen in Figure 7 are associated with the parameters considered in the study and correspond to a change in the amplitude of the vibrations as well as the size of the particles.

3.2.2. A new line of inquiry: TVC in viscoelastic fluids (AB)

The properties of TVC can also be heavily modified by changing the considered fluid itself. In this regard, AB investigated how TVC manifest itself in a particular class of fluids, i.e., viscoelastic liquids, thereby opening a new path of research. These fluids can exhibit complex states for relatively low values of the imposed temperature difference in comparison to their Newtonian counterparts. Figure 8 shows how these two classes of fluids can exhibit different behaviours even if a problem as simple as a two-dimensional square cavity is considered.

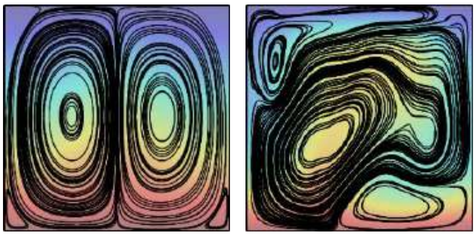

Figure 8: 2D TVC with vibrations parallel to the temperature gradient with Newtonian (left) and viscoelastic (right) fluid. Streamlines and flowfield colored by temperature.

In addition to this classical problem, an infinite layer with vertical vibrations has also been tackled. It has been shown that, like the companion 2D case, the viscoelasticity of the fluid allows the formation of flow patterns that cannot arise in Newtonian fluids in microgravity conditions. As an example, Figure 9 depicts two possible convective states showing well-ordered structures formed under the effect of sinusoidal (as in the T-PAOLA experiment) or square wave vibrations in a viscoelastic liquid.

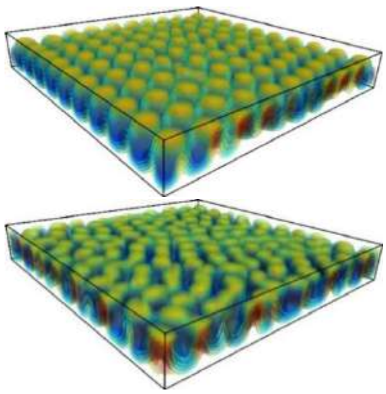

Figure 9: 3D viscoelastic TVC with sinusoidal (top) and square wave (bottom) vibrations. Isosurfaces of the temperature colored by the vertical component of the velocity.

DOI: 10.5821/conference-9788419184405.017

The fascinating patterns just presented, along with the complex dynamic of viscoelastic fluids, make this category of liquid the perfect candidate for future experimental investigations with dispersed solid particles in microgravity conditions. An extensive discussion of the work presented in this section can be found in [6], [8], [9].

3.2.3. Undergraduate student engagement

The T-PAOLA project has also engaged two Bachelor students. Indeed, the results shown in Figure 7 correspond to the work of a bachelor's project student supervised by GC, while the results in Figure 8 relate to another undergraduate project supervised by AB.

4. Conclusions

In conclusion, AB and GC have supported the T-PAOLA project over the last three years. In doing so, the authors have had the opportunity to partake in a real-world space experiment solving a range of problems of both theoretical and practical nature (developing bespoke data treatment algorithms and undertaking complex experimental and numerical simulation work). This has resulted in a mutual exchange of benefits, namely, the successful completion of a number of tasks relevant to the project on the one hand, and the development of a rich variety of PhD student skills and research "attributes", on the other hand. The realization of this "exchange" has involved a fruitful triadic relationship between the PhD students, the supervisor and the many external entities involved in all these processes.

Notably, the numerical work conducted in the frame of the project has also allowed the development of relevant undergraduate students' attributes, namely, the ability to understand the principles of microgravity experimentation and conduct (under the supervision of GC and AB) relevant numerical simulations using available commercial or open-source CFD software. For all these reasons, we recommend involving PhD students in this type of project whenever possible.

Acknowledgements

The authors would like to thank Dr Thomas Burel, (who preceded MK in the role of research associate in the science team), for his fundamental contributions to the project in terms of experimental and numerical work and for his continuous support of the PhD students.

This work has been supported by the UK Space Agency (STFC Grant Nos. ST/S006354/1, ST/V005588/1, ST/W002256/1 and ST/W007185/1) in the framework of the PARTICLE VIBRATION (T-PAOLA) project.

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The Sat-Comms Game: teaching a complex subject for interdisciplinary audiences

Dr. Paul ILIFFE[1]

Abstract

This paper addresses general space education for interdisciplinary audiences. In particular, this paper considers education in the field of Satellite Telecommunications (Sat-Comms).

The challenge in presenting the field of sat-comms for effective learning is two-fold. Firstly, this field is interdisciplinary, the disciplines are coupled, and it is complex. Secondly, the typical audiences for this subject often have diverse backgrounds. Hence, a suitable teaching strategy is required, so that all students can learn from a training session.

Publicly available sat-comms training is largely engineering focused. This study could not find suitable training for the purpose of interdisciplinary sat-comms education.

Hence, to address this absence in available training, the author has created a workshop, which provides sat-comms education to interdisciplinary audiences. The workshop was empirically developed from the author's experience at Inmarsat and at the International Space University. The workshop uses elements from Constructivist, Behaviourism, Cognitive, Connectivism, and Experiential learning theories. Furthermore, it was designed to be taught in person and online.

The Sat-Comms Game was first trialled in an online format in 2021. The workshop worked well in engaging the participants during the session. Additionally, feedback on the workshop was positive. Hence, this trial indicated that the workshop could function logistically and engage people pedagogically.

The author intends to conduct further trials and corresponding assessment methods to gauge the pedagogic effectiveness.

Keywords

Interdisciplinary Space Education, Satellite Telecommunications, Student focused teaching

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1. Introduction

The Satellite Telecommunications (sat-comms) sector forms approximately one third of the global space economy. According to Figure 1 the combined value of sat-comms in 2019, including television, Fixed Satellite Services (FSS), satellite radio, broadband, and mobile services is US$120.7 billion. The significant proportion of the global space economy, which sat-comms hold, deserves attention, particularly in how people learn about and, ultimately, understand it.

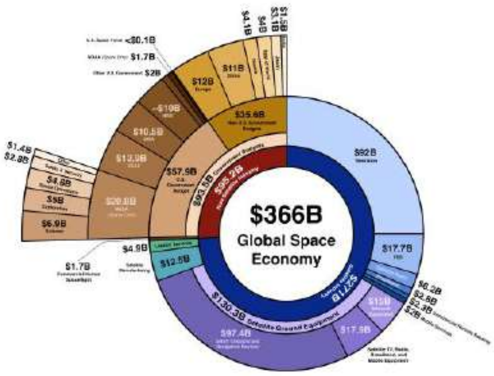

Figure 1. 2019 global space economy [1]

There are three typical audiences for sat-comms education: 1) employees in a sat-comms organisation, 2) adults in higher education or further professional development, and 3) outreach activities to school children. This study focuses on the first two groups.

The challenge in presenting the field of sat-comms for effective learning is two-fold. Firstly, this field is interdisciplinary, the disciplines are coupled, and it is complex. Secondly, the typical audiences for this subject often have diverse backgrounds. Hence, a suitable teaching strategy is required, so that all students can learn from a training session

This paper presents work on such a teaching strategy, namely The Sat-Comms Game. This approach is empirically based, is appropriate for interdisciplinary audiences, and can be taught both online and in person.

In section 2 some earlier approaches to sat-comms training are introduced. The Sat-Comms Game is described in detail in section 3.

2. Existing sat-comms training

Publicly available sat-comms training is largely engineering focused. Excellent examples are courses offered in the United Kingdom by the Institute of Engineering and Technology [2], Systems and Network Ltd. [3], and The Knowledge Academy [4]. These are strong models for technical training. However, this study could not find suitable training for the purpose of interdisciplinary sat-comms education.

Interdisciplinary education in sat-comms is often provided in-house by sat-comms organisations for its employees. In the author's experience as a past employee of a sat-comms organisation, such training suffers from several problems, most notably that too many details are given in too short a time.

3. The Sat-Comms Game

In this section the structure of The Sat-Comms Game is described, the background to the game is given, the key challenges are listed, and corresponding learning theories are mentioned.

3.1. How it works

The Sat-Comms Game is an introduction to the sat-comms sector, which is given in the format of a 2 hour workshop. The workshop lead gives a short presentation about the sector and thereby introduces the key topics: the market, the method, the money, and the rules. This presentation is intentionally brief. The role of the workshop lead is as an architect of the educative experience, not a conventional teacher.

After the presentation the participants are divided into small groups, preferably with less than five people per group. Each group is then tasked with creating a sat-comms organisation over three rounds of guided play.

At the beginning of each round the workshop facilitator distributes instructions for the corresponding round. In the first round the participants must consider their organisation's concept, in the second the system, and in the third the business. In each set of instructions, there are questions, which prompt the participants to think about the relevant topics.

Following each round the groups present their ideas. The workshop lead provides commentary on each idea and steers the group towards a better solution, if required. Imperfect ideas are welcomed and desired.

3.2. Empirical development

Inspiration for this workshop stems from the author's experience in tertiary and professional level education. Unfortunately, this experience has indicated that education at these levels often neglects effective teaching and learning methods. The reasons for this are varied, but include poorly structured learning content, insufficient deconstruction of concepts, and lack of engagement between the students and teachers.

In an attempt to provide more effective education in sat-comms, the author has combined his academic, professional and personal experiences. Inspiration was taken from the author's work at Inmarsat to support the workshop for new employees, to provide outreach work to primary school children, and to produce training material for the spacecraft operations team.

Inspiration has also been taken from the author's experience in Ballroom Dancing and in Athletic Conditioning programmes. Both of these disciplines make effective use of deconstructed information and experiential learning.

Furthermore, the author refined the approach in interdisciplinary lectures to MSc students at the International Space University (ISU), from training in facilitation skills by Integrated Works (a leadership and development consultancy), and from applying these facilitation skills at the ISU's Space Studies Programme (SSP) 2021.

3.3. Key challenges

There are three challenges in the delivery of the Sat-Comms Game: engagement, simplicity of information, and learning through play.

Engagement

In the author's experience of tertiary and professional education, engagement by the students is often lacking. Students are frequently subjected to excessively detailed and lengthy presentations and are, therefore, mostly passive during such sessions. This is not conducive to engagement.

In the Sat-Comms Game a set of approaches are taken to encourage and necessitate engagement. Before the session starts four images are presented together with a question. The question asks the students to select an image, which best reflects their state of being. For example, during the SSP'21 event the question was "Which image best represents how you feel about SSP'21 so far?". In this case the images included a martial artist, Kung-Fu Panda, a distressed looking infant, and an excited Lego figure. The purpose of this approach is to encourage communication between the students and workshop lead and thereby remove any psychological barriers to communication.

Simplicity and deconstruction of information

The sat-comms sector is complex. From the perspective of a layman, this complexity can be confusing and is not conducive to quick understanding. The appropriate simplification and deconstruction of information lend themselves to more effective learning.

The deconstruction of information in learning is exemplified by Josh Waitzkin in his book The Art of Learning. Waitzkin describes how he studied the endgame in chess. In such endgames, there may be only three pieces on the board: both kings and a pawn. The simplicity of this configuration is conducive to the study of certain chess principles, such as empty space and zugzwang (4).

In a similar manner to the chess example above, in the Sat-Comms Game a number of simplifications are made. Only a few details are given about ground and space-based hardware, the physics of signal propagation, orbital mechanics, spacecraft and launcher costs, and the global sat-comms market.

Learning through play (a.k.a. accepting wrong answers)

After years of social conditioning, adults are often reluctant to play. Learning through play for adults, therefore, can be challenging. To overcome the resistance of adults to play, The Sat-Comms Game is structured such that any solution is considered. It is imperative for the workshop lead to accept ideas, which would probably not survive contact with reality, and to subtly suggest amendments to the idea. The workshop participants must use their imaginations and not be given solutions.

3.4. Application of learning theories

Although The Sat-Comms Game was empirically developed, it has come to embody a set of learning theories. These theories and their application in the workshop are described below.

- Constructivist

According to the Constructive learning theory, people learn based on experience and learning is a process of active engagement [5]. In The Sat-Comms Game the participants are required to create their own sat-comms organisation. Participation is integral to the activity.

- Behaviourism

This theory states that positive and constructive feedback is essential for effective learning. This feedback reinforces the efforts made by the learner and, hence, encourages the continuation of these efforts [6]. In The Sat-Comms Game the workshop lead provides positive feedback to the participants to reward them for the thinking process, not so much for the proposed ideas.

- Cognitive

According to Cognitive learning theory, the way in which a person learns (the cognitive process) is key. Humans construct bundles of knowledge in the mind and learn through active discovery [7]. In The Sat-Comms Game, the participants are required to quasi-independently search for solutions, to try and to fail, and, to think openly. Their thought process is emphasised above the results.

- Connectivism

According to the Connectivism learning theory, people learn and grow, when they form connections between different fields and ideas, when there is diversity of opinion, and when decisions must be made [8]. The basis of The Sat-Comms Game is to guide the participants to understand the connections between the various elements of the sat-comms sector. Participants must assess these connections, make decisions, and present their ideas amongst and array of others.

- Experiential

Like Constructivist learning theory, Experiential learning theory also emphasises the importance of learning by doing, that is learning through experience. In this case, the learning process is cyclical and passes through four phases: concrete experience, reflective observation, abstract conceptualisation and active experimentation [9]. The Sat-Comms Game utilises a cyclic approach of similar structure. Participants must learn the key concepts, conceptualise sets of ideas, experiment by combining the ideas, and reflect upon their ideas following feedback.

3.5. First trials

The Sat-Comms Game was first trialled at the ISU's Space Studies Programme (SSP) July 2021. In this case, two workshops were run in an online format, whereby participants joined via Zoom. Both sessions were two hours in duration. A Teaching Associate from ISU supported the workshop by conducting the Zoom administration and by distributing the files with instructions. This support proved to be essential.

Feedback from the participants was very positive. In a post-workshop survey on a three point scale (poor – good – excellent), 100% of respondents from the first workshop and 88.9% from the second workshop rated the sessions as excellent. One respondent included the following note:

> *"One of the best courses during SSP21. The lecturer motivated us to use our critical thinking through very useful activities."*

This trial indicated that the workshop could function logistically and engage people pedagogically.

3.6. Future objectives

The author intends to conduct further trials of The Sat-Comms Game, in particular with employees of a sat-comms organisation. To assess the effectiveness of the workshop, it is proposed that the participants complete pre- and post-workshop questionnaires. Furthermore, the effectiveness could be assessed by also conducting questionnaires with non-participants.

4. Conclusion

In summary, this paper presents The Sat-Comms Game, which is a new approach to teaching people about sat-comms. This approach is empirically based, is appropriate for interdisciplinary audiences, and can be taught both online and in person. The first trial of the workshop indicated that it is effective in presenting the topic of sat-comms. The author intends to conduct further trials and corresponding assessment methods to gauge the pedagogic effectiveness.

If you would like to run The Sat-Comms Game at your organisation or to improve your organisation's training, please feel free to get in touch with the author via the provided email address.

Acknowledgements

The author would like to thank the following people for their help, guidance and inspiration in the formation of The Sat-Comms Game:

Inmarsat: Julie Hyam, Joanna Whatley,

Integrated Works: Jennifer Simpson, Emily Braucher, Anna King, Anna Crittenden, Christy Maurer

ISU: Nipuni Silva, Alex Ryan

Niall Dooley (EUMETSAT), Alessia Mauta (RHEA), David Rodriguez (EPFL)

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DOI: 10.5821/conference-9788419184405.018

DEAR project: Lunar Dust Surface interactions, Risk and Removal investigations

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Abstract

The DEAR project (Dusty Environment Application Research) investigates the interaction between lunar regolith and surfaces and components relevant for lunar exploration. Based on the TUBS regolith simulant which is representative in chemistry, size and shape properties to Moon soils to study the regolith transport, adhesion and strategies for cleaning. The regolith simulant will be applied to thermal, structural, optical sensor, sealing and other astronautic systems, providing input for requirements, justification and verification.

The key applications are split in human space flight regolith investigations, wrinkled surface with random movement and hardware surfaces, flat material defined movement. The paper provides an overview of the DEAR project including a discussion of the first results, in particular vibration, shock and micro-vibration on regolith bearing surfaces. The investigation shall enable better understand the regolith layers interaction and the release mechanism, as well as potential cross contamination and cleaning strategies. The research is complemented by simulation of the regolith motion as parameter surface plasma interactions. The project is funded and supported by the European Space Agency (ESA). DEAR specifically addresses the development and testing of lunar dust removal strategies on optics, mechanisms and human space flight hardware (e.g., space suits). As the Moons regolith is known to be highly abrasive, electrically chargeable, and potentially chemically reactive, lunar dust might reduce the performance of hardware, such as cameras, thermal control surfaces and solar cells. The dust can cause malfunction on seals for on/off mechanisms or space suits. Of particular interest are risk assessment, avoidance, and cleaning techniques such as the use of electric fields to remove lunar dust from surfaces. Representative dust (e.g., regolith analogues of interesting landing sites) will be used in a dedicated test setup to evaluate risks and effects of lunar dust. We describe designs and methods developed by the DEAR consortium to deal with the regolith-related issues, in particular an electrode design to deflect regolith particles, cleaning of astronautical systems with CO2, design of a robotic arm for the testing within the DEAR chamber, regolith removal via shock, and regolith interaction with cleanroom textiles.

Keywords

Astronaut space suit, Electrode design, Regolith (lunar dust), Robot arm, Specific cleaning (CO2)

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1. Introduction

Interest in lunar exploration has regained thrust in recent years around the world. ESA, private industries, and the academic sector strive to explore the Earth's satellite with ambitious new technologies. The hostile environment of the Moon, however, is generally perceived as a serious challenge, in particular the lunar dust. To minimise its impact on optical surfaces and mechanisms, seals, and in order to reduce operational risks during future lunar missions, the European Space Agency has contracted the DEAR (dusty environment application research) consortium to deal with regolith-related issues, catalysing European moon surface exploration missions in the near future.

1.1. Risks posed by Lunar Dust

Being highly abrasive, electrically chargeable, and potentially chemically reactive, lunar dust poses a high risk on the performance of hardware, such as cameras, thermal control, and solar cells. The dust can cause malfunctions on seals and influence the optical, mechanical and electrical as well as thermal properties of surfaces including space suits. For instance, during the sample processing on the lunar surface or in airlocks, reliable seals are mandatory. Furthermore, lunar dust is likely to be toxic and therefore needs to be avoided inside the lunar habitats, motivating the work on validated cleaning methods. Test setups shall be used to measure potential performance degradations within controlled dusty loads. A programmable robotic arm is used for repeated lifetime testing and for the mimic of the movement of an astronaut arm.

1.2. Cleaning methods

Cleaning is possible due to the avoidance of regolith dust built up or with active cleaning processes to remove the dust. Protection possibilities and cleaning efficiencies shall be experimentally extracted. In particular electrode structures creating electric AC fields for dust removal are in first order studied by simulation and test. Another cleaning method by applied vibration and shock is studied as well. The cleaning of astronautic systems is tested with CO_2 cleaning.

2. Discussion

2.1. Optical-Electrode simulation and Electrode breadboard

This work includes a simulation of how to remove dust particles covering optical windows e.g. photographic cameras, image sensors etc., utilising an electrostatic (electrophoretic) force on particles with inhomogeneous electric fields. The implementation of inhomogeneous electric fields is done via structured thin film electrodes, either metal films or transparent indium tin oxide (ITO) on a glass substrate. For simulation of the behaviour regarding the electrode, the following simulation codes are used:

- The Particle-in-Cell Monte-Carlo (PIC-MC) simulation code developed at IST Fraunhofer, using the distributed, parallel Poisson solver, which is based on the Gauss-Seidel algorithm with successive over relaxation (SOR).
- A simulation tool named “PALADIN”, for modelling the transport of macro-particles of variable sizes that considers particles of sizes ranging from nanometers up to millimeters, and may include various physical forces such as gravitation, gas friction, thermophoresis, charging and decharging, as well as electromagnetic field forces.

The combination of these tools allows the computation of the trajectories of a diluted ensemble of non-interacting nanoparticles on electrode structures. For a higher density of particles – as is the case of many dust layers covering a window, different simulation methods such as the Discrete Element Method (DEM) would be needed.

2.1.1. Simulation of electrode structure

Our simulation test geometry consists of a ceramic substrate material sized 10x10 mm^2 and a thickness of 1 mm (Fig.1). On the top side, the electrode structure is integrated into the substrate. It consists of metal lines with a thickness of 100 µm and a lateral width of 200 µm.

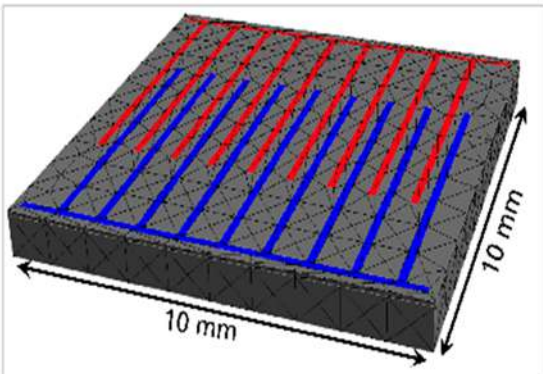

Figure 1. Geometric test structure used in simulation for various electrode designs

Two metal wire systems are connected to the positive and negative output of a voltage source.

DOI: 10.5821/conference-9788419184405.019

Table 1. Basic parameters used for the electric field computation of the test structures

Parameter	Value	
	Low resolution	High resolution
Wafer thickness	1.0 mm	
Simulation box size	10 * 10 * 11 mm^3	
Segmentation	4 * 4 * 2 = 32 segments up to 32 CPUs	
Cell spacing	0.1 mm	0.05 mm
Number of cells	1.1 * 10^6	8.8 * 10^6
Electrode voltage	± 1000 V	
Substrate material	Ceramic material $\varepsilon_r = 6.0$	
Solver	Poisson equation; Distributed Gauss-Seidel with SOR	

The simulation volume for solving the electrostatic potential via the Poisson equation comprises the substrate plus a 10x10x10 mm^3 cube on top of the substrate, which is facing the side with the electrode structure.

The computed electric field, the resulting particle trajectories and the dielectrophoretic forces are shown in Fig. 2. For the PALADIN simulation, particles with a relative dielectric permittivity of $\varepsilon_r = 3.0$, mass density of $\rho = 3.5$ g/cm³, and homogeneous size distribution between 10 - 500 µm are used.
Their starting positions are randomly distributed on the substrate surface with the electrode structure.
An important result is that on surface areas, where alternating poles are entangled, high electrophoretic forces up to several 100 g occur, allowing for particles to drift away from the electrodes. In contrast, in regions with only one polarity of the electrode structure, the dielectrophoretic forces are small, and particles have the tendency to remain sticking there.

2.2. Astronautic systems. Cleaning with CO_2

This activity is mainly focused on space suit materials but also equipment to be used by the astronauts. Following the “AMADEE-20” Mars analog field campaign in the Israeli Negev desert, a carefully selected crew of analog astronauts were deployed for one month.

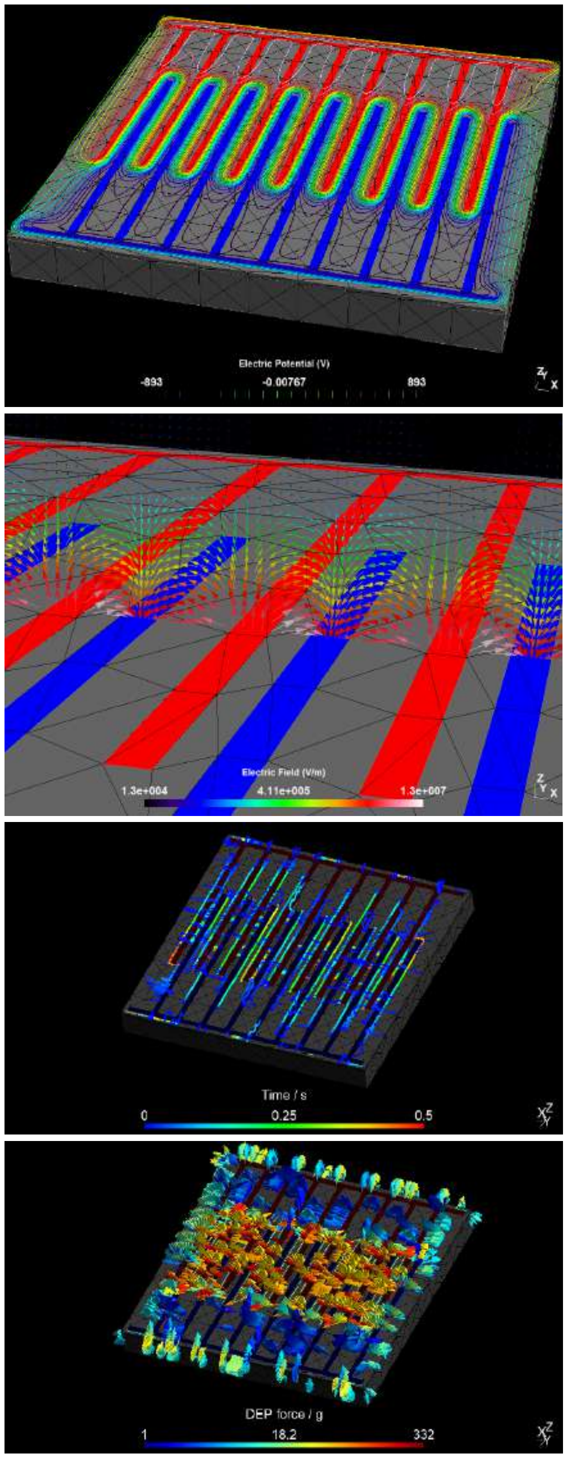

Figure 2. (1) Electric potential in a cut-plane located 100 µm above the substrate with the electrode structure;
(2) Central cut plane of the electric field showing the inhomogeneous regions in between alternating poles;
(3) Particle trajectories computed by PALADIN;
(4) Computed dielectrophoretic force in units of the gravitational field

Their work included performing simulated extra-vehicular activity (EVA) – with tasks pertinent also to lunar exploration, such as geosampling activities, maintaining critical hardware infrastructure of surface translation. In total, 61,35 EVA hours were conducted.

The spacesuits were representative of what is to be expected for future lunar missions, with a mass of 50 kg, 3 hour so donning time and a complex technical infrastructure for satisfying the needs of a human body, technical and biomedical monitoring and human metabolite management [2] and performing the EVA's in a manner pertinent to what is expected during a planetary surface operation [3].

Figure 3. Field work with spacesuit simulators during the AMADEE-20 expedition in Israel. (Photo courtesy of Florian Voggeneder (OeWF))

The surface textiles of the spacesuit simulators accumulated "regolith simulant" in a realistic fashion and were then transferred to a CO_2-cleaning facility to investigate the effectiveness of the cleaning workflow.

2.2.1. DEAR Test Textile Selection

The outermost layer to be focused upon will be in direct contact with regolith and the physical environment of the Moon. Based upon the parallel ESA project PExTex where dozens of candidate textiles were investigates, a shortlist of potential candidates was selected based upon the following criteria presented in Table 2:

The resistance to dust abrasion, electromagnetic compatibility (EMC) and discharge protection and dust mitigation were priorities for the choice. The selection is Inventex F1120Al, having following properties: (Kevlar ® orthofabric)

- Tensile strength 5 times higher than steel
- Permanently non-inflammable
- The fiber starts to degrade at 420 °C, for short duration can withstand higher temperatures
- Panox ® preoxygenated polyacrylnitril fiber with >60% carbon content very high LOI (limited oxygen index) of 45 starts to segregate graphite above 700°C and as such has a very high thermal resistance
- low mechanical strength → Kevlar has been combined

Table 2. Selection criteria

Withstand Lunar Temperature	Withstand and/or reduce Lunar radiation
Compatible with lunar vacuum	Must sustain pressure-vacuum cycling (?)
EMC and discharge protection	Resistance to wear by abrasive regolith
Bendability (?)	Fatigue integrity over the expected suit life
Shall not off-gas toxic substances	Shall be non-flammable
Dust mitigation	Impermeability to water and fluids

Several CO2 Cleaning Methods to remove lunar dust from the space suits are being tested, including blast cleaning with super-critical CO2 jets.

2.2.2.Benefits of Cleaning with CO_2

The CO_2 Snow-Jet Cleaning method requires 80% less space than conventional power-wash systems which are water-based. The time which is needed for one cleaning cycle is as well 80% shorter and the costs are reduced by up to 40%. This cleaning method is not adding any excess CO2 impact on the environment because the used CO2 has been re-captured from existing industrial emissions.

2.3. Robotic Arm

The objective is to develop a robotic arm testbed for the DEAR chamber. The testbed will be able to articulate in an easily programmable and repeatable manner with/without the application of lunar regolith, based upon a PincherX 150 robotic arm from Interbotix. The PincherX 150 Robot Arm features, 5 degrees of freedom using DYNAMIXEL XL430-W250-T smart servos motors, with a resolution of 4096 positions per rotation and user definable PID parameters. It allows the following parameters to be logged

- Cartesian Coordinate at end effecter (m)
- Angular Displacement of the joints (rad)
- Angular Velocity of the joints (rad/s)
- Effort produced by joints (Nm)
- Temperature of joints (°C)
- Present load of the joints (% of maximum torque)
- Input Voltage of each joint (V)

DOI: 10.5821/conference-9788419184405.019

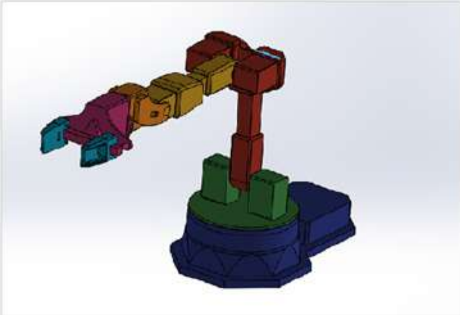

Figure 4. CAD drawing of PincherX-150 robot arm from Interbotix

The PincherX 150 is controlled by a Robotis DYNAMIXEL U2D2 which interfaces with a range of commonly available robotics software such as ROS, Gazebo, Coppella Sim and Move it.

It is of interest to measure the maximum payload the arms can reliably perform typical manoeuvers with. The Pincher- X150 is rated for a 50g payload at its end effector but can carry larger masses when the weight is distributed over the full length of the arm, as it the case when covered in textile. A series of tests were performed by wrapping the arm in a textile of known mass and measuring the maximum effort in the joints, during an “arm curl” movement repeated 50 time.

2.4. Regolith removal from surfaces using various external forces (shock, vibration, magnetic field)

One of the first choices to remove unwanted dust is a shock or vibration mechanism. Apart from the efficiency of the method, we bear in mind, an example of spatial activities with mechanical shock tasks as, for instance, the crushing station, part of the ExoMars rover, is equipped with a little hammer mechanism. After a drill sample is crushed, the hammer is applied to remove potential powder contamination from the sensitive surfaces prior to the next sample investigation.

2.4.1. Shock testing

Measure the displacement of dust applied to a surface by means of mechanical shock. The purpose of the experiment is to quantify the displacement of dust particles as function of the momentum transferred to the system. The control parameter is mass displacement for a well-defined mass, angle, and height of the pendulum (linear momentum transfer).

Experimental set-up consists of a pendulum with a rigid arm, a support, a Si wafer with applied regolith on it. The camera was used for recording of experiment. In a rectangular area of 50 x 16 (= 800 mm^2), we are placing the five types of particles, that differ by shape and sizes. The chosen particles for the experiment are: NaCl, anhydrous $CaSO_4$, $CaSO_4$*$2H_2O$, Talcum powder, regolith simulant TUBS-M.

Figure 5. Experimental setup

The set-up has been improved in the following way:

- The arm of pendulum is rigid and without torsion
- The area of particle covering is well defined by using a “window” of sieving the powder;
- The applied concussive force is automatic, excluding direct human intervention.

As control parameter, the mass of particles is measured, that has crossed the line on the side of the pendulum, by carefully removing the particles with fine brush into a watch glass, then measuring its weight. The control of the accuracy of that operation is done by weighting the remaining powder inside the initial area and deciding whether the difference to the original amount is within the limits of error tolerance. Experimental results are presented in Table 3.

Table 3. Experimental results for dust removal with identical shocks, and distribution of dust on surface

Particles type /% of displaced powder	Exp.1	Exp.2	Exp.3	Exp.4	Exp.5
NaCl	19.34	31.53	39.74	32.98	36.06
$CaSO_4$ anh	24.65	20.91	40.86	27.45	66.60
$CaSO_4$ * $2H_2O$	29.68	37.75	28.07	29.91	38.86
Talc	29.61	38.86	20.06	26.13	25.9
Regolith	66.5	57.5	46.66	50.88	50.80

2.5. Regolith interaction with textile

Motivation for this experiment is checking the border conditions (high and low pressure) and see how well cleanroom textiles can protect against fine Regolith particles.

2.5.1. Regolith penetration through textile by applying only gravitational force

Cleanroom textiles used in this experiment were by Dastex: ION-NOSTAT VI.2 without Carbon, and PFG DASTAT I1800. Using elastic bands, the textiles were tautly fixed on the beakers. A certain amount of Regolith was placed on the surface of textiles using a sieve. Then the beakers were sealed for 7 days in a chamber to exclude external disturbances such as streaming air. After 7 days, the chamber was unsealed and the beakers were taken out of it. The regolith on the top of textile surface was carefully removed, avoiding particle shoehorning. After that, the textiles were taken for an analysis. Observed range of lengths of particles that penetrated the textiles: ION-NOSTAT VI.2 without Carbon: 6,09 - 51,72 μm; PFG DASTAT I1800: 11,06 - 49,09 μm.

Experimental results are presented in Table 4.

Table 4 Experimental Data for Regolith penetration through textile by applying only gravitational force

Textile	Mass of Regolith before experiment (mg)	Mass of remained Regolith (mg)	Mass of Regolith penetrating the textile (mg)
ION – NOSTAT without Carbon	307,6	286,1	21,5
PFG DASTAT I1800	299,8	270,5	29,3

2.5.2. Regolith penetration thorough textile by applying additional pressure

Textile has been placed in a mortar, covering all mortar's surface. Regolith was placed on the surface of the textile, and then using a pestle it was forcefully pressed into the textile.

We have pressed 800 mg of Regolith against 26,5 cm^2 of both materials. The penetration rate, visually detected is in-between 5-10%. For calculation we have considered roughly 53 mg. The surface density of penetrated Regolith through textile (the control parameter) is then 53mg/26,5cm^2, resulting 2mg/cm^2, or 0,02 kg/m^2.

3. Conclusions

The DEAR project has been successful in achieving its objectives. Simulations of electrode structure suggests that on surface areas where alternating poles are entangled electrophoretic forces are pointing outward i.e., regolith will be removed outside of the covered area. Next steps will be the manufacture of prototypes to evaluate the results of simulation, investigation of effects from magnetic fields and adding the interaction between particles in simulations. Cleaning with CO_2 is also of particular interest because it can be used on a variety of human space flight hardware. Further investigations will be related to cleaning with CO_2 of robotic arm for wear issues and dust penetration. Robotic arm is an asset for doing experiments in regolith environments e.g., testing potential degradation of space suits exposed to regolith and testing mechanical systems in dusty environments. Regolith removal using mechanical shock is one of the simplest and effective methods, but further research is required.

Acknowledgements

This project was supported by the European Space Agency.

Following are the experts and contributors, as well as our reference for the presented activities within the article: Andreas Pflug, Philipp Schulz (IST Fraunhofer), Gernot Groemer, Seda Özdemir-Fritz (OeWF), David McKeown (UCD), Ole Gusland (Gusland Consulting), Axel Mueller (OHB) and Christian Schwartz (ESA), to whom we thank for their wisdom, passion and patience shown to us.

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Monitoring natural phenomena from the classroom with Edusat. Proposal for a teaching guide (and support material)

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Abstract

Satellite images and remote sensing allow us to identify the effects of natural and human-made changes that occur on Earth: fires, floods, urban development, deforestation, etc. Thanks to the Copernicus programme, satellite images of the entire world are now available, with a near-daily frequency that allow the identification and monitoring of all these natural phenomena and human activities that produce notable changes to the Earth's surface.

All these phenomena are forming part of the concerns of many young people who see the future of their planet in danger. The Edusat platform explores these phenomena from space and provides a didactic guide to understanding the effects of global environmental change, right in the classroom. In this way, we bring remote sensing closer to a public that until now was rarely involved in this discipline. We do it from a didactic and practical point of view, connected with real data from Sentinel satellites and thanks to EO Browser application.

Keywords

Climate change, Copernicus, remote sensing, satellite images, teaching material

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1. Introduction - Remote sensing as an educational resource

The social, economic and territorial dynamics that humanity has adopted since the First Industrial Revolution have led to the indiscriminate consumption of natural resources. The exploitation of these resources has put the well-being of the inhabitants of planet Earth, as well as the physical systems that support it, at severe risk. This process has been described as “Global Environmental Change” and results in four well-known phenomena: pollution, biodiversity loss, change in land use and land cover, and climate change [1] [2].

The scientific strength of the negative consequences of climate change, pollution or biodiversity loss further intensifies critical reflection among citizens. This sense of protest and struggle is especially intense among young people, who are fighting against the passivity of politicians for policies to mitigate climate change. As such, these young people need to have the necessary competences in order to evaluate and disseminate the consequences of global environmental change in a critical and objective manner.

The availability of satellite imagery from around the world on a daily basis (depending on weather conditions) makes it easy to identify and monitor all of these natural phenomena and anthropic processes that involve notable changes to the land surface [3]. These images taken from space make it possible to study the evolution of natural and anthropic episodes such as wildfires, floods, melting glaciers, deforestation or urbanization [4].

Copernicus is the Earth observation program coordinated and managed by the European Commission and the European Environment Agency, with the aim of providing accurate and up-to-date information on six areas: climate change, security, emergency, atmosphere, marine environment, and land surface [5].

All of this information is especially designed to provide a global view of the Earth’s health, with the aim of helping governments to focus on environmental policies and to effectively monitor their implementation. Industries, organizations and researchers are also encouraged to make use of this data in conjunction with their own data in order to develop new functionalities and applications. Copernicus offers a complete set of open data, including the large volume of images captured from Sentinel satellites. This data is available through various websites, applications and services, and it is designed for different user profiles, from highly specialized to less experienced ones.

The Edusat project [6] presented in this paper aims to set out, in an educational and interactive way, the fundamentals of remote sensing in order to make the process of collecting and processing satellite images understandable.

Therefore, the main objective of this reference material is to present remote sensing to a non-specialized audience and to offer a user-friendly tool for the analysis of land surface changes as well as a tool for the dissemination of results.

2. The Edusat platform

Edusat is a web platform that contains educational resources for exploring satellite images that are open to the entire educational community.

The website was launched in May 2021 and is a multilingual (Catalan, Spanish and English) platform. Edusat offer resources in a dynamic way (images, videos, time lapses, maps, gifs, etc.) in order to clearly explain global environmental change. The resources offered are:

- basic principles of remote sensing,
- case studies (explaining various natural and anthropological phenomena),
- exercises to work on with the EO Browser teaching guide.

Using Edusat, we propose a teaching guide that aims to bring remote sensing to a non-specialized audience and to provide teachers, students and researchers with support material. This paper sets out a teaching guide for a classroom workshop.

The overall aim of Edusat is specified in these three specific objectives:

- To introduce students to the field of remote sensing and to show them how to identify real natural phenomena.

- To introduce students to the Copernicus programme, giving them access to freely available satellite images.

- To enable students to identify the causes and consequences of natural phenomena such as floods, drought, deforestation, etc.

The purpose of making the materials openly available is to empower users to learn about a resource, regardless of whether or not they have completed the courses we offer. The dissemination of the materials enables anyone to become familiar with the applications and the usefulness of satellite imagery.

At the moment of writing this paper there are nine case studies developed that allow us to demonstrate the usefulness of satellite images to observe and analyze the current phenomena of global environmental change. The case studies are accompanied by videos which explain step by step how to obtain the results we show for each phenomenon studied so that the user can get the same results using the videos as a quick-start guide.

3. The learning material

The teaching guide is the proposal that we offer educators to use Edusat in order to work with remote sensing and case studies in the classroom.

It is structured as a single session -or set of sessions, depending on teaching context- with different parts or blocks (Figure 1).

3.1. Block 1. Context and assumptions

Estimated duration: 2 hours

3.1.1. Context

The first block comprises of a theory session in which the teacher explains the principles of remote sensing (satellites, sensors, electromagnetic radiation and band combinations), showing students how this technology can help to detect natural disasters or human activity resulting from the climate crisis. The goal of this block is to provide the students with context on the issue of global environmental change and to explain the principles of remote sensing in a simple, enjoyable way.

3.1.2. EO Browser [7]

This block also contains a section in which the teacher shows the students how to use the EO Browser application to search for satellite images and make band combinations.

EO Browser is an application developed by the Sentinel Hub company [8] which makes it possible to view high-resolution images from Sentinel, Landsat and other satellites on a single website.

Furthermore, the EO Browser enables users to create comparisons or time lapses of satellite images so that the changes that have occurred in the territory can be easily identified by comparing several images taken on different dates.

For now, this application is an open-access tool that offers basic functions such as displaying the natural-colour images of satellites; as well as advanced parameters of band combinations or the application of multiple indices through inter-band algorithms.

Figure 1. Teaching guide infographic

3.1.3. Case study

The students explore real examples of phenomena from around the world that can be studied using satellite images and well-documented case studies available in Edusat, related to phenomena such as fires, floods, receding glaciers, volcanic eruptions, logging, drought or urban sprawl. The case studies documented in Edusat are listed in table 1.

Table 1. Table of Edusat case studies for territorial analysis based on remote sensing

Phenomenon	Case study	Date
Forest fires	Ribera d'Ebre, Spain	June 26, 2019
	Amazon, South America	Summer 2019
Floods	Storm Gloria, Spain	January 20, 2020
Glacier regression	Aneto Peak, Spain	2015-2020
	Amery Ice Shelf, Antarctica	October 2019 – February 2020
Volcanic eruptions	Kilauea, Hawaii	May 3 – August 15, 2018
Deforestation	San José de Chiquitos, Bolivia	August 2015 – November 2020
Droughts	Acuelo lagoon, Chile	September 2016 – October 2019
Urban sprawl	Beijing airport, China	2014 – 2019

For each case study, the following is stated:

- The causes and consequences of the studied phenomenon (fire, flood, etc.)
- How Sentinel sensors can detect it: satellite types, indices, band combinations, etc.

As such, in a truly practical manner, students can become familiar with the principles of remote sensing and how the Copernicus program can be used to detect real and up-to-date phenomena.

3.2. Block 2. Researching a new case study

Estimated duration: 2 hours

The second block is based on group work. The aim is to explore the information that satellites give us on a specific event and identify what changes occurred before and after the phenomenon.

Students must search digital media and compile information on their case study (exact date when the phenomenon occurred, where it occurred, photographs of the event and any other information that might be of interest for their research). Then they must explore satellite images using the EO Browser application and make the corresponding band combinations in order to produce a result.

3.3. Block 3. Presentation of the results

Estimated duration: 1 hour

In the third block, each group presents its case study, explaining the results to the other groups. For the presentation, the group has to share satellite images and explain why it has used certain band combinations and not others.

In this block, the student can also practice communication skills and techniques that are also related to geographic information, such as story maps.

4. Discussion

Since we launched the Edusat website in May 2021, we have been using this educational and didactic resource in several workshops and webinars, not only for students but also for teachers and other interested groups. Teaching these workshops has helped us to evaluate the quality of the learning guide and put it into practice in the context of extra-curricular education. The different experiences are listed below in table 2.

Table 2. Table of workshops organized using Edusat teaching material

Institution	Age	Duration	Nº of students
Foundation for Helping Children and Youth with High Capabilities (FANJAC)	13-17 years old	12 hours (4 sessions of 3 hours each)	20
Foundation for Helping Children and Youth with High Capabilities (FANJAC)	11-15 years old	3 hours	20
Rafael Campalans High school (Anglès)	17-18 years old	1 hour	25

Campus Prebat (University of Girona) – online	15-16 years old	2 hours	30
Campus Jove de Recerca (University of Girona)	17-18 years old	2 hours	40
Inmaculada Concepció High school (Lloret)	17-18 years old	1 hour	20
Montessori High school (Girona)	17-18 years old	1 hour	37

Some workshops have been organized in collaboration with the Department of Geography with the aim of disseminating the discipline of geography and encouraging new young students to study this subject. The innovative and up-to-date character of the workshop has confirmed the engagement of the students who have shown a proactive attitude investigating and exploring new natural phenomena by themselves.

At the same time, the workshops have given us the opportunity to show and disseminate the research and projects being undertaken in the university and to introduce young people to the world of academia.

Most of the workshops have been performed in person. However, the technological and digital component of the Edusat learning material allows us to also teach in a virtual context during the pandemic lockdown or when the measures were more restrictive.

One strong factor of the Edusat platform is its flexibility, which allows us to adapt the content and the exercises to different levels and ages (from 11 to 18 years old). On the other hand, having a well-documented teaching guide has allowed any teacher to teach the workshop according to the needs of the class.

During the workshops, the students have explored different case studies documented on the website such as wildfire in the Ribera d'Ebre region (Figure 2), the effects of Storm Gloria on the Catalan coastline, or the fires in Amazonia. However, we have also worked and explored other current natural phenomena such as the La Palma volcano in the Canary Islands, the floods in northern Europe, or the rupture of the A-76 iceberg. However some of these case studies are not yet documented on the website.

Figure 2. High school students observing the flooding in the Ebro Delta after Storm Gloria with Sentinel 1

As we can see in table 3, we also have organized different online webinars to present the Edusat website to teachers and the general public. These webinars have focused on how to use the teaching guide in order to encourage teachers to use Edusat website in their classroom.

Table 3. Table of webinars organized using Edusat teaching material

Title	Attendance	Language
Edusat, learning platform for Earth Observation	51	Spanish
Demo: Edusat, learning platform for Earth Observation	34	Catalan
Edusat Platform: a new tool to analyse the transformations on the earth's surface	25	English

The recorded sessions can be viewed on the Vimeo channel:

https://vimeo.com/channels/unigisgirona

5. Conclusions

The teaching process we propose at Edusat has been designed based on the different experiences we have carried out in sessions with young people.

Depending on the context, the process has been extended to 15 hours, in others it has been compressed into a 1-hour session. In each case, the youngsters were able to sit in front of the computer and manipulate satellite images directly.

As a result of these experiences, it was possible to capture the interest of teachers in providing advanced but affordable technological tools, as well as encouraging methods to get closer to digital natives.

With the publication of Edusat, we hope to extend it to a much wider audience and that many teachers can follow the instructions and offer this resource in the classroom.

Also, from our point of view, we plan to continue developing case studies, to connect them with the phenomena that may be taking place, and to fill the platform with more visual resources to better explain, for example, the complex concept of remote sensing.

We believe that Edusat is a borderless platform that can be exported to many educational contexts worldwide to meet a global phenomenon that often has local effects, and we believe that this double dimension is well reflected in the case studies.

Acknowledgements

Edusat has been developed with the funding of the Cordinet program from the European Commission, as well as local funding from the University of Girona. For which we would like to thank to these institutions their support.

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Testing campaign for ECRIDA: the UV resin 3D printer flying on REXUS

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Abstract
ECRIDA is a student project participating in the REXUS/BEXUS campaign that develops a UV resin 3D printer device capable of working in the low-gravity environment offered by the REXUS rocket flight. Our main objective is to describe the impact of low gravity on the UV resin 3D printing process by comparing samples printed on Earth with samples printed in space. Due to the requirements of the host vehicle and driven by the novel design of our device, a thorough testing campaign must be planned and completed to qualify the device for flight and maximise the success of the scientific objectives. This paper describes the requirements that the device must fulfil and goes into the design of our test plan describing the procedures and the results. Vacuum, vibration, pressure, and functional tests were performed and described together with our learned lessons and conclusions in our will to help student teams with their testing activities.

Keywords
3D printing, REXUS/BEXUS, milligravity, testing

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Acronyms/Abbreviations

REQ	*Requirement*
ESA	*European Space Agency*
REXUS	*Rocket Experiments for University Students*
BEXUS	*Balloon Experiments for University Students*
SNSA	*Swedish National Space Agency*
DLR	*Deutsches Zentrum für Luft und Raumfahrt*

1. Introduction

It is known that additive manufacturing is a key technology when it comes to human space flight [1] as it gives the possibility of manufacturing desired parts right in orbit while relying less on the supply missions from ground that involve big costs and risks.

3D printers based on resin UV polymerization might be a great candidate for space applications due to their mechanical simplicity and better resolution compared to the already widely used Fused Deposition Modeling technology [2]. Together with the promises of the technology, a few challenges arrive when one could think to implement this manufacturing process in a low gravity environment.

Project ECRIDA proposes a proof-of-concept UV resin 3D printer based on the Digital Light Processing (DLP) technology to be tested on board the REXUS 29 rocket. The main objective of our project is to prove that the DLP technology can be used for additive manufacturing applications in low gravity by printing some traction samples during the REXUS flight. We also plan to compare them with samples printed on Earth to assess the impact of gravity on the UV polymerization process [3].

Figure 1. The ECRIDA 3D Printer

The flight model of our experiment is shown in Figure 1 and it was built by a team of 8 students participating in the REXUS/BEXUS campaign. REXUS/BEXUS is a campaign organized by SNSA, DLR, and ESA that gives the possibility to students to propose and implement a project that will be operated inside a sounding rocket or a high-altitude balloon. The whole campaign replicates the process of designing, integrating, testing, and launching a real space project while educating the participants on all these aspects.

To deliver the experiment for launch, the student teams must prove that they fulfill all the requirements that were agreed with the campaign organizers. The most important requirements like the main functionalities of the experiment or the safety ones must be proven by actual tests. The purpose of this paper is to give a high-level description of the test campaign that the ECRIDA project designed and performed to prove the main requirements of the project.

2. Testing Campaign

The testing campaign started in September 2021 and lasted 3 full months with a tight schedule. The main two locations where the tests were performed are the CAMPUS Research Center from University Politehnica of Bucharest and the Romanian Institute of Space Sciences.

The equipment used for each test was made available by the hosting facilities or it was acquired by our team via sponsorship agreements.

Each test is described in what follows by mentioning the main requirements (REQ) that need to be verified, a brief description of the proposed procedure, and the success criteria. Two types of tests were performed: functional and environmental. The authors considered to give only a brief mention about the functional tests and to focus more on the environmental ones as they consider them to be more relevant for the reader since most student experiments hosted by a launch vehicle usually must undergo the same procedures, whereas the functional ones are more experiment specific.

2.1. Constraints

The testing campaign needed to end before the Experiment Acceptance Review (EAR) that took place in mid-November. The EAR marks the end of the integration and testing periods performed by the REXUS teams and its completion proves that the experiment is ready to be delivered for the final pre-launch tests.

Manpower constraints were also considered as the campaign took place during university time and the COVID-19 crisis added many restrictions over the normal usage of the testing equipment. Constraints like the limited number of allowed team members inside a lab or the lack of trained personnel available to help us with the equipment affected the nominal execution of the campaign. The team reacted confident and faced these challenges with success without delaying the initial schedule of the campaign by more than a few days.

2.2. Functional Tests

All the functional requirements of the experiment were tested by a comprehensive printing test that consisted of running 3 times the complete timeline of our experiment from power on to power off.

The procedure consisted in running the launch timeline while tracking all the sub-systems activity (power, communication, data collection, data storage, motor, LEDs) and measuring the dimensions of the printed samples (as in *Figure 2*) to prove that the printing function achieves its purpose and that the samples are printed in the tolerances needed to perform the post-launch analysis campaign.

Figure 2. Samples after printing

2.3. Safety Pressure

REQ: *The pressure inside the resin container shall be the atmospheric pressure when closed at the ground during pre-flight and experiment operation.*

The containment of the resin is done inside a pressurized chamber that is sealed on the ground during the assembly. The experiment will be exposed to vacuum conditions during the flight and proving that the chamber can hold the resin at a pressure of 3 bar (x2 safety factor) is the main driver of our proposed procedure.

It was decided that a pressurized air test would be more accessible and proving that the chamber is airtight is sufficient to tick the requirement.

The experiment has by design two valves, one input valve and one output valve. A manometer was connected to the output valve and pressurized air was introduced via the input valve using a household compressor. As soon as the chamber established an inside pressure of 3 bar, the input valve was closed. The experiment was also submerged into a transparent container filled with water and its sides were recorded with cameras to observe any potential leaks (as shown in Figure 2).

The success criteria summed to observing a decrease of less than 0.2 bars of pressure over a period of 1 hour.

Figure 3. Safety Pressure Test

2.4. Absorbent Material

REQ: *The absorbent material shall be capable of absorbing 20 times the quantity of the used resin.*

To comply with some functional requirements of the experiment, a special type of UV resin is used for the printing process. Utilizing 4 liters of it for the test would have had quite an impact on our budget and for this reason we agreed with the organizers to perform this test with a cheaper liquid with almost identical properties (engine oil).

The procedure was quite straightforward, the exact volume of absorbent material used in the flight model was placed on a table and 4 liters of engine oil were spilled over it while trying to cover its surface as much as possible with the same pouring rate (as shown in Figure 4).

The success criteria of the test consisted in proving that after a time of 1 hour, all the oil is absorbed, and no oil traces are found on the other side of the absorbent pad.

DOI: 10.5821/conference-9788419184405.021

Figure 4. Absorbent Pads Test

2.5. Thermal

REQ*: The experiment shall have nominal performance at temperatures of up to 45 °C.*

REQ: *The experiment shall maintain functionality with nominal performance after being exposed to a temperature of almost -30°C before the flight.*

Extreme temperatures must be considered before the operation of the experiment. The launch will take place from the ESRANGE launch site inside the Arctic Circle. so, the experiment could be exposed for a long period of time to very low temperatures before the launch. Also, the heat coming generated during the flight can drastically rise the temperature inside our experiment module before the milligravity period.

The procedure consisted in artificially exposing the experiment to low (using a household freezer) and high (using a lab oven) temperatures and running the full printing sequence immediately after (see Figure 5). This test is quite conservative as in reality, thermal insulation is used inside the rocket module and the organizers can heat the rocket to a desired temperature before the flight.

The success criteria was represented by the successful completion of the printing procedure after the cold/heat exposure.

Figure 5. High(left) and Low(right) temp. tests

2.6. Vibration

REQ: *The experiment shall withstand the vibration loads during the launch of REXUS rocket.*

Figure 6. Vibration Test Set-Up

The vibration test was the most conventional test performed by our team compared with all the others.

The procedure was entirely specified by the REXUS User Manual [4] and by the REXUS/BEXUS organisers. The experiment was mounted on a shaker and different vibration input profiles were used while observing and recording data from the accelerometers placed on different spots on the experiment's body.

One of the challenges of performing the test was the design and manufacturing of the interface board to the shaker that was needed to match the shaker mechanical interfaces with our experiment.

The success criteria was to have a functional experiment after exposed to vibrations.

2.7. Vacuum

REQ: *The experiment shall have nominal performance in vacuum conditions (pressure below 0.5 mbar).*

Most of the electronics used are off-the-shelf components that will be exposed to vacuum for a short time during operation in milligravity. For this reason, all the electronics parts were tested while in operation inside a vacuum chamber at a pressure of less than 0.5 mbar.

The procedure consisted in running the electronics with the printing software inside the vacuum chamber while measuring and recording temperature data via the sensors placed on the most critical parts of the assembly (the stepper-motor and the most power consuming chips of the PCB). To command the electronics while inside the chamber, we implemented a Bluetooth communication that allowed us to control the process.

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The success criteria consisted of confirming full functionality of the electronics while inside the vacuum chamber and to prove that the hotspots' temperatures of the assembly were in line with the requirements.

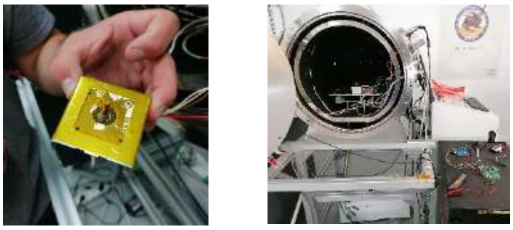

Figure 7. Electronics Vacuum Test

3. Results

All the test procedures presented in Section 2 were successfully carried out by the team in the given timeframe. The Thermal Test was performed with some delay as the initial plan was to access a thermal chamber but given the high number of COVID infections at that time, we continued with the freezer/oven procedure.

All the success criteria were achieved, and extensive test reports were delivered to the campaign panel. The test activities ended with a successful Experiment Acceptance Review and with the delivery of the experiment to the REXUS/BEXUS organisers for the launch campaign pending to take place in 2023.

4. Conclusions

The test campaign executed by the ECRIDA team participating in the REXUS/BEXUS framework is presented. Our method of designing the campaign, the constraints we faced, and a high-level description of every test performed are described with focus on the more general aspects and without digging into the specifics of our experiment. The purpose of the authors is to make all the information valuable to any student project that will be hosted by a launch vehicle and that must undergo test procedures.

Given the circumstances of the COVID pandemic, our team faced various challenges while performing the test plan but eluded them with confidence resulting in a successful test campaign. The experiment was delivered to the REXUS/BEXUS organizers and now final preparations for the launch are performed.

Acknowledgements

The team behind ECRIDA would like to acknowledge the invaluable help during the testing campaign of prof. Bogdan Vasile and prof. Bogdan Ionescu from CAMPUS Research Centre, University Politehnica of Bucharest, and Claudiu Cherciu from the Romanian Institute of Space Sciences. The team gratitude also goes to our advisors from the REXUS/BEXUS framework: Koen DeBeule (ESA), Armelle Frenea-Schmidt (SSC), Dieter Bischoff (ZARM), and to all the people involved in organising and running this amazing campaign.

The authors would also like to acknowledge the institutional and private sponsors of ECRIDA, namely: University Politehnica of Bucharest, Thales, GMV, RISE, TechLounge Association, 2Space, Faulhaber, Top Metrology, SNSA, DLR and ESA.

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Developing a 3U CubeSat Engineering Model - FlatSat & Chassis Design

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Abstract

WUSAT-3 is a 3U CubeSat being designed to carry an experimental RF signal direction finding payload in Low Earth Orbit (LEO). Successful outcome of this experiment could lead to significant benefits for the field of wildlife monitoring from Space. Commercial adoption of this process would enable the development and use of much smaller, lighter RF tracking tags, which in turn would considerably increase the potential range of species that could be tracked by Satellites.

The effect of the Covid-19 pandemic lockdowns has limited physical progress over the past 18 months, but the team continues to gain enormous experience and motivation from pursuing this exciting project with a very real-world mission. A recent return to near-normal working patterns has enabled the team to fully engage with the practicalities of progressing the previously produced WUSAT-3 Configuration Model, towards a testable Engineering Model.

This paper outlines the development of both the initial chassis prototype (including mechanisms) and a subsystem FlatSat as a first stage towards building the complete Engineering Model.

The chassis prototype was required to meet all the requirements of the FYS Design Specification [1], the NanoRacks CubeSat ICD [2], the CubeSat Design Specification [3] and those features identified by the outcomes of the WUSAT-3 Configuration Model.

The FlatSat was required to include all subsystems capable of being constructed and tested without the availability of certain proprietary items that will be purchased later. The function and interface of these items, where it was necessary for the purpose of testing the assembled subsystem units that were available, was met by the design and inclusion of temporary substitute arrangements that provided similar performance.

Systems Engineering methodologies were employed throughout as a means of ensuring that the design features of both chassis and FlatSat met all necessary requirements.

Keywords

CubeSat, Engineering-Model, FlatSat, Space, Systems,

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Acronyms/Abbreviations

ADC	*Analogue-to-Digital Converter*
DDD	*Direct Displacement Damage*
DoD	*Depth of Discharge*
EEPROM	*Electrically Erasable Programmable Read-Only Memory*
EM	*Electromagnetic*
EPS	*Electrical Power System*
FlatSat	*Flat Satellite, internal subsystems of the satellite constructed and connected outside of the chassis*
FYS	*Fly Your Satellite*
LDO	*Low-Dropout*
LEO	*Low Earth Orbit*
OBDH	*On-Board Data Handling*
RF	*Radio Frequency*
SEE	*Single Event Effect*
SEU	*Single Event Upset*
TID	*Total Ionizing Dose*
TMR	*Triple Modular Redundancy*
WUSAT	*Warwick University Satellite*
XCAM	*The CubeSat Camera & Company*

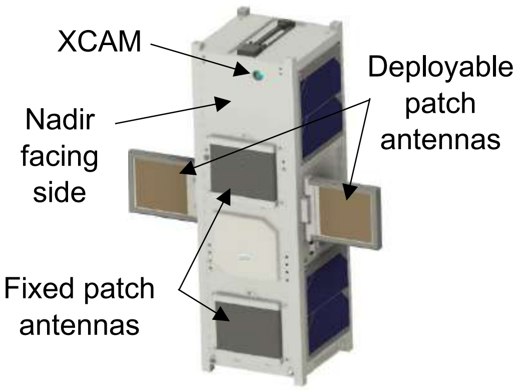

Figure 1. WUSAT-3 CubeSat Diagram

1. *Introduction*

In previous years, work carried out has been highly conceptual in nature, owing in no small part to the impact of the Covid-19 pandemic. Building upon the work of previous teams, the focus this year was translating conceptual designs into reality – manufacturing, assembling, and testing as many CubeSat subsystems as possible in preparation for the project's ambition of admission to the European Space Agency's Satellite Program [1].

2. Discussions

Detailed below is a summary of each subsystem developed this year by the WUSAT-3 team, outlining the key design features, their function, their testing and verification as well as relevant major considerations for each.

2.1 Chassis

The primary function of the chassis is to support the payload's ability to fulfill the satellite's mission. It provides a stable base to secure internal components during launch from Earth, as well as to withstand the vibrations and large forces experienced. The chassis consists of two side panels which incorporate four external rails, nadir and back panels, top and bottom plates alongside an additional internal structural support. The panels act as anchors to attach multiple patch antennas in addition to the solar panels required to power the system. Where required, cut outs were implemented to facilitate connections between external components and internal systems, with all designs conforming to the dynamic envelope specification [1].

2.2 Chassis Testing

Static stress testing was conducted using finite element software. Through Abaqus relevant parameters such as Von Mises stresses highlight areas which may be prone to yielding failures from loading and vibration during launch. This information has been used to inform design on key loadbearing components where reinforcement or redesign has been required. Additional simulation outputs investigated component deflection, which is presented as the displacement magnitude in Abaqus.

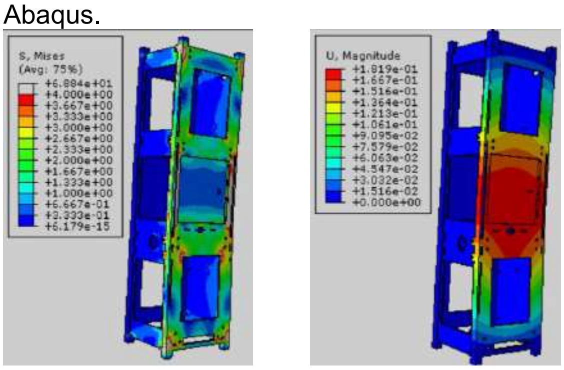

Figure 2. Results of simulation in Y axis showing the Von Misses stress in MPa (left) and deflection in mm (right)

The first simulation for stresses in the X axis shows values lie well within tolerated levels peaking at only 42.90 MPa. The maximum deflections of 0.04 mm are also well within reasonable safety margins. Similar results are seen across the Y axis with peak stress at 68.86

DOI: 10.5821/conference-9788419184405.022

MPa causing a 0.18 mm deflection, and over the Z axis a peak 73.18 MPa resulted again in a small 0.18mm deformation. With the use of aluminium 7075 as the material for the chassis construction these forces are well below the 310 MPa yield limit.
Dynamic vibrational testing was also performed to gain insight on the natural frequency of the satellite chassis. This was carried out in similar fashion by simulation - with results yielding a first natural frequency 547.77Hz, which is well outside the required minimum tolerated 130Hz [1]. This testing however, indicated that large deformations of the structure up to 8.68mm could occur, which could potentially damage internal components, whilst also potentially exceeding the allowable dynamic envelope [1].

2.3 Internals

The internal components are separated into ‘shelves’, each containing a motherboard with the PC/104 form factor. Standoffs situated in the corners of each shelf, allow them to be arranged into a stack configuration across the axial length of the CubeSat, and maintain controlled separation between each internal component. This shelf stack fits within the chassis and is attached via the standoffs at two mounting points, located at the top and bottom plates respectively.

Figure 3. Configuration of Component Shelves

2.4 Patch Antenna Frame and Hinge

There are four payload patch antennas on the CubeSat (Abracon ARRTN5-915.000 MHz), each receiving data from the frequency of the RFID tags. Two are fixed and located on the nadir (Y+) panel of the satellite, and two are deployable from the side panels. The latter are constrained with a hinge to the X+ and X- panels respectively, where a deployment mechanism allows them to rotate 90° about the Y axis to face the Earth. Deployable antenna mechanisms were necessary, as there is insufficient space on the nadir panel to host all four of the earth facing antennas required by the payload – given the position of the camera aperture. Given the thickness of 6.9 mm of the antenna module, these could not be mounted flush onto the side panels of the chassis since it will exceed the maximum 6.5 mm of allowable dynamic envelope protruding from the side. Therefore, a recess in the aluminum chassis was implemented to house the patch antenna in its deployed configuration.

2.5 Deployment Mechanisms

The reliability of the deployment mechanisms for the patch and TM/TC antennas was a critical factor for guaranteeing the success of the WUSAT-3 mission. For this reason, the deployment mechanisms underwent rigorous design, testing and validation to ensure the designated mechanisms were sufficient. Both deployment mechanisms utilize a nichrome melt wire device to release the appropriate spring-loaded deployment mechanism for the respective antenna system. In order to increase the effectiveness of the burn wire break point, a spring mechanism pulls the melt wire in the direction of cutting across the respective burn wire. Collectively this mechanism is known as a “thermal knife”.

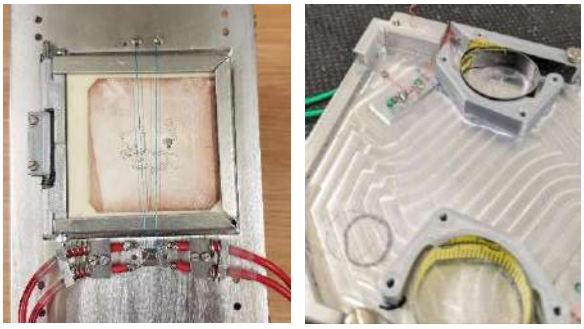

Figure 4. WUSAT Deployment Mechanisms

To reduce the likelihood of deployment failure – which would result in mission failure, redundant pairs of thermal knives were employed in the deployment mechanisms for each antenna. During testing, it was discovered that a sufficiently high current of 2.6 A would be required to ensure a successful cut within the acceptable time frame (< 10 seconds). For this reason, it would be necessary to activate only a single thermal knife at any given moment, to

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remain within the limited power budget available from the satellite's battery. Thus, a sensor would be employed to detect unsuccessful antenna deployment and enable power to be re-routed to the redundant thermal knife. In addition, this design choice eliminates the possibility of burn wires becoming a source of space debris.

2.6 Thermal Radiation Considerations

Despite the abundance of literature about thermal radiation effects and shielding pertaining to CubeSats, there is a significant dearth of investigations into the effect of thermal radiation in space on the temperatures of internal electronic components. This lack of analysis seems strange – given that the internal electronics are the components for which a suitable temperature equilibrium must be maintained. For this reason, building on data obtained through previous thermal analyses, an investigation into the effects of thermal radiation – and specifically – how they affect the temperatures of internal electronics, was undertaken. The data yielded that, without insulation, the current design of the WUSAT-3 CubeSat would not be capable of sufficiently insulating its internal electronics, and that the minimum and maximum temperatures of at least one or several components would be exceeded in worst case, eclipse, or maximum solar flux scenarios.

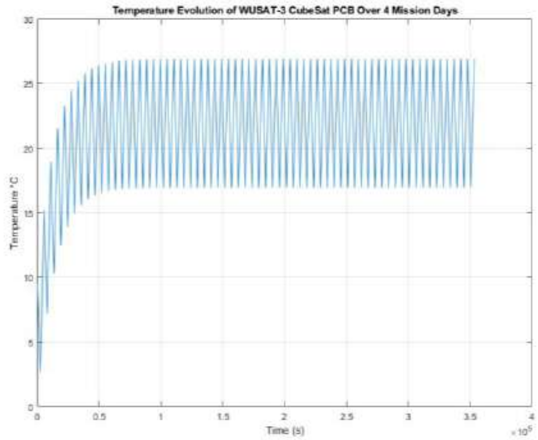

Figure 5. Internal Operation Temperature

This resulted in the implementation of aluminumized mylar multi-layer insulation within the interior of the chassis panels between the outer faces and the internal components. With the addition of this new insulation, results determined that the CubeSat would be capable of ensuring sufficient thermal stability for the duration of its deployment "survival" period, as well as the entire mission.

2.7 Electrical Power System (EPS)

Figure 6 illustrates the block diagram of the EPS, showing the basic layout for the power network. Power is generated by photovoltaic cells and subsequently transmitted to the EPS control, which includes components such as buck converters and additional subsystems to protect against under and over voltages. After this, the EPS control can proceed to distribute this power to the battery to charge it as well as to sensing subsystems within the CubeSat. The On Board Data Handling (OBDH) controls the EPS system and battery - distributing stored charge when needed and within the correct operating conditions. The battery outputs a range of voltages depending on the amount of remaining stored charge. In ideal conditions, it outputs 8.26 V DC, however this must still be reduced to a usable voltage for the range of components on the satellite. This is achieved with two buck converters; one to deliver regulated power to various subsystems and the other the delivered power to the OBDH microcontroller. These buck converters are a part of the power distribution in **Figure 6.** They were successfully designed, manufactured, and tested and are able to provide sufficient power to the satellite during operation.

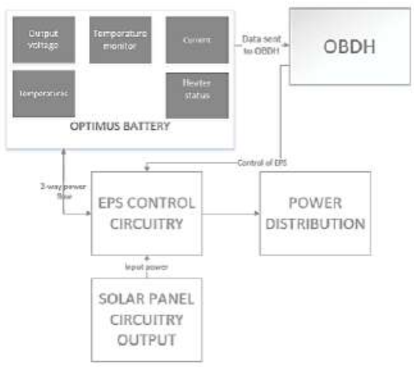

Figure 6. EPS Block Diagram

2.8 EPS Testing

The constructed buck converters, seen in **Figure 7Error! Reference source not found.**, were tested for their output voltages and their ripples to determine if they were suitable and could thus be accepted as feasible for further development. The LM22679 buck converter was found to successfully supply 5 V and 3.3V power rails for various subsystems, although outputs were measured at 5.2 V and 3.6 V respectively. The LM1036 buck converter delivers exactly 3.3 V to the microcontroller (PIC16), as desired. The ripple of all the power rails was found to be negligible due to the Low Dropout (LDO) regulators, names given respectively for each buck converter.

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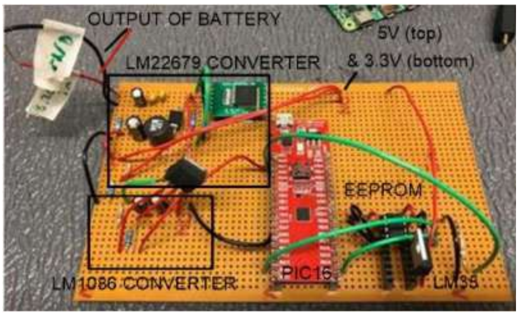

Figure 7. EPS Buck Converters and OBDH Components

2.9 On-Board Data Handling (OBDH) Coding

The OBDH is responsible for the data processing and storage needs of the various subsystems onboard. This includes coordinating, decoding, and executing telecommands received from the TM/TC component as well as providing the downlink data from the spacecraft. Therefore, the OBDH provides a platform for onboard subsystems and ground station to communicate with each other. Examples of operations the OBDH would perform include, processing sensor data such as temperature and voltage, and ensuring the system is in a safe operating window. Another example would be to send a command to the camera system to take a picture, process it and then transmit it to the ground via the S-Band payload downlink system. Most recently, work was undertaken to realise simulations of the I^{2}C, Digital and Analogue protocols and subsequently to connect it to the EPS and verify the function of both subsystems. These protocols will provide the foundations of the OBDH and allow further work to focus on the operation of the satellite.

2.10 OBDH Code Verification

Code for the I^{2}C, digital and analogue protocols was successfully written and tested with the chosen microcontroller, PIC16F15376. The I^{2}C protocols were tested with the PIC16, by writing 'WUSAT' in ASCII to an EEPROM, non-volatile memory, which was then removed and read by an Arduino MEGA using a serial monitor to read the addresses. The analogue and digital protocols were tested by using the analogue-to-digital converter (ADC), in the PIC16, by taking the analogue output of a temperature sensor (LM35) and converting it to a digital 10-bit reading, to then be stored in the EEPROM. Both tests were successful, confirming the successful function of the protocols' code.

The temperature sensor test was repeated on the EPS board in **Figure 7**, but an unknown source of error meant that random noisy readings compromised results for 40 seconds. After this initial settling period, the readings were as expected.

2.11 Battery

After a critical design review, it was decided that it was necessary to use a commercially sourced battery to ensure battery suitability for crew-rated missions. The Clyde Space Optimus battery was selected due to its flight heritage and features such as the on-board current and voltage measurements which can communicate via I^{2}C to the OBDH as well as integrated heaters [2]. The battery size, however, was not yet justified with respect to the power budget. The battery chosen is the 40Wh as this is large enough to sustain the operation of the satellite whilst in eclipse.

2.12 Camera

Located at the top of the nadir panel, the C3D CubeSat camera board from XCAM was selected to fulfil the Earth imaging requirements of the WUSAT 3 mission. The reasons for its selection include previous flight heritage of the design, adherence to standard CubeSat dimensions and stacking connections and the offer from XCAM of the donation of a C3D board for the WUSAT 3 mission.

2.13 XCAM Camera Emulation

Figure 8 shows the camera emulation created to emulate the function and operation of the XCAM camera system. It uses I^{2}C protocols [3], just as the real camera would, to send the image to the microcontroller. The model was tested successfully, with a connected computer receiving the image taken by the Raspberry Pi camera (left). A limitation of the XCAM system is its use of volatile memory, which increases the power consumption of the satellite.

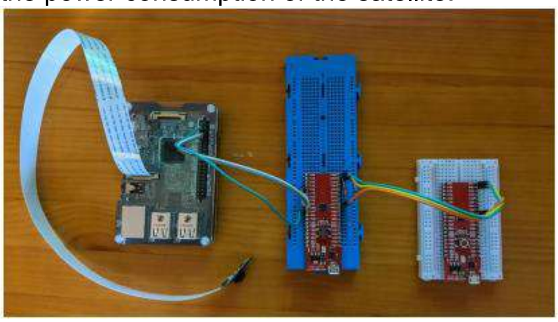

Figure 8. XCAM Stand In

2.14 Attitude Determination and Control System (ADCS)

To confirm which configuration of ADCS would be the most optimal for fulfillment of mission requirements, simulation data provided by CubeSpace Ltd allowed for the model

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specification as well as selection of optional components to be determined. From this data, the Y-Momentum CubeADCS model was selected for implementation in the CubeSat. [4]. This item will be purchased when funds are available.

2.15 Electromagnetic (EM) Radiation Considerations

Electromagnetic radiation is of significant concern to satellite engineers, particularly given the small size of the WUSAT-3 CubeSat and the potential options for shielding. For this reason, an investigation into EM radiation effects on onboard silicon devices was undertaken, using industry standard modelling toolkit – SPENVIS. Given relevant mission and design parameters, it was determined that the effects of persistent radiation such as Total Ionizing Dose (TID) and Direct Displacement Damage (DDD), were not of significant concern given the planned thickness of aluminum shielding (**Figure 9**). Over the course of the entire mission, the expected TID was determined to be just 100 rad – significantly below the dangerous limit for silicon devices of 10-25 krad.

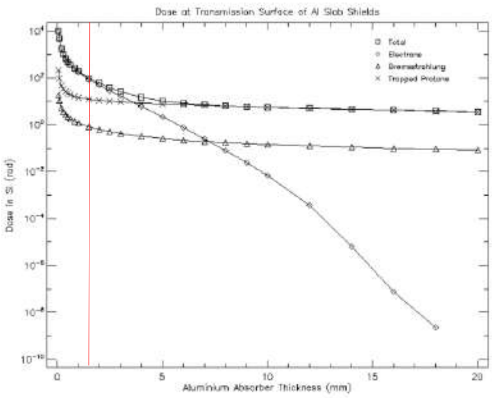

Figure 9. TID with varying Al Shielding Thicknesses

Transient radiation, such as Single Event Effect (SEE), warranted more significant concern and required specific mitigation, as the total number of expected bitflips within transistors was determined to be 896 for the duration of the mission. As this could lead to disruption of communications or data corruption in the OBDH, triple modular redundancy (TMR) was implemented to alleviate the threat posed.

Following a review of potential EM radiation counter measures, an altered version of TMR was chosen. This altered TMR will act as a data storage device and the majority voter with the microcontroller used for the on-board data handling, as seen in **Figure 10**. The PIC16 will read the data in each of the devices, using I^{2}C, and determine the majority response. In doing this, it will also be able to replace any discrepancies between the data devices. The trade-off will be minor as the data storage, EEPROMs are very light weight (1g), compact (under 1cm^3), low power (17.5μW) and each can store 1Mb so they can easily be integrated into the system. The limiting factor of this design is if the PIC16's bandwidth is sufficient to process comparative commands on top of monitoring the satellite's vitals and other on-board data, which all rely on the amount of RAM available.

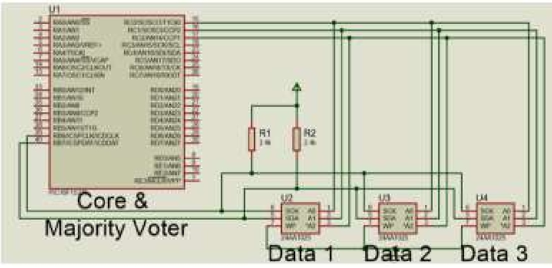

Figure 10. Altered TMR Schematic

By designing the electronic architecture to incorporate three parallel cores and a majority voter system, the probability of an SEU simultaneously corrupting data values within multiple voters – and then propagating this error into the data handling system – is significantly reduced. With the implementation of TMR – the expected number of bit flips over the mission, is reduced to just 1.68 - a reduction of 99.8%.

3 Conclusions

This work represents a sizeable leap forward in moving WUSAT-3 development towards an Engineering Model ready for testing. The integrated work of the WUSAT-3 team has produced a number of working subsystem units that will allow rapid development to the next stage.

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DOI: 10.5821/conference-9788419184405.022

Space Education in Europe: Status and Prospects

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Abstract

The space education landscape in Europe continues to evolve as the demand for a skilled workforce with interdisciplinary and multidisciplinary backgrounds, grows. This study aims to map the higher education landscape in Europe and understand trends and patterns among the higher education programmes within the European space sector. Indeed, the space sector is changing constantly as new technologies, challenges, and actors emerge, and the educational background must meet this demand for highly specialised and competent professionals. This analysis stems from the consolidation of a database of all higher educational space study programmes across all ESA and EU Member States within Europe, as well as a comprehensive view from students and young professionals entering the space sector. Further analysis groups the study programmes across Europe into so-called “macro-areas”, which support an in-depth analysis of the fields of study available for students in Europe, as well as their distribution across the continent. Overall, the study demonstrates key trends at the national level, both in terms of study programmes available and government strategies and initiatives influencing the space education landscape per country. European-wide trends are also identified. The study contributes to a better understanding of the space sector overall and allows for the identification of key trends among European higher education in space-related study fields. Additional key messages can be gleaned from an increased understanding of how the space sector is perceived by students and young professionals, complementing the analysis conducted of the space education landscape at the university level.

Keywords

Higher education, space education, Europe, students, young professionals.

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1. Introduction

The space sector, including its development, competitiveness, entrepreneurial mindset, and capacity to innovate, strongly relies on its workforce. Academia plays a crucial role in training specialised profiles. The transformation of the space sector, as a result of new technology and business and policy trends, creates new challenges for the European education system, which must adapt to the changing needs of the space sector.

The development of the space sector has given rise to an increasingly diverse educational landscape with various space-related curricula offered in different fields, from science and engineering to policy and law. In addition, the development of new space technologies shaped by other emerging fields and the interconnection between the space sector and other domains demonstrate the need for a more interdisciplinary education.

Considering that education is an integral component of public policy and action, ESPI examined the state of play of the European space education landscape and gathered insights into available curricula in Europe and into views and expectations of European students and young professionals studying space-related programmes or working in the space sector.

2. Paper structure and methodology

The paper is organised as follows. In Chapter 3, an overview of a wide range of space-related higher education programmes hosted in Europe, is presented. ESPI compiled a comprehensive database of space-related education programmes in Europe. The database aims to cover all fully space-related higher education programmes for the academic year 2021-22 in EU and ESA Member and European Associated Member States. This includes educational programmes offered by universities and higher education institutes as well as space agencies, governments, international organisations, and other educational institutions.

ESPI organised programmes into four categories: Bachelor, Master (including master, double master, LLM, 5Y degree, double degree, second level master, integrated master programme, etc.), PhD, and other (including seasonal schools, short courses, online courses, etc.). In order to provide a more representative picture of the European space education landscape, bachelor/master programmes and PhDs are addressed in two separate sections.

ESPI organised these curricula into five macro-areas to allow for systematic grouping and analysis:

- Aerospace Engineering,
- Space Sciences,
- Juridical, Economic, Social Sciences and Space,
- Space Applications,
- Multidisciplinary Programmes.

The results of a survey providing insights into the views and expectations of students and young professionals are included in Chapter 4.

Finally, conclusions are covered in Chapter 5.

3. European Space Education Landscape

Overall, Europe offers a wide range of space-related higher education programmes that are distributed throughout the continent. ESPI identified and mapped a total of 866 programmes offered by 325 high-institutions and distributed across 30 European countries.

The mapping exercise highlighted that space education is mainly offered as a specialisation area, with second and third cycle degrees (master and PhD) representing the vast majority of space-related educational programmes in Europe. This situation varies slightly by macro-area. In aerospace engineering and multidisciplinary fields, for instance, bachelor programmes outnumber PhD programmes.

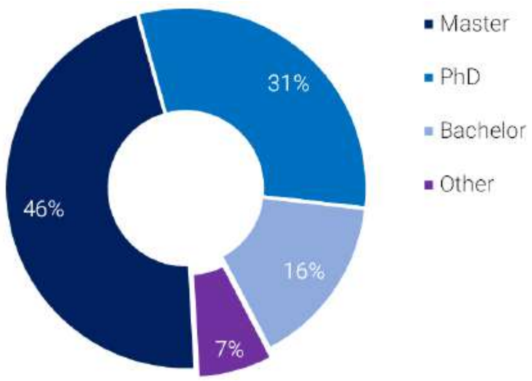

Figure 1. Course level distribution [1]

3.1.1. Space-related bachelor and master programmes in Europe

The majority of European countries have a limited space education landscape with less than five institutions offering bachelor and master level programmes. France and the UK are the countries with the highest number of higher education institutions offering space-related programmes, followed by Spain and Germany. Italy and Poland host between 11 and 20 institutions offering space-related programmes.

The main hubs for space education are Paris, Toulouse, Madrid, London, Barcelona, and Rome (Table 1).

Table 1. Top cities in Europe by number of space-related programmes [2]

	Cities	Space Programmes
1st	Paris	26
2nd	Toulouse	23
3rd	Madrid	22
4th	London	19
5th	Barcelona	11
5th	Rome	11

Similar to the ranking by number of higher education institutions, the UK and France host the largest number of space educational programmes, followed by Germany, Italy and Spain. Most countries host less than 20 space-related programmes.

Some countries host a high number of programmes offered by a limited number of educational institutions. Examples include the UK, Italy, the Netherlands, Spain, and Switzerland. Italy, for instance, houses approximately 50 programmes, but less than 20 institutions. Spain offers more than 50 programmes distributed across approx. 30 higher education institutions. Conversely, some countries have an educational offer that is more distributed among the universities, including Ireland, Greece, Denmark, and Croatia.

In addition, general trends among bachelor and master level programmes can be identified when programmes are grouped according to the macro-areas:

• Aerospace engineering and space sciences represent a vast majority of space educational programmes, respectively 36% and 30% of the total bachelor and master offer, and 65% of the countries house at least one programme in both fields. In addition to the traditional programmes, the aerospace engineering macro-area includes programmes in satellite telecommunications and navigation engineering, space systems engineering, and space propulsion engineering, among others.

• The programmes offered in the space sciences macro-area are more distributed across the countries compared to aerospace engineering. 83% of the countries offer at least one programme in the field of space sciences and 76% in the field of aerospace engineering. Nevertheless, the UK is home to approximately 27% of Europe's bachelor and master programmes in space sciences, and France holds the second highest share (9%).

• After aerospace engineering and space sciences, programmes in the multidisciplinary macro-area represent the third largest share in Europe. Multidisciplinary programmes account for 18% of the total offer at the bachelor and master level in Europe. While the number of multidisciplinary programmes varies significantly by country, these programmes are distributed across 69% of the countries.

• Curricula related to space applications represent 13% of all bachelor and master programmes in Europe and are offered by 65% of the countries. This macro-area encompasses all curricula concerning the space applications and services domains, and particularly educational programmes targeting them directly and addressing their use in other fields.

• The juridical, economic, social sciences, and space macro-area represents 2% of all bachelor and master level study programmes, mainly distributed across the countries that offer the highest share of space-related curricula in Europe. Luxembourg represents an exception since it has a limited offer of space-related bachelor and master programmes. Nevertheless, Luxembourg is an important European hub for both space law and multidisciplinary space-related education.

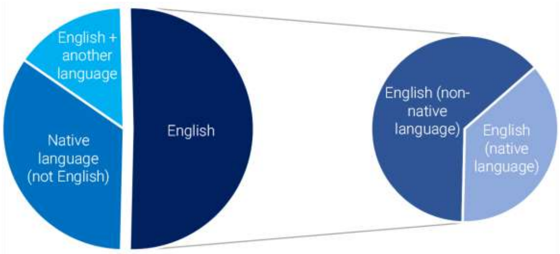

Figure 21. Language of instruction for space-related programmes [3]

Furthermore, language-related statistics highlight the strong European and international dimension of space education. Indeed, curricula offered entirely in English represent 51% of all mapped bachelor and master programmes. 34% are non-English programmes and 15% constitute multi-language programmes, with the

DOI: 10.5821/conference-9788419184405.023

majority being offered in both English and the country's domestic language.

Out of the programmes offered entirely in English, 40% are hosted by English-speaking countries, and particularly by the UK. The remaining 60% of English-taught programmes are offered by countries where English does not constitute the main domestic language. Additionally, to appeal to a wider audience, many students and academics seek to conduct their work and publish their research in English.

Additional considerations arise when the intersections of language of instruction is analysed by programme level or macro-area. There is a significant difference between the number of bachelor and master level programmes entirely taught in English. Outside of the UK and Ireland, English is the language of instruction for only 6% of bachelor programmes, whereas approx. 93% of master level programmes are taught in English.

Finally, the majority of space-related educational programmes at the bachelor and master level in Europe do not include a mandatory or optional internship. Particularly, 54% of bachelor and master programmes do not include an internship, 27% require an internship and 19% offer an optional internship. The shares of bachelor and master programmes including an internship, mandatory or optional, are 26% and 74%, respectively.

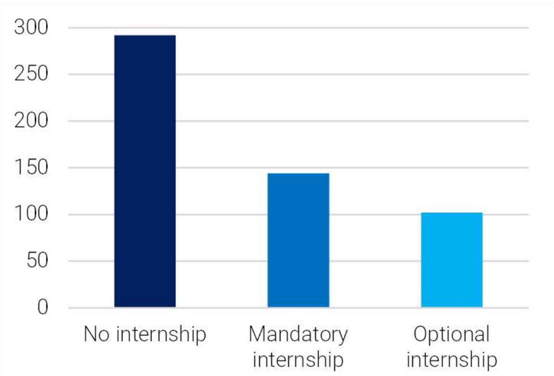

Figure 3. Internship requirements for space-related programmes [4]

On the other hand, internship requirements differ by fields of study. Aerospace engineering (44%) and multidisciplinary (23%) programmes represent the highest share of curricula offering optional and mandatory internships when compared to the other macro-areas. On the other end of the spectrum, only 2% of the programmes in the juridical, economic, social sciences, and space macro-area require or offer an internship opportunity. In the space sciences field, 20% of curricula require or offer an internship and within this share, 57% require a mandatory internship and 43% offer an optional one. Internship requirements may also differ based on the countries' educational systems.

3.1.2. Space-related PhD programmes in Europe

In addition to a wide range of first and second cycle degrees, European countries also offer a variety of PhD programmes which represent the second-highest share of space-related programmes in Europe (31% of the total offer). However, doctoral programmes vary not only based on the national education system, but also on the institutions offering them, making the analysis of s fully comprehensive list of PhD programmes not viable.

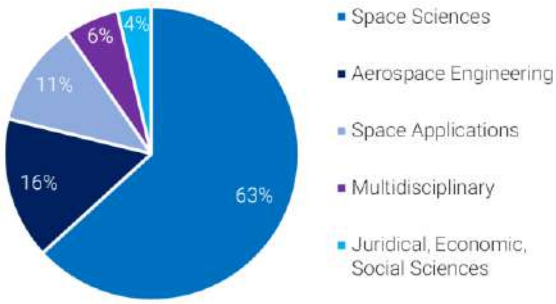

Figure 4. Language of instruction for space-related programmes [5]

Investigating the relation between PhDs and study fields, the analysis demonstrates that 63% of space-related PhD programmes in Europe fall into the field of space sciences. Most of the multidisciplinary PhD programmes are offered by universities in Toulouse and Athens. Finally, PhD programmes in the juridical, economic, social sciences, and space macro-area are the least represented in Europe (4% of the total offer). However, doctoral studies in these fields are often conducted in the framework of other study programmes such as political sciences, law, and economics.

4. A view from students and young professionals

ESPI also conducted a survey targeting students and young professionals who have personal experience and insight into space-related education in Europe. The objective was to better understand their perceptions on the challenges and opportunities related to the European space-related educational landscape as well as the bridge between education and employment in the space sector. After review, the final sample included 284 individual qualified responses.

Students studying space-related programmes who are not yet employed in the space sector

DOI: 10.5821/conference-9788419184405.023

represent 57% of the sample, whereas young professionals with different employment situations and educational backgrounds represent the remaining 43% of the survey sample.

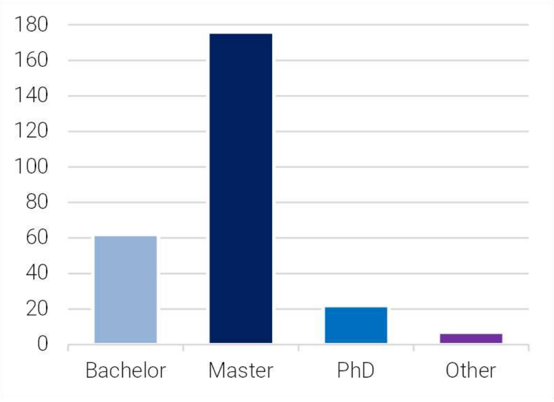

Figure 5. Respondents' level of degree [6]

The respondents' levels of degree mirror the level of degree programmes available in Europe, as highlighted in the Space Education Landscape. In particular, the significant number of master-level respondents confirms that space education is indeed a specialised field of education that prepares students for employment in the space sector. 23% of survey respondents are pursuing or hold bachelor level degrees, 8% constitute PhD level respondents, and 3% of respondents study or studied space in the context of a different type of programme, such as post-graduate diploma programmes and certificates, among others.

The sample also contains respondents who have completed their studies and entered the workforce, including respondents who are actively working in the space sector, a percentage of whom are working in the space sector, but did not complete a fully space-related degree programme.

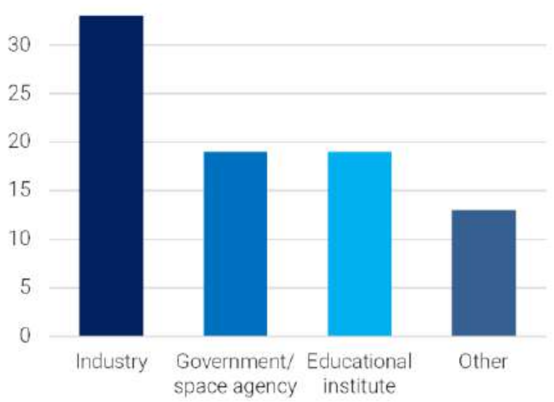

Figure 6. Young professional respondents' employers [7]

39% of the respondents currently employed in the space sector are working in industry, 22% in government or space agencies, as well as in educational institutes or universities, 6% in think tanks, and 9% in other organisations, such as NGOs, non-profit entities, and start-ups, among others. The majority of respondents who are currently working in industry studied a space-related programme in the aerospace engineering field. Additionally, almost all respondents employed in the space sector hold master-level degrees or higher.

Respondents confirmed that most space-related programmes offered international options, such as Erasmus, international training, international competitions, and international exchanges. The high number of international opportunities for students is not unique to the space sector and stems from the increasing internationalisation of the European higher education landscape as a whole. The same is true for internships as many university programmes promote their students' participation in internship activities, especially in the aerospace engineering and multidisciplinary areas, within the space sector as well as in other sectors. However, despite this general trend, the spread of these opportunities confirms the international dimension of the space sector.

Moreover, 53% of the respondents reported that their study programmes are taught in English. 52% of the English language programmes are hosted by English-speaking countries. Most programmes taught in English outside of the UK and Ireland are masters and PhDs, while the majority of bachelor programmes are taught in the country's domestic language. Additionally, 27% of programmes are taught in multiple languages and usually combine instruction in English and the domestic language.

Despite students partaking in a multitude of international activities within their programmes, the majority of survey respondents are studying or studied in their home country.

Students were also asked about their expectations regarding the transition to the professional environment. Although the space sector is growing, students seem to perceive a lack of opportunities in the sector. Therefore, the space education sector needs to work on issues like disinformation and lack of advertisement, which may contribute to shape students' perception. Additionally, students who did not study an explicitly space-related programme find the transition to the professional space sector difficult. 65% indicated that they think it will be difficult to find

DOI: 10.5821/conference-9788419184405.023

a job in the space sector and 8% think they will not find a job in the space sector. Only three respondents will search for a job in a different sector.

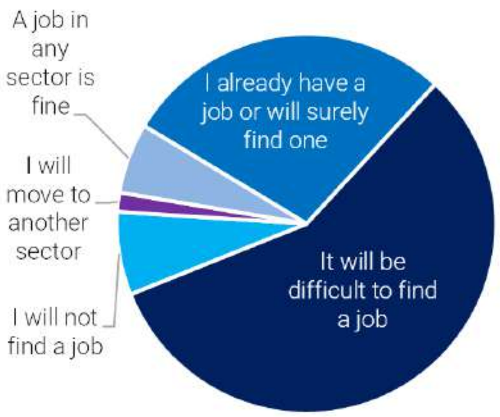

Figure 7. Students' perceptions of job prospects in the space sector [8]

Finally, students and young professionals working in the space sector specified their long-term career goals. Less than 1% of respondents indicated that they want to move to another sector, with over 99% preferring to work in the space sector in some capacity.

5. Conclusions

Through this study, ESPI provides evidence of a well-established, broad, and diverse space education landscape in Europe which is nested in national educational landscapes but has also a strong European dimension. Space education is poised to continue to play a major role in shaping the future European space sector and contributing to address upcoming sectorial developments. Additional efforts from governmental and institutional actors to raise the place of education in the space policy agenda and to support the evolution of the European space education system in close relation with the transformation of the space sector would be welcome.

Indeed, the main challenge for the European space education system is to continuously adapt to the needs of the sector. In a context of transformation of the space sector at various levels, this challenge is particularly high. Despite the emergence of new educational programmes across Europe, various areas of development will require a sustained effort to ensure that the education system can actively contribute to address the challenges ahead of the European space sector.

Technological developments in the space sector are increasingly shaped by other emerging fields such as artificial intelligence, machine learning, additive manufacturing, blockchain, or quantum. The interconnection between the space sector and other domains increases the need to train multidisciplinary profiles able to strengthen synergies between different fields and areas of application. The growing relationship between space and other areas also concerns fields such as policy, business, and law. The integration of new competences in space study programmes as well as in extracurricular activities, which are also valuable tools of education, is increasingly required.

These needs are not limited to higher education but also concern professional training programmes that are increasingly required to prepare the workforce to address emerging trends and to attract new professional profiles to the space sector.

Acknowledgements

ESPI would like to express gratitude to the experts and officials who were interviewed for this report and who provided their insightful perspectives. Those comprise Hugo Marée (ESA Education Office), Natacha Callens (ESA Academy), Luisa Santoro (ASI), Michaela Gitsch (FFG), Volker Kratzenberg-Annies (DLR). This paper is part of a broader project conducted in the area of space education. The full report can be downloaded at this link: https://espi.or.at/news/espi-report-81-space-education-in-europe.

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Experiences in Firmware Development for a CubeSat Instrument Payload

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Abstract
Recent advancements in gamma-ray detector technology have brought new opportunities to study gamma-ray bursts and other high-energy phenomena. However, there is a lack of dissemination on the development methods, tools and techniques used in the production of instrument flight firmware. This is understandable as firmware for spacecraft payloads may be proprietary or exceptionally hardware specific and so is not always published. However, this leaves a gap in the knowledge for CubeSat teams, especially those consisting of university students who may be building a custom spacecraft payload with limited initial experience. The Gamma-Ray Module (GMOD) on-board EIRSAT-1, a 2U CubeSat in the 2nd European Space Agency Fly Your Satellite! programme, is one such instrument. GMOD features a 25x25x40mm Scionix CeBr3 scintillator, coupled to an array of 16 (4x4) JSeries OnSemiconductor MicroFJ-60035-TSV silicon photomultipliers (SiPMs) with readout provided by the SIPHRA IDE3380 application specific integrated circuit. The instrument is supported by the Gamma-Ray Module motherboard which controls and configures the instrument, providing regulated voltage and current sources as well as generating time tagged event packets and a temporary on-board flash storage. At the core of this system is the Texas Instruments MSP430FR5994 microcontroller. A custom firmware was produced for the instrument by the EIRSAT-1 team over numerous cycles of testing and development to reliably perform the long duration tasks of readout, storage and transfer of time tagged event data to the EIRSAT-1 on-board computer. Recognising the value of sharing our experiences and pitfalls on firmware development with the wider CubeSat community, this paper will provide an introduction to GMOD, with focus primarily on the development approach of the firmware. The development, testing, version control, essential tools and an overview of how the resources provided by the device manufacturer were used will be examined, such that the lessons learned may be extended to other payloads from student-led missions.

Keywords
EIRSAT-1, GMOD, FYS!, Gamma-Ray Detector, Firmware, Software, MSP430

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1. Introduction

The simultaneous detection of the gravitational wave (GW) GW170817 [1], and its coincident electromagnetic counterpart GRB170817A [2] has resulted in a new era of gravitational and gamma-ray burst (GRB) astronomy. However, this comes at a time when the main GRB detecting flagship missions are operating close to and beyond their intended operational lifetime [3]. One method for enhanced capabilities is the use of CubeSats, which can be developed for relatively low cost, on short timescales, with reduced risk and technology acceptance levels. This provides opportunities for industry and university teams to develop and test hardware, to progress the maturation of novel technology and contribute to the scientific community.

The Gamma-Ray Module (GMOD) is a <1U, gamma-ray detecting instrument which has been developed based on a heritage of tests (e.g. [4] and references therein). GMOD is the primary science payload on the 2U CubeSat EIRSAT-1 (Educational Irish Research Satellite) [5], a participant of the 2nd European Space Agency (ESA) Fly Your Satellite! (FYS!) programme, consisting of three scientific payloads, custom software and off-the-shelf hardware.

From our experience, there is a lack of dissemination of firmware development methods for payloads, on large missions and CubeSats. This is understandable as there may be legal issues surrounding publication of software for proprietary hardware, or simply that the firmware solutions are seen as too specific to the mission. However, this leads to a gap in the literature and a paucity of references on common techniques when it comes to firmware development and testing. To encourage further sharing of knowledge in this area we present an overview of GMOD (§2), our firmware development approach (§3), the tools used (§4), as well as an overview of some pitfalls and lessons learned (§5) throughout its development.

2. The Gamma-Ray Module

GMOD [6] consists of a 25x25x40mm Scionix CeBr3 scintillator coupled to a 4x4 tiled array of 16 OnSemiconductor MicroFJ-60035 silicon photomultipliers (SiPMs) readout using the SIPHRA application specific integrated circuit (ASIC). GMOD is a novel instrument primarily developed to study GRB events in the GW era while also demonstrating the use of SiPMs in earth orbit and their role in future missions.

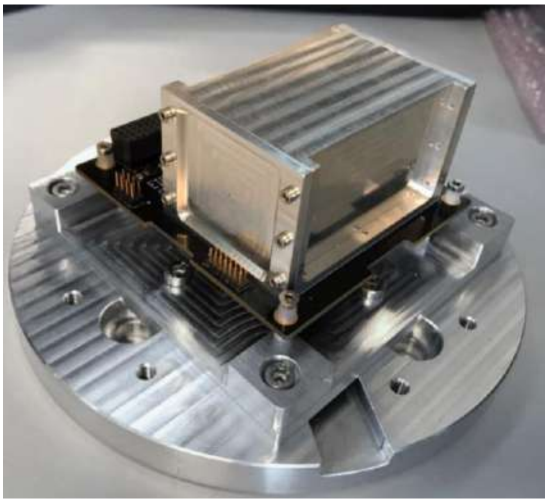

Figure 1. GMOD, the Gamma-Ray Module, the primary experiment payload on EIRSAT-1 mounted on an aluminium test fixture (lower)

The GMOD motherboard is a readout and control system responsible for carrying out the operation-critical duties of the instrument. This is accomplished using a custom firmware [7] developed in C/C++ for the Texas Instruments (TI) MSP430FR5994 16MHz microcontroller. The firmware requirements include:

- Readout of the detector assembly.
- Generation of time tagged event (TTE) data from the detector readout.
- Processing and temporary on-board storage of TTEs in 128MBit flash.
- Constant current supply (ASIC) and bias voltage generation (SiPMs).
- Transmission of TTE data to the EIRSAT-1 on-board computer (OBC).
- Configuration of the instrument.

3. Firmware Development Approach

This development cycle, as demonstrated in Figure 2, begins with an assessment of the requirements followed by implementation and testing on a subsystem level. If satisfactory, testing is then done with the OBC in the loop. If either test fails, the firmware is revised and retested. This approach was selected as it provides a structured approach to development and testing from the perspective of the OBC, payload and the interface between them.

3.1. Firmware Requirements

It is necessary to order the production of firmware in a structured fashion. Typically instrument firmware would be framed around the requirements set out in the preliminary design review (PDR) and critical design review (CDR) products. These are developed as part of phases B/C of the typical project lifecycle and encompass the design specification of the

DOI: 10.5821/conference-9788419184405.024

spacecraft and its payloads. For ESA FYS! the project structure closely adheres to the ECSS standards set out in ECSS-M-ST-10C as the “Design Your Satellite” phase, which include producing the design definition file (DDF) and design justification file (DJF) documents. These documents form the bedrock of firmware development for the payload and are the fundamental starting point and reference when developing any new functionality.

3.2. Outputs From Testing

Throughout the design and qualification stage of the life cycle, the spacecraft and payloads undergo numerous tests. Environmental testing may be conducted on the subsystem [4] and system level [8], which may also require pre-campaign functional and mission tests [9]. All of these tests can be used to inform additions or amendments to the existing functionality, providing feedback not found within the scope of the basic payload firmware requirements. Furthermore, these tests should be used as key milestones along the path of development. Certain functionality will be required at these milestones (ie. pre/post vibration functional tests), thus the build up to these tests can be used to assign priority and pacing to certain blocks of functionality. It is important to ensure that priority is maintained and the appropriate time is allocated where needed. As in Figure 2, requirements, documentation and testing all feed into development of new functionality, with some being introduced as outputs from test campaigns throughout the project life cycle.

3.3. Introducing Functionality

Payload requirements are initially distilled into individual deliverables during a review of the documentation or through team meetings post testing. In some cases, these deliverables may be so low level that they do not appear in the design documents. Interface documents (between the OBC and payload) can then be produced which outline the operations and form of communications. For instance, an interface document may describe the command structure to activate certain functionality on the payload. In more intricate situations, an interface document may explicitly outline how this functionality is expected to behave if that operation impacts the interface.

For example, on GMOD, a “Function List” exists with all commands, descriptions of their operation, the size of data expected to be received and transmitted and any fail scenarios listed.

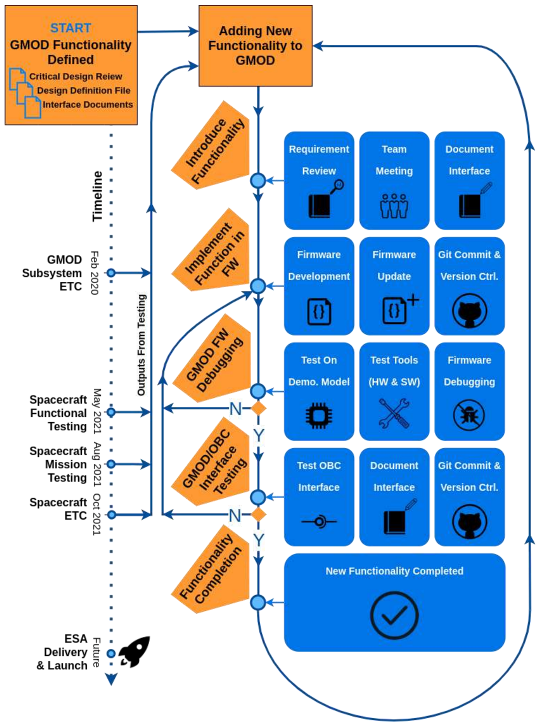

Figure 2. Process flow diagram describing the addition and development of new functionality

Similarly, in the case of complex operations like the serving of full channel TTE data from GMOD to the OBC, a more detailed overview of how the functionality should be implemented was produced. We have found in our experience that it is sufficient to produce these documents as required, without firm document control, but that the final iteration would be appropriately documented for OBC interfacing.

3.4. Implementing Functionality

This functionality is then implemented in C/C++ using the *Code Composer Studio* (CCS)[1] integrated development environment (IDE) provided by TI. An important part of this development is version control. This is performed using the Git version control tool. Upon completion of the new functionality, committing and pushing to the Git remote, the firmware is then tested.

3.5. Firmware Debugging

Before testing new functionality with the OBC, it is tested and debugged separately on a test setup (as shown in Figure 3) replicating the OBC interface to confirm all functional requirements are met. This is done using ground support equipment (GSE), some having been developed and used during the EIRSAT-1 environmental test campaigns (ETCs). Additionally, it is possible to drill

[1] https://www.ti.com/tool/CCSTUDIO

DOI: 10.5821/conference-9788419184405.024

further into the firmware operation mid-execution using the CCS IDE debugging capabilities, which offer numerous breakpoint, timing and variable reporting tools. If a bug is found or the functionality does not behave as expected the firmware is revised (from §3.3) with edits to the firmware code, as seen in Figure 2.

When testing is complete, a binary file is generated after compilation, which is renamed with the version ID and timestamp of creation. The version ID code records *major, minor* and *patch* updates in a two byte ID as in Table 1:

Table 1. The version ID convention adopted for the GMOD firmware development

Versions	**Major** 4 bits (0-15)	**Minor** 8 bits (0-255)	**Patch** 4 bits (0-15)
DM	0	-	-
EQM	0x1	0x00 - 0xFF	0x0 - 0xF
FM	0x2	0x00 - 0xFF	0x0 - 0xF

The version ID is also hardcoded into the firmware and is accessible over I2C. A *major* increment indicates the firmware model. A *minor* increment may be any change judged to be larger than a patch. A *patch* update could be something as small as a bug fix or comment correction (a rollover of the patch increment from 0xF to 0x0 implies a minor increment has occurred). For example, V1.2.3 is encoded as two bytes as 0x1023. When completed the firmware is tagged on Git using its version ID for later reference.

3.6. GMOD/OBC Interface Testing

Once there is confidence in the newly developed firmware the interface between the OBC and GMOD is tested. The binary file is reformatted into serial bootloader commands used by the OBC to program GMOD. The OBC can then command and control GMOD using the *Mission Control Software* (MCS), provided by *Bright Ascension*. Throughout these tests the general operation of the new functionality can be confirmed for both OBC and GMOD while any deviations or changes to the interface can be discussed in a post test context. Any deviations from the original interface can be agreed and amended by revision of functionality (from §3.3). Once satisfied, the new functionality is considered complete and the cycle begins anew, as in Figure 2. For instance, development of GMOD's demonstration model firmware was produced in a closed loop without input from the OBC software team. This was acceptable for this iteration, as it was intended to simply demonstrate the instrument operation as a standalone system. However future iterations have strict interfacing between the OBC and GMOD and require close collaboration with the OBC software team. The EQM version was redeveloped from the ground up using this flow.

4. Development Tools and Resources

It's not possible to describe a universal configuration for testing firmware applicable to all. However, many of the tools used with GMOD are generic, off the shelf and for the most part relatively accessible. Similarly, while other payloads use different hardware and may be locked into a given device manufacturer's documentation, compilers and drivers, many reputable manufacturers share the same level of high quality in these areas. For this reason, we describe the development and test tools used, such that other teams might find similar services provided by their chosen device manufacturer.

4.1. MSP-EXP430FR5994 Launchpad

Development kits are intended to provide a starting point for unfamiliar audiences. These kits allow the users to develop skills when working with embedded devices as well as in understanding the fundamentals of the device and its peripherals. For instance, TI produces the *MSP-EXP430FR5994 LaunchPad,* with similar kits for their range of products. These are invaluable tools to begin firmware development by exploring the limits and potential quirks of the chosen device while also allowing the user to evaluate its suitability, potential design ideas and capabilities before incorporating them into their application. By far its most useful application is its ability to act as a programmer for any MSP430 device with accessible SBW pins. The LaunchPad PCB consists of two blocks: the MSP430 target and the eZ-FET debug probe. The eZ-FET, which is connected to the target device via jumper pins, can be broken out from the LaunchPad and connected to any MSP430FR5994 device. This provides access to TI's debugging tools in CCS, TI's *EnergyTrace* capabilities (for live power management analysis) and a low-cost programmer, which as compared to a generic flashing device would normally be priced up to €200 per unit. The LaunchPad can be seen in Figure 3.

DOI: 10.5821/conference-9788419184405.024

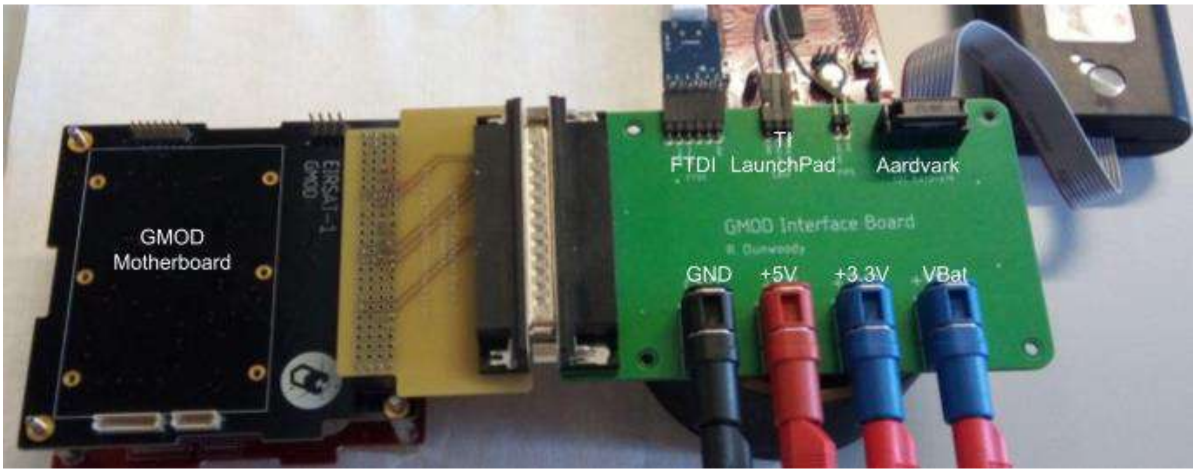

Figure 3. The hardware setup used to test GMOD firmware, including the motherboard, interface board, Total Phase Aardvark, MSP-EXP430FR5994 LaunchPad and FTDI LC234X UART module

4.2. TI's Code Composer Studio

Code Composer Studio is an Eclipse based IDE which supports TI's MSP430 devices. As such, CCS allows the creation of project profiles which can be integrated with Git, a source code editor, compilation and even register and memory browsing on active debugging code along with all the other general debugging operations. Furthermore, given that CCS is built upon the Eclipse open framework, there is no licence fee to access or develop using CCS, a quality which is especially advantageous for university teams.

4.3. TI's MSP430 Driverlib

Depending on the application, a choice can be made on how the firmware developer interacts with the device peripherals in C/C++. For the MSP430 there is the option for direct register level interaction (the developer directly sets/resets bits in the device/peripheral control registers) or indirect interaction where the developer may use a set of abstracted libraries developed by TI called *Driverlib*. This is very useful for several reasons as it allows almost immediate access to the device peripherals without in-depth knowledge of the MSP430, but also may be used as a reference when looking for an example implementation.

4.4. TI Documentation and Examples

Developing for hardware of course requires reference to device documentation. This is a must for successful development of any application. TI have compiled a comprehensive user manual and data sheet for the MSP430FR5994 while also providing application reports describing best practice and the use of the device peripherals. TI provides a number of example scripts in the TI *Resource Explorer*, describing in detail how to operate the device and the internal peripherals for both register level and Driverlib applications.

4.5. Ground Support Equipment

Testing of firmware requires simulation of the intended interface between the payload and the spacecraft. A GMOD interface board was built to break out the PC/104 header for the ETC. GMODs primary channels of communication are through I2C (command and control) and 128k baud asynchronous serial (science data). To allow control of GMOD in the absence of the OBC, a *Total Phase Aardvark I2C/SPI Adapter* is used to interface with GMOD using Python scripts. Readout of science data over serial can be achieved using any generic USB to serial interface, in the case of GMOD an *FTDI LC234X* UART module was selected. To emulate the role of the OBC and MCS during testing, a Python Jupyter Notebook was developed which provides access to the GMOD command set. Both the Total Phase Aardvark and FTDI LC234X modules can be seen in Figure 3.

5. Discussion and Lessons Learned

5.1. Structure is Essential

As mentioned in §3.1, firmware development needs structure, primarily based around the requirements of the payload, but also in terms of the scheduling of deliverables and priority assigned to functional blocks as described in §3.2. This structure is informed by the existing documentation from mission planning, testing and design.

5.2. Know When Enough is Enough

In §3.2, a reference is made to time allocation regarding firmware development. There are

DOI: 10.5821/conference-9788419184405.024

diminishing returns when fixating on the implementation of functionality, particularly when it comes to the impact on schedules. Typically if firmware works as expected, satisfies the requirement criteria and has been tested - little can be gained by further modification.

5.3. Balancing Schedules

As a student team consisting mostly of PhD and masters students, working on a demanding project such as CubeSat development means maintaining a balance between academic work and work related to EIRSAT-1. This is not at all straightforward and the amount of time required to be dedicated to the project should not be underestimated.

5.4. Testing Firmware

There is no "one size fits all" when it comes to firmware/hardware testing. However, from our experience, we have found it is important during testing to introduce a level of "randomness" as expected during actual operation, to better stress the firmware. For one example, externally triggering GMOD with periodic pulses does not test the robustness of the firmware in the same way as triggering randomly in time, which better simulates realistic detections and strains detector readout, access to flash and transmission of data to the OBC.

Another aspect is unit testing firmware. Typically firmware developed for embedded systems is not usually unit tested. This is often due to the belief that it is impossible or impractical due to hardware specifics, or simply because it is acceptable on embedded systems for there to be no defined boundary between pure software and hardware/register manipulation. However, unit testing during development on embedded systems is possible. Test driven development (TDD) has a number of benefits, including reduced time spent debugging, confidence in the final product, continued confidence after modification of the firmware and well-structured code, which stands as objectively reliable. While unit test development is underway with the GMOD firmware, it would have been advisable, and saved time, to have begun test driven development from the start.

6. Conclusion

This paper presents the payload firmware development approach of a student-led CubeSat team. The importance of a structured development cycle, availing of manufacturer resources, balancing PhD and project related work as well as adequate stress testing of the firmware have all been highlighted. In conclusion, there is no single way to develop payload firmware, however it is hoped this may offer some advice and a starting point to other teams to begin their own payload firmware development.

7. Acknowledgements

EIRSAT-1 is carried out with the support of ESA's Education Office under the Fly Your Satellite! 2 programme. This study was supported by The ESA's Science Programme under contract 4000104771/11/NL/CBi. JM and SMB acknowledge support from Science Foundation Ireland (SFI) under grant number 17/CDA/4723. We acknowledge all students who have contributed to EIRSAT-1.

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Educational activities with Arduino to learn about astronomy

Federico Di Giacomo[1], *Maura Sandri*[2]

Abstract

There is a need to promote better science, technology, and mathematics (STEM) education at all school levels. Arduino makes it possible by creating the next generation of STEAM programs that empower students on their learning journey through middle school, high school, and university. These kinds of technologies make it possible to make abstract concepts concrete and manipulable, far from the experience of children and young people, increasing the possibilities of learning. Following the constructionist ideas and practices, the National Institute for Astrophysics has developed *play.inaf.it*, a web platform that collects various coding, educational robotics, making, and tinkering activities, using astronomy and astrophysics as a tool to develop computational thinking and all the skills that are typical of scientific research in the STEM field.

In this paper we want to present two projects created by the Play group. The first one aims to create, using an Arduino board, one LED and a photoresistor, an exhibit capable to describe one of the methods most used to identify exoplanets: the transit method, which exploits the fact that the brightness of a star decreases when the planet passes in front of it, with respect to our line of sight. Thanks to this project it is possible both to know Arduino and understand the information that astronomers can obtain from so-called light curves, such as the orbital period, the size of the planet, etc. The second activity aims to create and turn on one or more constellations using Arduino and some LEDs. In this way it will be possible to describe - through an active, cooperative, and operational approach - what are the stars, the constellations and the close relationship that has linked man to the sky since the dawn of time.

Thanks to Arduino it is possible to encourage creativity, allowing everyone to give shape and substance to their ideas because the only limit we can set is our imagination.

Keywords

Arduino, Astronomy, Coding

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1. Introduction

Today we are facing an extremely fast and constantly evolving technological evolution. In this context, the development of new digital skills is essential. For this reason, it is necessary to find new strategies and didactical tools that allow to provide those skills related to logical and critical thinking and communication skills.

Boys and girls know how to use computers and mobile devices quite effectively, but most of them have only a little experience and understanding of how a computer works and the general principles of how electronic devices work. Furthermore, in a rapidly changing era, it is important that they develop skills and practices that involve innovative technologies. Therefore, the need to promote understanding on these topics, which fall under the broader term STEM (Science, Technology, Engineering and Mathematics), is essential [1]. Hardware platforms, such as Arduino, and educational robotics make this possible by creating the next generation of STEAM programs that accompany students on their learning journey from elementary school to university. Technologies such as these represent a unique educational tool that provides hands-on teaching activities to create attractive learning environments that satisfy students' scientific curiosity.

Following the constructionist ideas and practices of J. Piaget, who claimed that the learning process is an energetic process of building knowledge, and S. Papert [2], who considers robotic technologies as "objects to think" stating that the acquisition of new knowledge is most effective when students are engaged in building products that have personal meaning for them, the National Institute of Astrophysics has developed Play INAF, a web platform that brings together different codes, educational robotics, manufacturing, and tinkering activities using astronomy and astrophysics as a tool to develop computational thinking and all the typical skills of scientific research in the STEM field.

In this paper we describe two projects, made with the Arduino board, and show how this hardware can provide a great contribution to the dissemination of astronomical knowledge.

2. *Play.inaf* platform

Following the constructionist ideas and practices of Papert and Piaget, the National Institute of Astrophysics has developed *Play.inaf* (Fig. 1). It is a web platform, which collects various coding, educational robotics, making and tinkering activities, which use astronomy and astrophysics as a tool to develop computational thinking and all the typical skills of scientific research in the STEM field. Computational thinking and research activity are inseparable, and it is essential that children develop this ability from an early age, to face all the challenges that will arise in life. It is for this reason, for its importance and for its link with research, that the National Institute of Astrophysics has decided to engage in the development of resources capable of helping children to develop computational thinking in accordance with its research field and with what is his third mission.

Figure 1. The home page of the Play INAF web platform.

3. The Arduino board

Microcontrollers, like Arduino are very popular in STEM education.

Arduino is an open-source electronics platform based on easy-to-use hardware and software. Arduino boards can read inputs, like a light on a sensor or a finger on a button, or a Twitter message, and turn it into an output, activating a motor, turning on an LED, publishing something online.

All the inputs are processed by the code that is loaded onto the board and suitable outputs are produced. The code is mainly developed in a C-like programming language using the Arduino IDE, an open-source environment that helps users write code and load it onto the board. Arduino's advantages range from being economical, to being multi-platform, to being extensible with additional shielding, i.e., electronic boards that implement specialized operations such as WIFI communication.

4. The two activities

In this section we will describe the two activities carried out thanks to the Arduino board and which have been published on the Play INAF web platform.

4.1 How to detect an extrasolar planet with the transit method

This first activity, designed for high school students, aims to create, using an Arduino board, one LED and a photoresistor, an exhibit capable to describe one of the methods most used to identify exoplanets, the transit method.

In the last year, almost 4000 extrasolar planets have been discovered, and their number is constantly increasing. Most extrasolar planets were discovered through the method of transits; each time a planet is placed in the same direction of view as the observer, and passes in front of its star, it causes a periodic decrease, equal to the intensity of the brightness of the latter. Through ground or space telescopes, a periodic variation of the star's brightness can be detected, whose periodicity is equal to the rotation period of the exoplanet. If we project the change in the brightness of the star on a graph, we will see a regular increase and decrease in the star's light caused by the transit of the planet. By studying the frequency of the curve of light, the astronomers obtain information on the period of revolution of the planet.

To build a planetary transit simulator, students use two Arduino boards. With the first one, and thanks to a stepper motor, they can realize the model of the planetary system. The stepper motor is an electric synchronous motor very precise, quick, and easy to control through an electronic card, called driver. To modify the rotation speed of the planetary system, we will use a potentiometer, whereas to change the direction of rotation we will use a button.

With the second Arduino board instead, the students can realize the sensor to detect the variation of the luminosity. The variation of the luminosity is detected by photoresistor connected to the Arduino board (Fig. 2) Furthermore, just as happens in telescopes and other research tools, all data will be recorded on an external memory, in particular all time and brightness variation data will be loaded on a microSD card. This will allow us to study the data also later by means of other software such as Excel, Mathlab, etc.

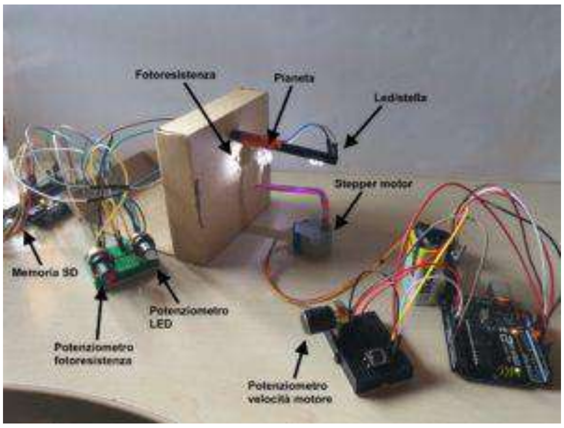

Figure 2. Photo of the circuit realized to describe the transit method. In this image you can see the two Arduino board and all the elements of the circuit.

Finally varying a few parameters – as for example the rotation speed, the dimensions of the planet, the distance of the planet from the star – the students can see how the relative curves of light change and how the astronomers can study the characteristics of the extrasolar planets (Fig. 3).

DOI: 10.5821/conference-9788419184405.025

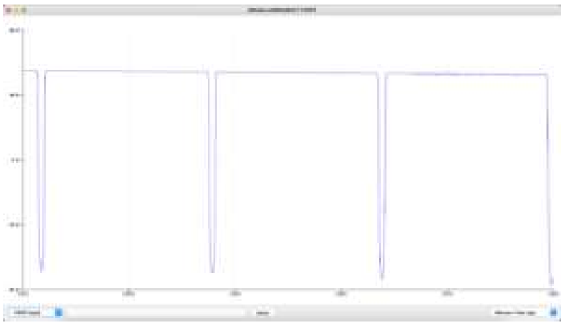

Figure 3. Example of a light curve obtained thanks the Arduino board.

On the Play INAF web platform, you can find all the details, the electronic scheme, the code, and many other information about this project.

4.2 Light up the constellation

The second activity aims to create and turn on one or more constellations using Arduino and some LEDs. In this way it will be possible to describe, through an active, cooperative, and operational approach, what are the stars, the constellations and the close relationship that has linked man to the sky since the dawn of time.

First, the students have to choose the constellation that they would like to represent. After that, they should carefully measure, with a ruler, the apparent distance between the various stars which compose it, and their position, so they can precisely reproduce the constellation you have chosen. At this point, the students place on the breadboard the various LEDs (which represent the stars of the constellation), taking care of placing them in the right position and at the right distance from each other. To make this easier, you can print the map of the constellation, in the scale you prefer, so that you already have the right organization of stars. To correctly represent the colors of the stars, you can use LEDs of different color. The colors of a star depend on the temperature of its photosphere. If the star is very warm, it will appear white, if it is colder, it will be yellow orange, if it is even colder than that, it will be red. Once they have arranged all hardware connections, we can pass on to programming the board. In this way, after uploading the software, they can see the constellation that they have realized light up (Fig. 4).

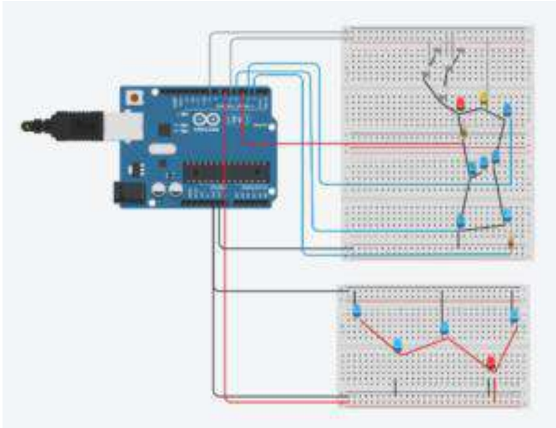

Figure 4. Example of the circuit with the Orion e Andromeda constellation

5. Discussion

Due the pandemic, these activities were presented for only in a virtual mode during the *European Code Week 2021*. Both projects are described in detail, with all the instructions for creating the circuit and writing the code on the Play INAF web platform.

The constellation project turns out to be very simple both in the construction of the circuit and in the writing of the code. For this reason, it can represent the first step to start making simple projects with Arduino. In fact, given its simplicity, this activity has been tested, with great success, with about 80 middle school students who, using coding, discovered what constellations are and the importance. However, having developed this activity during the lockdown period due to the COVID - 19 pandemic, this activity was carried out in virtual mode and both the code, and the circuit were developed using thinkercad. Despite this, all the students managed to create their own constellation by discovering the beauty of the sky that surrounds us.

Finally, both activities were presented, for the first time, to various schools in two webinars during the European Code Week 2021.

6. Conclusions

Education in the scientific method in school is often limited to the reproduction of historically relevant experiments, according to a logic that makes the transmission of consolidated knowledge prevail over their (re)construction by the subjects who have to learn them. This logic can be overturned by adopting a constructionist perspective for which learning is the result of a relationship between ideas and the construction of objects related to them, on the one hand, and the comparison and sharing of ideas and objects, on the one hand. other side. In this perspective, the use of platforms such as Arduino represents an element of novelty as it allows to create the conditions for carrying out experimental laboratory activities in which the aspects of invention (personal contribution) and reproduction (the reconstruction of accumulated knowledge) are in the right balance. In addition, the theoretical richness inherent in coding is also reflected in the methodological choices, first of all the laboratory setting, typical of a constructivist learning environment that uses new technologies such as mindtools, tools with which students build knowledge. Coding and robotics allow you to develop computational thinking, which is configured as a fourth skill after reading, writing and arithmetic. Also with the right tool, even very young children can get closer to programming. Coding offers the possibility to learn computational thinking in a fun and engaging way, suitable for school-age boys and girls, because learning takes place in the interaction with a 'real' object and in this sense, Arduino offers an excellent tool for developing all these skills

These activities and the others present on Play INAF offer the opportunity to learn computational thinking in a fun and engaging way, suitable for school-age boys and girls because learning takes place in the interaction with a 'real' object and in this sense, Arduino offers a great tool to develop all these skills. These projects were realized with Arduino, a platform with which it is possible to stimulate creativity, allowing everyone to give shape and substance to their ideas because the only limit we can set is our imagination.

Acknowledgements

I would like to thank Maura Sandri and Sara Ricciardi for the opportunity and for all the help and support.

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Design and calibration process of solar sensors for small satellite missions

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Abstract

In combination with magnetometers, solar sensors are one of the most used instruments for determining the attitude of small satellites. These devices use the photoelectric effect to produce an electrical current. This electrical current, or the voltage associated with the electrical circuit of the solar sensor, is measured in order to compute the angle of incident of the sun with the normal direction of the sensor. Then, together with the computed angles of other solar sensors on different faces of the satellite, the sun's direction in relation to a spacecraft can be calculated. Solar sensors are simple devices whose low-cost design based on photodiodes can be developed by students. During the design and fabrication process of a solar sensor, one of the most important tasks is the accurate estimation of the sensor response in the space radiative environment. It is possible to simulate the Sun's radiation spectrum, but the equipment and facilities needed are costly for a university project. In this paper, the design and calibration process of satellite solar sensors carried out together by students and teachers from the Master's degree in Space Systems (MUSE) from the *Universidad Politécnica de Madrid* is described. The process uses a calibration method that calibrates the photodiodes for space use without simulating the Sun's radiation spectrum in the laboratory.

Keywords

ADCS, UPMsat-2, master in space systems, photodiodes, solar sensors

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Nomenclature

α	*sun incidence angle*
λ	*Wavelength*
Φ_{eff}	*Effective radiant flux*
$V(\lambda)$	*Luxmeter spectral sensitivity*
κ	*Boltzmann's constant*
A_s	*Photodiode area*
a	*Ideality factor*
C_v	*Luxmeter constant*
E_λ	*Spectral irradiance*
$\hat{E}_\lambda$	*Normalized spectral irradiance*
I	*Current*
I_0	*Reverse saturation current*
I_{pv}	*Photovoltaic current*
M	*Linear fitting slope*
n	*Linear fitting offset*
K	*Irradiance magnitude*
P	*Conversion efficiency factor*
q	*Electron charge*
R_L	*Resistor*
R_s	*Series resistor*
R_{sh}	*Shunt resistor*
$\hat{S}_\lambda$	*Normalized sensitivity function*
T	*Temperature*
V	*Voltage*
V_T	*Thermal voltage*

Acronyms/Abbreviations

COTS	*Commercial off-the-shelf*
IDR/UPM	*Instituto Universitario de Microgravedad Ignacio Da Riva*
LEO	*Low Earth Orbit*
MUSE	*Master on Space Systems at UPM*
UPM	*Univesidad Politécnica de Madrid*

1. Introduction

The Master on Space Systems (*Máster Universitario en Sistemas Espaciales* - MUSE) at *Universidad Politécnica de Madrid* (UPM) is project-based learning oriented [1], as it is characterized by a significant amount of practical work by the students, directly linked to *Instituto Universitario de Microgravedad "Ignacio Da Riva*" (IDR/UPM) running space projects. This master's degree is designed to reduce as much as possible the initial training required by graduates once enrolled in a space engineering company. One of the most recent and successful examples of this philosophy is the UPMSat-2 [2].

The UPMSat-2 is a 50 kg microsatellite designed, developed, and tested at the IDR/UPM, that was launched in the VV16 VEGA mission in September 2020. This project transmitted a great impetus to MUSE involving several promotions of students in the design and validation of different subsystems of this spacecraft [3,4]. Moreover, the development of UPMSat-2 has also allowed students to participate in different research projects, as it proves the different works published in the main lines of research of the institute as Attitude Determination and Control Subsystems, thermal control subsystems, structural analysis, spacecraft power subsystems and spacecraft instrumentation, which is the topic of this work.

Sun sensors are instruments responsive to a light source. With the information provided with these sensors, the relative orientation of the satellite in relation to the Sun is calculated. Given the simplicity, low cost, and low weight of these sensors, it is easy to understand why they are widely used, in combination with magnetometers, in small spacecraft for attitude determination [5,6].

In the present work, a simple way to test, calibrate, and operate a solar sensor based on COTS components is described. The selection and placement of the photodiodes plays an important role in the performance of the system, but if an accurate measure of the Sun vector is desired, it is necessary to calibrate each one of the photodiodes to characterize their specific response curve. This process, in appearance easy, can become complicated, especially if specialized equipment is missing. Both students and professors of MUSE faced this problem of characterizing the expected response of the photodiodes in space. The solar spectrum reaching Earth (AM 1.5) is not the same as the one received in space (AM0). Most of the photodiode calibration techniques found in the literature [7–9] are based on the simulation of the AM0 spectrum, but this requires specific instrumentation, which is usually costly for a university project. Fortunately, it is possible to characterize the in-flight performance of the photodiode if the photodiode is tested with a source of light whose spectrum is known. In this work, a simple process to calibrate photodiodes without requiring any specialized instrumentation is described.

2. Sun sensor electrical design

The Sun sensor developed for the UPMSat-2 consists of a total of six OSRAM BPX61 photodiodes [10], each facing one of the main positive and negative axes (±*X*, ±*Y*, ±*Z*) of the satellite. The photodiodes are connected to a 5 V power line from the power distribution unit and a resistance R_L (see Figure 1.A). The voltage drop across the resistance is recorded by the computer. Each photodiode voltage is compared to the maximum expected response of the photodiode, and the sun direction is derived. Regarding the selection of *RL,* as it is desirable to work near the short-circuit point of the photodiode, where the behaviour is more linear, the value of R_L should be small (in this case, a 32 Ω resistor was selected).

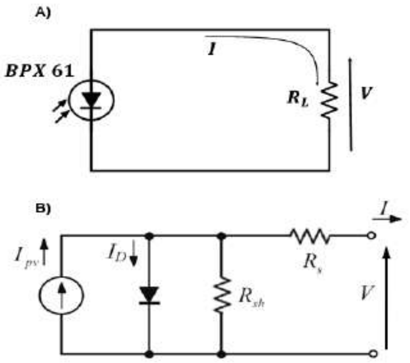


Figure 1. A) Sketch of the electric circuit to read the voltage response of the photodiodes. B) 1-Diode/2-resistor equivalent circuit model.

To select a correct value for the resistance and know its expected response in space, it is necessary to have a model that approximates the electrical behaviour of the photodiode. In this case, the equivalent circuit model of a 1 diode / 2 resistor (see Figure 1.B) is implicitly correlated with the output current with the photodiode voltage by the following equation:

$$I = I_{pv} - I_0\left[\exp\left(\frac{V+IR_s}{aV_T}\right)-1\right]-\frac{V+IR_s}{R_{sh}}, \quad (1)$$

where the thermal voltage, V_T, is defined as follows:

$$V_T = \frac{\kappa T}{q}. \quad (2)$$

The 1-Diode/2-resistor equivalent circuit described in Eq. (1) contains five parameters I_{pv}, I_0, *a*, R_{sh}, and R_s, that must be adjusted with the experimental data. Testing set-up and methodology

To fully characterize the photodiode response with the instrumentation available at an academic laboratory, two separate tests were performed. First, an illumination test was performed to measure the expected response of the photodiodes to the light they will receive in orbit. Second, an angular test was done to characterize the response of the photodiode when the angle between the normal of the sensor and the light source is changed.

2.1. Illumination test

The illumination test (see Figure 2) can be summarized as follows. The sensor is exposed to a light source with a known illuminance (red LED light for this case). The electrical circuit of Figure 1 is completed with a resistance. The output voltage and current shall be measured. Also, a luxmeter [11] placed near the photodiode is needed to measure the brightness of the light source.

Figure 2. Illumination test set-up.

Once the set-up is done, a correlation process is required to know the photodiode response to any source of light. The first step is to calculate the spectral irradiance that reaches the photodiode from the illuminance value given by the luxmeter. Eq. (3) provides the expression to calculate the illuminance provided by the luxmeter, as the photopic function is a normalized curve, a constant C_v = 683 lm/W is necessary to obtain the value in SI units.

$$E_v = C_v \int_\lambda V(\lambda) E_\lambda(\lambda)\mathrm{d}\lambda \quad (3)$$

$$E_\lambda(\lambda) = K\,\hat{E}_\lambda(\lambda) \quad (4)$$

Taking into account that the spectral irradiance can be expressed as the product of the normalized irradiance with a constant denoting its magnitude (Eq.4), the constant can be calculated as follows:

$$K = \frac{E_v}{C_v \int_\lambda V(\lambda)\hat{E}_\lambda(\lambda)\mathrm{d}\lambda}. \quad (5)$$

DOI: 10.5821/conference-9788419184405.026

Then, the effective radiance flux that the sensor converts into current can be expressed as:

$$\Phi_{eff} = A_s K \int_{\lambda} \hat{S}_{\lambda}(\lambda)\hat{E}_{\lambda}(\lambda)\,\mathrm{d}\lambda\,, \tag{6}$$

where the normalized spectral sensitivity function of the sensor is provided by the manufacturer.

The next step in this process is to correlate the effective radiant power in the photodiode with the voltage response that is being measured. As the manufacturer provides the normalized sensitivity curve and its constant, the output current can be expressed as follows:

$$I_{pv} = S_{\lambda}\Phi_{eff} = P\int_{\lambda} \hat{S}_{\lambda}(\lambda)E_{\lambda}(\lambda)\,\mathrm{d}\lambda\,, \tag{7}$$

where P is a new parameter defined as the product of the photodiode area and its spectral sensitivity constant. This new parameter can be seen as the conversion efficiency between the effective irradiance and the generated current. The manufacturer values of $\hat{S}_\lambda$, A_s and S_λ are typical values that allow the calculation of the photodiode response for any spectrum. However, these typical values do not represent the exact response of each photodiode. Therefore, the objective of the calibration process is to correctly characterise the parameter P, among the I_0, a, R_{sh}, and R_s parameters of the 1D/2R equivalent circuit. Ideally $\hat{S}_\lambda$ should also be characterized, but this would require specialized instrumentation, which was not available. The parameter P can replace the parameter I_{pv} with the following equation:

$$P = \frac{I_{pv}}{K\int_{\lambda} \hat{S}_{\lambda}(\lambda)\hat{E}_{\lambda}(\lambda)\,\mathrm{d}\lambda}\,. \tag{8}$$

The advantage of using P is that it is an intrinsic characteristic of the photodiode that does not depend on the illuminance received, in contrast to I_{pv}. The calibration process can be seen as an optimization problem with five degrees of freedom. The proposed objective function to minimize is the root mean square error (RMSE) between the model and experimental results:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(I_{i,exp} - I_{i,model}\right)^2}\,. \tag{9}$$

The different experimental results are obtained by varying the resistor value connected to the photodiode. This process must be repeated for different illuminance conditions (a minimum of two sets of experiments should be done considering that the voltage response grows linearly with the illuminance near the short-circuit region). Therefore, once the illumination test has been done for different illumination conditions, it is possible to determinate the slope of $\mathrm{d}V_{\mathrm{exp}}/\mathrm{d}E_v^{\mathrm{LED}}$ through a linear fitting. Then considering that $\mathrm{d}I/\mathrm{d}E_{eff}$ is a constant of the photodiode, the relation between E_{eff} of the LED and the AM0 is known, and the values of the test resistance and flight resistance are also known, it is possible to calculate the the variation of the measured voltage with the solar irradiation as follows:

$$\frac{\mathrm{d}V_{\mathrm{flight}}}{\mathrm{d}E^{\mathrm{AM0}}} = \frac{\mathrm{d}V_{\mathrm{exp}}}{\mathrm{d}E_v^{\mathrm{LED}}}\,\frac{R_{\mathrm{flight}}}{R_{\mathrm{exp}}}\,\frac{E_v^{LED}\Phi_{eff}^{AM0}}{\Phi_{eff}^{LED}}\,. \tag{10}$$

2.2. Angular test

The main idea of the angular test (see Figure 3) is to characterize the behavior of the photodiode when the relative angle between the sensor and the light source changes. It is common to approximate the angular response of the photodiode as the product of the cosine of the incidence angle measured from the normal direction of the sensor, and its maximum response the source of light reaching the photodiode. Although a cosine law is a good approach for most of the angular behaviour, this law lacks accuracy when there are high incidence angles between the normal of the sensor and the light source. Therefore, to obtain the maximum accuracy, it is necessary to calibrate the angular response of the photodiodes in their operative range.

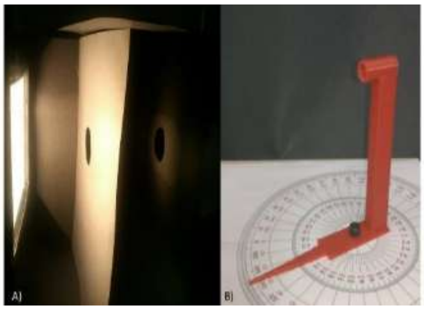


Figure 3. Angular test set-up.

3. Result and Discussion

3.1. Illumination test results

The results regarding the illumination test are presented graphically in Figure 4 where the *I-V* of the photodiode is obtained changing the value of the resistance connected to the sensor as noted for the resistance of 10 Ω and 50 Ω. In this figure, the results of the fitted model are also plotted to compare the modelled results with the experimental data, showing good concordance between them. Finally, in Table 1 are shown the parameters of the fitted model for one of the photodiodes. It is interesting to note that the value obtained from the P parameter showed a significant deviation from the typical value provided by the manufacturer (P = $4.35{\cdot}10^{-6}$ Am^2/W) which do not adequately represent the conversion efficiency.

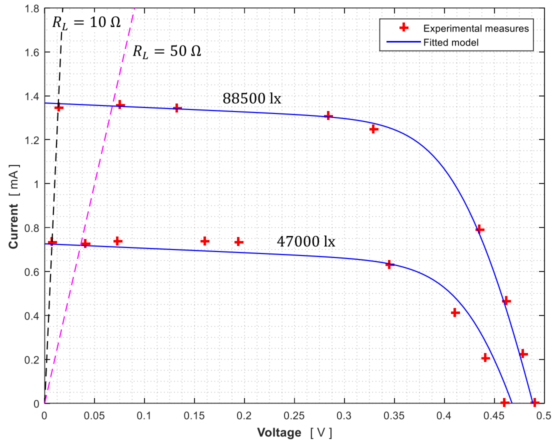


Figure 4. Results of the illuminaton testing campaign of one of the photodiodes and comparison with the fitted model.

Table 1. Value of the parameters extracted from the fitting process of the data from Figure 4.

Parameter	Fitted value
P [Am^2/W]	$5.56{\cdot}10^{-6}$
I_0 [A]	$1{\cdot}10^{-10}$
a	1.1754
R_s [Ω]	34.01
R_{sh} [Ω]	4902

The results of the expected performance of the photodiodes in the AM0 spectrum for the Low Earth Orbit (LEO) are presented graphically in Figure 5. In the first graph, it is possible to observe how the experimental data present an almost perfect linear correlation between the measured voltage and the illuminance reaching the photodiodes. Then in Figure 5. B) the expected measurements for the AM0 spectrum in relation to the solar irradiance are presented. The information of this figure is completed with the coefficients calculated for each light source (See Table 2).

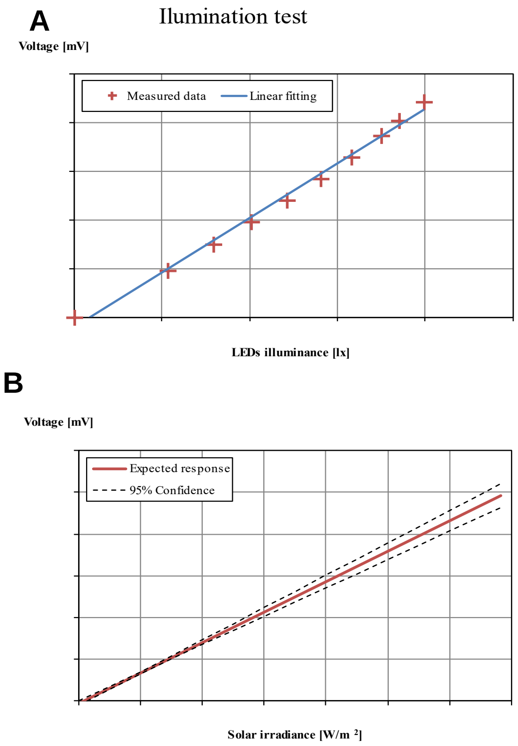


Figure 5. A) Fitting of the photodiode in relation to the illuminance. B) Expected response of the sensor to the AM0 spectrum irradiance.

Table 2. Coefficients obtained from the linear fitting of the results plotted in Figure 5.

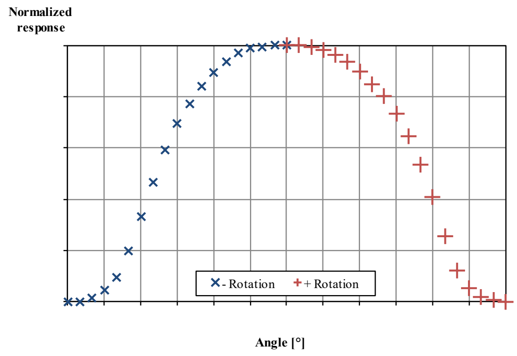
Irradiance	M	n [mV]
LED	$5.59{\cdot}10^{-4}$ mV/lx	–0.992
AM0	$7.27{\cdot}10^{-2}$ mV/(W/m²)	–1.01

3.2. Angular test results

The results of the angular test are represented graphically in Figure 6. In the first graph, the normalized experimental results with a halogen source of light are represented. Then in the second graph it is represented the relative incidence angle between the normal direction of the photodiode and the source of light in relation to the measured voltage. It is important to note that the incidence angles in bracket [0° - 45°] show a distribution that resembles a cosine function. However, for angles larger than 45° this approximation starts to lack of accuracy. Therefore, instead of a cosine law, a 7th degree polynomial was used:

$$\alpha = b_0 + \sum_{n=1}^{7} b_n \left(\frac{V}{V_{\max}} \right)^n . \qquad (11)$$

A



B

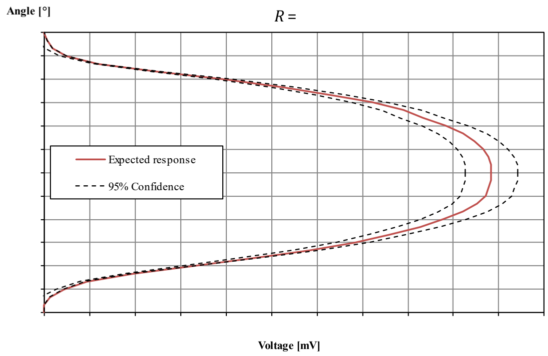


Figure 6. A) results from the angular test. B) Expected angular response of the photodiode in AM0 spectrum for LEO conditions.

4. Conclusions

The proposed methodology allows the calibration and determination of the expected performance of photodiodes in the direct polarization zone for any light spectrum without requiring any specialized equipment. This methodology was applied to the photodiodes of the Sun sensors of the UPMSat-2, resulting in a successful calibration of the photodiodes to LEO environment. Besides, it allowed a quite accurate estimation of this spacecraft attitude within its orbit. Additionally, the Sun sensors can be combined with data from solar panels to improve the accuracy of the attitude estimation.

Acknowledgements

This research has been partially supported by the project 478 Y2020/NMT-6427 OAPES from the program "Sinérgicos 2020" from *Comunidad de Madrid* (Spain). The authors are indebted to the Horizon 2020 IOD/IOV Programme of the European Union that funded the UPMSat-2 launch.

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Cosmic Call Tech – A hands-on space radio workshop for students in secondary education

Stefan Lobas[1], *Mario Geisler*[1], *Frank Fischer*[1]

Abstract

The DLR_School_Lab Braunschweig, Germany, organized an amateur radio contact with an astronaut on board the International Space Station (ISS) for students from five different schools for the third time. While the contact itself was always an exciting event for the participating students our goal was to increase the sustainability in learning with a deeper understanding of the technology used for the radio contact. As a result, we present our concept for engaging with the students and preparing them for the actual radio contact with an inexpensive hands-on space radio workshop that was conducted remotely via video conferencing and thus is independent in regard to distance between the lecturer and the group.

During the workshop the students built their own ground station to receive amateur radio satellites and the ISS. Due to the COVID-19 pandemic the workshop could not be conducted fully as an in-person learning experience.

To overcome this obstacle, we chose a hybrid approach. Each session started with a short introductory lecture using a video conferencing software. After the introduction the students worked in groups following a written guide which we provided. During the rest of the session we assisted online in case of any questions or technical difficulties. We also supplied the schools with a Raspberry Pi single board computer, an inexpensive software defined radio and some coaxial cables for building antennas. The tasks necessary building the ground station included setting up the hardware, configuring the software and building antennas.

The written guide gave detailed information on how to complete the individual steps. It also provided some optional more in-depth information on propagation of electromagnetic fields, antenna theory and orbital mechanics to accommodate the range of participating school forms with different levels of proficiency and wide range of age of the students participating.

The students were very motivated to take part in this workshop, even as an extracurricular activity during their spare time. The students as well as the teachers involved also highlighted the interesting and useful lectures and the professional support via video conferencing software. This kind of hybrid approach was a new and innovative learning experience for the schools.

Our workshop offered the students an introduction to radio technology and space which would be otherwise beyond most teachers' knowledge and capabilities. We demonstrated that such a workshop can be realized over distance besides pandemic conditions broadening the field of schools that can be involved.

Keywords

Amateur Radio, Education, International Space Station, Software Defined Radio

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Acronyms/Abbreviations

ARISS	*Amateur Radio on the International Space Station*
DLR	*Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)*
DVB-T	*Digital Video Broadcast – Terrestrial*
ESA	*European Space Agency*
ISS	*International Space Station*
SBC	*Single Board Computer*
SDR	*Software Defined Radio*
STEM	*Science, Technology, Engineering and Math*

1. Introduction

1.1. The DLR_School_Labs

Germany has a growing need for professionals especially in the fields of science, technology, engineering and math (STEM) [1]. To promote the topics of STEM to students in secondary education the German Aerospace Center (DLR) currently operates fifteen out-of-school learning laboratories partly in cooperation with universities distributed all over Germany. These laboratories enable the students to gain first hand experiences with experiments related to the research topics of DLR (aerospace, space, transportation, energy, security and digitalisation) often with high-end equipment which is not available in schools, e.g. a wind tunnel or high-end flight simulators. It has been be shown that the DLR_School_Labs succeed in promoting interest in STEM [2].

1.2. Amateur radio on the International Space Station – Enabling ham radio contacts for students

Starting with the crewed operations on the International Space Station (ISS) the educational payload Amateur Radio on the International Space Station (ARISS) was deployed. Since then many radio contacts between students on the ground and astronauts on orbit took place and inspired thousands of students in the STEM field [3]. These radio contacts require a direct line-of-sight between the ground station antenna and the ISS. Therefore, these contacts usually last approximately ten minutes due to the movement of the ISS from horizon to horizon.

Schools and organisations can apply for such an amateur radio contact with an astronaut on orbit. They can decide if they want to use the telebridge infrastructure provided by ARISS so the equipment needed by the schools is reduced to just a telephone. Alternatively, the schools can use their own radio equipment often in cooperation with local amateur radio enthusiasts. Selected applicants are then carefully guided through the preparation process up to the actual contact by experienced ARISS mentors. The astronaut's time is a very precious good and ARISS does everything possible for the contact being a success.

1.3. Past ARISS contacts carried out by the DLR_School_Lab Braunschweig

The DLR_School_Lab Braunschweig carried out three successful radio contacts with the ISS so far. For each contact four or five cooperating schools were invited to select students asking the astronaut interesting questions. From this pool twenty questions in total were selected evenly distributed over the participating schools.

The first contact took place in 2014 with European Space Agency (ESA) astronaut Alexander Gerst during his "Blue Dot" mission. The second contact was part of Alexander Gerst's mission "horizons" in 2018. The most recent ARISS call took place in December 2021 as part of ESA astronaut Matthias Maurer's mission "cosmic kiss".

All three contacts were conducted using the purposely on-site installed radio equipment. Planning these contacts involved a steep learning curve. The administrative workload for a successful contact was more or less constant for all three radio contacts. From an operator's point of view the technical preparations before the radio contacts decreased with increasing knowledge and experience for each contact.

The preparation of the first contact in 2014 was mainly driven by the selection and permanent installation of the radio equipment followed by intensive training for the operators.

For the second contact in 2018 the technical preparations were focused on optimising the process and some operator training. The resources not needed for setting up the radio equipment were used to create a video stream of the event. This stream was distributed over social media channels but also using amateur radio television in cooperation with the amateur radio group of the *Technische Universität Braunschweig*. These channels enabled even more students and amateur radio enthusiasts to attend the event.

For all three contacts the participating students prepared the radio contacts in class but in 2014 and 2018 the students experience was mostly limited to an exciting one-day event. For the most recent contact in 2021 our goal was to increase the engagement of students with regard to radio technology before the contact and possibly inspire them to continue with their own projects using the gained knowledge.

2. Project description “Cosmic Call Tech”

Most of modern radio technology appears like a black box for students. It is not part of the curriculum in physics or informatics while being ubiquitous in our world at the same time. With our project “Cosmic Call Tech” we wanted the students to discover radio technology as a hands-on experience enabling them to use the gained knowledge to follow their own projects and enrich the ARISS experience. To achieve this, we enabled the participating students to build a single board computer-based receiver which could be used to listen to ARISS contacts and small satellites.

The project was planned considering the types of participating schools (*Gymnasium*, *Integrierte Gesamtschule* and *Realschule*, see [4] for further details on the German school system) and the age of the students. The youngest students participating were in the 8th grade (13-14 years) and the oldest students were attending the 13th grade (18-19 years).

The project was structured to be worked on once a week for 45-90 minutes over a course of six to eight weeks. This mode enabled schools to use this project within the regular lectures, as a compulsory selected practical training or as an extracurricular activity during the students’ free time.

2.1. Aims of the project

We wanted to create a lasting and sustainable learning experience. Using a space-themed setting enhanced the attraction of the students’ interest as this is widely regarded as something special that only large space agencies do. We also wanted the students to use a broad range of capabilities (e.g. software configuration and manual building) with the intention that as many students as possible will find their place in the project and are eager to actively participate. A qualitative and quantitative differentiation was especially important because of the wide range of ages and the different forms of schools that took part in the project. The students heading for *Abitur* graduation in the 13th grade do have more previous knowledge than an 8th grade student attending a *Realschule*.

2.2. Online guided lessons and support

Each of the topics was introduced by a short online lecture of no more than fifteen minutes. These lectures were used to give the students an overview and a classification of the importance of the topic as well as explaining the goals and tasks ahead in this lesson. This was conducted by one of two DLR_School_Lab -team members so that the students had a constant contact person they could relate to.

After the lecture the students started working on the project on their own with the in-classroom support by their teacher. We stayed connected via video conferencing software during the rest of each session. This allowed us to provide low threshold support as the required skills to troubleshoot or answering questions which arose while working often beyond the teachers’ knowledge.

2.3. Script - step by step to success

We supplied the participating schools with a PDF-document covering the topics and giving detailed instructions on what to do. This document was structured into six chapters corresponding to the topic of each week. Besides the instructions more in-depth theoretical aspects, e.g. on antenna theory and movements of satellites, were covered, too. These parts were completely optional so that progressing in the project was possible even when skipping these sections. This scheme allowed differentiation and a hands-on connection to aspects covered in the upper secondary curriculum (e.g. waves and oscillations, electromagnetic fields, circular movements and force equilibriums).

2.4. Hardware

The available information technological infrastructure available in German schools

DOI: 10.5821/conference-9788419184405.027

differs a lot. For simplification we decided to use a comparatively cheap single board computer (SBC) as a hardware base together with an inexpensive DVB-T USB key used as a software defined radio (SDR). This selection allowed us to prepare a unified guide on how to configure the device and maximise the student's success.

Each school was supplied with one set of the needed hardware but most schools bought some additional hardware so that even more students were able to work simultaneously.

2.4.1. RaspberryPi

The RaspberryPi 4B with 8 GB memory was chosen as the base SBC. This version of the hardware was easily available and proved to being capable enough for the task of decoding the signals from the SDR. As the RaspberryPi 4B has only Micro-HDMI outputs we included an adapter cable from Micro-HDMI to normal HDMI so that the schools could use a regular monitor or projector as a display.

To power the SBC the original RaspberryPi USB power supply unit was used to guarantee stable operations.

2.4.2. Software Defined Radio

For receiving the radio signals regular USB receiver keys for terrestrial digital television (DVB-T) were used. These inexpensive devices consist of a tuner chip and a software defined radio chip with USB interface to pass the data to the host computer. The SDR chip samples the signal to generate its in-phase and quadrature components which can be used to demodulate the signal using software.

We chose DVB-T USB keys with a Realtek RTL2832U tuner chip because this tuner is supported by most of the available software and it offers a radio reception from about 60 MHz up to 1700 MHz. Our kit included also a small antenna with a suitable SMA connector for the first reception experiments. As intended, the small antenna provided only a very limited gain and was only useful to receive strong local radio sources.

2.4.3. Half-wave dipole antenna

When trying to receive the ISS or a small satellite a better antenna with more gain is needed. The project included the instructions to build a half-wave dipole for the 2 m band (144 MHz). This corresponds to the band used for the downlink from the ISS (145.800 MHz). This antenna is very easy to build and provides sufficient gain to successfully receive the ISS. The most complicated to build part is the connecting pigtail cable with a SMA connector on one end because a special crimping tool is needed. We provided each school with a few coaxial cables with a crimped connector.

2.4.4. J-pole antenna

While the half-wave dipole is very well suited for the 2 m band a lot of small satellites also use the 70 cm band (430 MHz). The instructions included a so-called J-pole antenna ([5]) which is suitable for 2 m and 70 cm. Building this antenna was more ambitious but it was not mandatory for the progress of the project.

2.4.5. Software stack

The software stack consisted of a Raspbian Linux operating system ([6]) and OpenWebRX ([7]) as demodulating software and graphical front end. OpenWebRX works as a web application and is used with a web browser. After downloading and setting up everything the RaspberryPi was configured to start OpenWebRX automatically as a service after booting. The integrated wireless hardware was then re-configured to work as an access point so that the students could connect with a tablet or smartphone to the RaspberryPi and open the web application provided by OpenWebRX. With this setup it was easily possible to going outdoors and powering the RaspberryPi with a battery pack in order to receive weaker signals.

3. Results and Discussion

All participating students successfully completed the project. Several students were able to listen to the downlink from the ISS with their self-built receiver and antenna combination during the actual ARISS call with astronaut Matthias Maurer. The teachers reported their students were very excited when they heard the astronauts voice with their own receivers and self-built antennas.

At the end of the project we collected feedback from the students and their teachers. The students enjoyed the project and highlighted that they learned something new and interesting. The students as well as the teachers also perceived the support via video conferencing software as very helpful. Even though some teachers wished it to be in-person instead of using video conferencing. Nevertheless, several teachers told us that this low threshold support using video conferencing was an actual enabler for such a project because they did not have the knowledge needed and it worked out really well.

We received some remarks on the readability of the script as it was sometimes difficult for the students to distinguish between an “O” and “0” (zero) for the configuration of the RaspberryPi. We will revise the script to increase the readability for the configuration of the RaspberryPi as this caused a non-working configuration in one case that had to be troubleshooted.

The involved teachers fed back that the project was not only interesting but useful for their students as it motivated them to engage with STEM even further. The extent and topical depth of the project was perceived as adequate.

It was highlighted that the broad range of skills used by the students made the project inclusive for the students and promoted teamwork and enabled them for their own future projects. Some of the teachers also reported that they want to continue to build on space as a theme for their regular lectures (e.g. building a Mars rover in manual training lectures).

4. Conclusions and Outlook

We presented a hands-on space radio workshop for students in secondary education based on a RaspberryPi SBC and a digital TV USB key used as a software defined radio to receive signals from the ISS.

From the received feedback we conclude that we succeeded in creating an enjoyable, lasting and sustainable learning experience for the students involved. As there was no negative feedback stating the project was boring, too complicated or overwhelming we infer that our differentiation worked as intended.

The overall positive feedback encouraged us to repeat the project with other schools detached from seldom ARISS calls. We demonstrated that it is possible to conduct the workshop remotely by video conferencing enabling this kind of content for schools that are not close nearby. We are also considering to offer this project within the frame of a holiday program for students as an in-person project at the DLR_School_Lab Braunschweig while continuing to offer it in the described hybrid format.

Acknowledgements

This project would not have been possible without the generous support of Frank Fischer (Head of DLR_School_Lab Braunschweig), Steffen Jauch (Realschule Calberlah) and the amateur radio enthusiasts and DLR employees Niels Siegmund (DH1ALF) und Micha Przybilla (DD2MIC).

We would like to thank them for their steady support and encouragement to realize this project.

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EIRFLAT-1: A FlatSat platform for the development and testing of the 2U CubeSat EIRSAT-1

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Abstract

The Educational Irish Research Satellite (EIRSAT-1) is a 2U CubeSat being designed, built and tested at University College Dublin. A FlatSat platform known as EIRFLAT-1 has been constructed to enable the testing and development of the CubeSat. EIRFLAT-1 facilitates the electrical connections between CubeSat components while leaving key interfaces accessible for test equipment and allowing for the hot swapping of components. Commercial Off The Shelf and in-house developed hardware has been tested using EIRFLAT-1 at component, subsystem and full system level. In addition, the FlatSat has been used for flight software development. This paper describes the design of EIRFLAT-1 including electrical and mechanical components and additional ground support equipment developed to assist in the testing and development activities. EIRFLAT-1 has proven to be an invaluable tool for testing and has led to the discovery of issues and unexpected behaviour with flight hardware which would have contributed to schedule delays if undiscovered until after the satellite was assembled. Moreover, EIRFLAT-1 facilitated early and incremental testing of both software and operations procedures. The schematics for the electrical design of EIRFLAT-1, which is compatible with all CubeSat Kit PC/104 components, has been made publicly available for use by other educational CubeSat teams.

Keywords
EIRSAT-1, CubeSat, FlatSat, Ground Support Equipment

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1. Introduction

The Educational Irish Research Satellite (EIRSAT-1) is a 2U CubeSat currently being developed under the second edition of the European Space Agency's educational "Fly Your Satellite!" programme. The satellite contains three novel payloads and a custom antenna deployment module that are supported by an AAC Clyde Space Commercial Off The Shelf (COTS) platform which has been adapted to interface with these novel hardware components [1]. Combining COTS components with in-house developed hardware, software and firmware results in a complex system which requires extensive testing [2, 3].

To ensure compatibility between all the spacecraft components and to allow for pre-assembly system level testing, a FlatSat called EIRFLAT-1 has been constructed (Figure 1). A FlatSat is a test bed into which satellite components can be integrated to represent the final spacecraft configuration, while allowing for access to individual components which you may not have in the flight configuration. FlatSats allow for power transmission and communication between all or some spacecraft components, hot swapping of development model payloads and access to the spacecraft interfaces for testing and verification purposes. FlatSats are used in the development of multiple classes of satellite from large spacecraft such as Solar Orbiter [4] and Emirates Mars Mission [5] to CubeSats such as ISTSAT-1 [6] and Aalto-1 [7].

Since the CubeSat standard was first proposed in the 1990s, university teams developing new technologies have utilised them as a quick and cost-effective path to space. Companies such as GOMSpace, AAC Clyde Space and ISI Space produce COTS platforms which allow CubeSat teams to focus on their payload development without the overheads involved in producing their own power systems, on-board computers, structures, communication systems or attitude control systems, providing both time and cost savings. EIRFLAT-1 has been designed in a manner which allows it to be compatible with a wide array of COTS components to allow for a focus on rapid iterative payload development. A full description of the design and manufacture of EIRFLAT-1 is provided in Section 2.

EIRFLAT-1 has been used extensively for the acceptance and functional testing of EIRSAT-1's Engineering Qualification Model (EQM) components at both subsystem and system levels prior to satellite integration [8]. Additionally, the FlatSat has been used by the team for flight software development and the development and testing of operational procedures in simulated mission scenarios. The FlatSat is also being used for the testing of Flight Model (FM) components. Further information on the testing conducted using EIRFLAT-1 can be found in Section 3.

The importance of the FlatSat was demonstrated by the discovery of a number of issues and unexpected system behaviours prior to the flight configuration assembly of the EQM. These could then be solved or noted without the need to disassemble the entire satellite. One such example was the discovery of a fault with one of the On-Board Computer's (OBC) I^{2}C buses for payload communications which required the OBC to be returned to the supplier for repair.

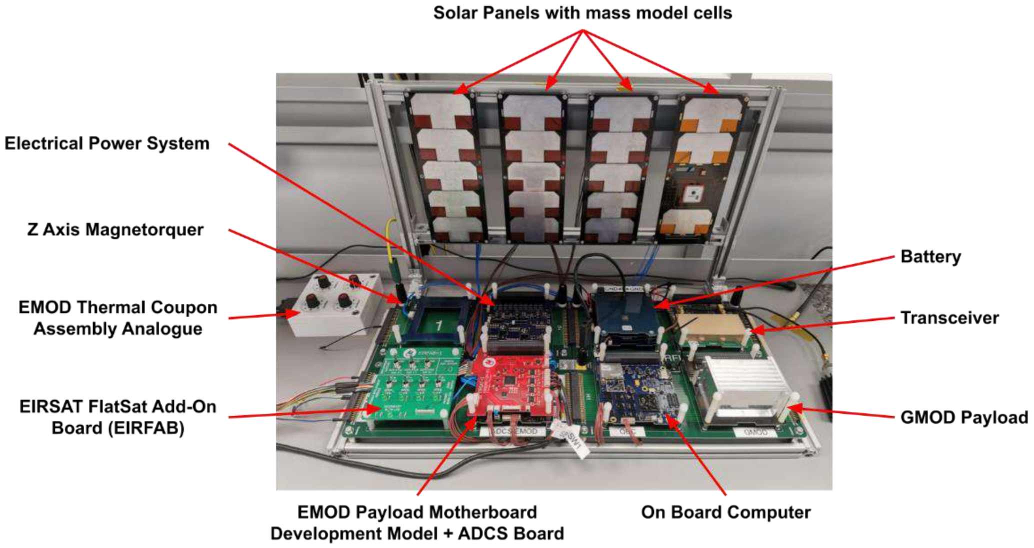

Figure 1. Labelled photograph of EIRFLAT-1 with Engineering Qualification Model components taken during a system level test campaign.

EIRFLAT-1, as the first integration of the EIRSAT-1 system, provided an excellent learning experience for the team in the handling of flight hardware, space systems engineering and flight software development. Lessons learned during the development of EIRFLAT-1 and the testing conducted to date will be taken into consideration during the design phase of an updated FlatSat. When EIRSAT-1 is in orbit, the EQM hardware will be integrated in this updated FlatSat configuration for software validation and debugging. These lessons are discussed in more detail in Section 4.

2. Design and Construction of EIRFLAT-1

EIRFLAT-1 consists of several key mechanical and electrical components which allow the FlatSat to function as a whole system which can interface with test equipment such as multimeters and oscilloscopes. A description of these components and how they are integrated with one another is provided in this section.

2.1. EIRFLAT-1 Electrical Interface Board

Printed circuit boards (PCBs) called Electrical Interface Boards (Figure 2) enable the electrical connections between spacecraft components which follow the CubeSat Kit's modified PC/104 standard [10]. This standard is used by many in the CubeSat industry, including manufacturers like GOMSpace and AAC Clyde Space. The electrical interface boards consist of four slots, each with their own 104 pin header through which most of the power and data is transmitted. The spacecraft buses are broken out into headers at the sides of the boards for access with test equipment or to expand the FlatSat by linking two interface boards together.

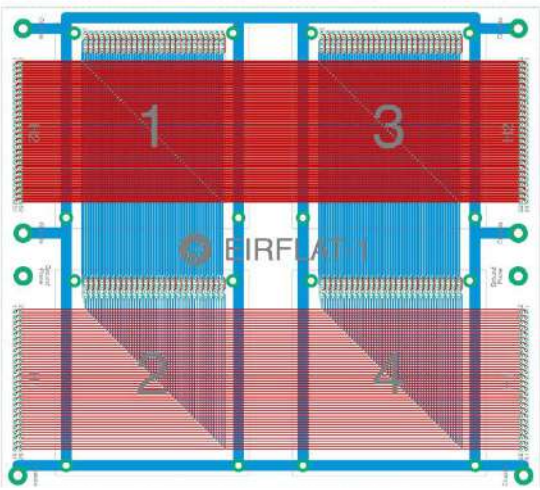

Figure 2. Schematic of an Electrical Interface Board which electrically connects subsystems.

The four slots all share a common ground plane, to which the subsystems are connected via conductive M3 spacers located at the corners of the slots. These spacers are also used to secure the components in place on the FlatSat. Banana sockets allow for the ground plane of the interface board to be referenced to a piece of test equipment or to one of the spacecraft's subsystems to match the grounding scheme of the fully assembled system.

The schematic of the electrical interface boards has been made available at www.github.com/ucd-eirsat-1/FlatSat for use by university CubeSat teams making use of the CubeSat Kit standard.

2.2. Structure

EIRFLAT-1's electrical interface boards are mounted on an aluminium structure which provides mechanical support. A schematic of the structure is shown in Figure 3. The structure consists of lengths of 20mm x 20mm aluminium profile secured using M5 hardware including T slot nuts, angle brackets and bolts. In addition to the main base of the structure which supports the electrical interface boards, a detachable stand can be used to support solar panels in a vertical orientation. The solar array stand reduces the surface area required on a bench when solar panels are added to the FlatSat assembly, allows test operators to illuminate the panels directly without holding torches above the panels, minimises the surface area upon which dust can fall, and allows for a protective screen to be placed around the cells, protecting one of the more fragile and expensive components of the CubeSat from damage.

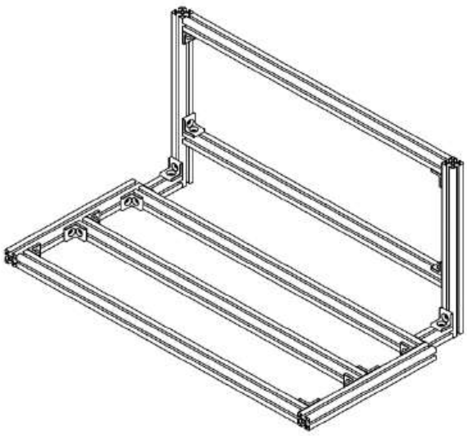

Figure 3. EIRFLAT-1 Aluminium Structure including the flat base and the solar array stand.

Aluminium tape running along the lengths of profile allows the structure to act in the same manner as the conductive elements of the CubeSat structure from an electrical grounding perspective. The ground plane of each interface board is connected to the structure through the mounting holes. The aluminium then connects this to the solar panels through the panel mounting holes. The conductive tape was added to EIRFLAT-1 after the structure had been assembled, when it was noted that the aluminium profile was anodised and was therefore not conductive as originally assumed.

2.3. *Additional Ground Support Equipment (GSE)*

It is possible to connect all the subsystems of EIRSAT-1 together for system level testing using just the structure and electrical interface boards, however, several additional pieces of GSE have been designed to improve EIRFLAT-1 for development purposes and for testing individual subsystems.

2.3.1. *Fake Electrical Power Subsystem (EPS)*

In order to supply power to the spacecraft, EIRSAT-1 uses a COTS electrical power subsystem consisting of solar panels, a battery and a motherboard which handles battery management, power conditioning and power distribution. For testing and development, it is preferable to supply power to components on the FlatSat without using the flight EPS hardware in several situations. This saves the EPS from the risk associated with over-cycling the battery, or with connections to previously untested components of the spacecraft. In order to supply power to the FlatSat the Fake EPS (Figure 4) is positioned in one of the electrical interface board slots and connected to a bench power supply unit using 4mm banana cables. The Fake EPS has a banana socket for each of the spacecraft power buses, plus two grounding connectors. The Fake EPS PCB distributes the power from these banana sockets to the main header, supplying power to the other subsystems on the interface board just as the EPS would during a full system level FlatSat test.

2.3.2. *EMOD Thermal Coupon Assembly (TCA) Analogue*

One of EIRSAT-1's payloads is the Enbio Module (EMOD), an experiment designed to monitor the performance of thermal surface treatments on orbit [1]. This is achieved by using PT100 resistance temperature devices to measure the temperature of four coupons located in an assembly on EIRSAT-1's exterior. To verify the functionality of the supporting electronics and software for this experiment, the EMOD TCA Analogue (Figure 4) was designed to allow test operators to provide the EMOD electronics with a resistance to measure which corresponds to the temperatures expected on orbit using potentiometers. This way, testing and development activities can ensure that the experiment is working over the full expected temperature range while at ambient conditions and without having the sensitive coatings of the thermal coupons exposed to the environment.

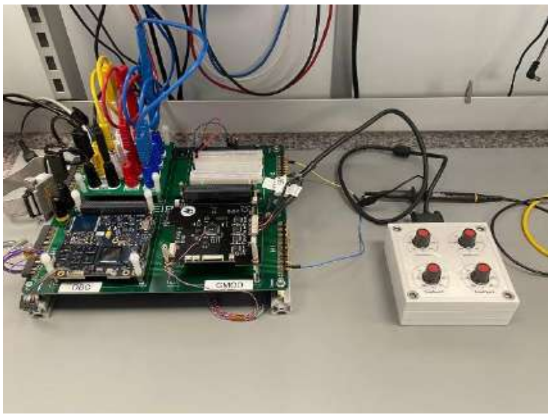

Figure 4. Photograph of an electrical interface board being used for software development of the EMOD payload using the Fake EPS and the EMOD TCA Analogue.

2.3.3. *EIRFLAT-1 Add-On Board (EIRFAB)*

EIRFAB, a PCB which connects to EIRFLAT-1, has been designed to functionally test several components of the spacecraft which are electrical in nature but are parts of mechanical components of the spacecraft.

CubeSats have deployment switches mounted on the exterior of the structure. These micro-switches ensure that the spacecraft remains powered off until it has successfully been ejected from the deployer. These switches are not ideal for testing purposes, as they can easily be damaged and are open by default. Instead of using these micro-switches, EIRFAB has three toggle switches which replace the deployment switches during FlatSat testing. These switches are robust and allow for the spacecraft to be left in a stowed or deployed configuration.

One of the other major mechanical components of EIRSAT-1 is the Antenna Deployment Module (ADM) [9]. The ADM has large tape spring antennas which are deployed when the satellite is in its separation sequence. During FlatSat testing it is not practical to use the ADM. The deployed elements take up a lot of space on the workbench and as they deploy quickly, they could potentially damage other components of the FlatSat. It is also time consuming to re-stow the antenna elements which reduces the time available for testing. The EIRFAB-1 PCB contains the same electronics as the ADM which allows the testing to be conducted without deploying antenna elements. Since the elements will not deploy, LEDs have been added to the circuitry to provide a visual indicator that the deployment mechanism is active. The ADM also uses micro-switches to tell the on-board computer when the doors have opened, and the elements have been deployed. On EIRFAB these have been replaced with toggle switches which allow operators to test how the system responds on deployment failure.

The third and final piece of electronics on EIRFAB is a coarse sun sensor circuit. EIRSAT-1 uses five of these sensors in its attitude determination and control system. Four of them are located on the solar panels, however, the fifth is attached to the exterior of the ADM. The circuit on EIRFAB has one sun sensor and a connector which allows it to interface with the attitude control subsystem.

2.4. Layout and Harnessing

Many of the electrical connections between EIRSAT-1 components and the required GSE cannot be made through the main spacecraft header. Within the main stack assembly there are some connections which do not rely on the PC/104 header, but on a harnessing system or other board to board connectors. Components on the spacecraft exterior (e.g. ADM, EMOD TCA, solar panels and sun sensors) are also connected to the main stack assembly via a harnessing system. For EIRFLAT-1 a harnessing system using the same materials as the system on the spacecraft has been built to replicate the spacecraft configuration as much as possible, despite the extended distances between components. This choice ensured that the connections between the components were in a worst-case scenario, and if all of the integration tests passed on the FlatSat then the team would have high confidence in the harnessing system fulfilling its requirements in the flight configuration. The addition of this harnessing system, and the board-to-board connections placed restrictions on the layout of EIRFLAT-1. Ensuring that the harnesses could be neatly arranged allowed for better access to testing interfaces and reduced the risk of connection errors. The layout of EIRFLAT-1 is shown in Figure 1. The EMOD board is located directly on top of the ADCS board to facilitate a board-to-board connection between these subsystems. These PCBs are located towards the left side of the FlatSat as the main spacecraft umbilical cable is connected to the left side of the EMOD board and runs to GSE located out of shot to the left of EIRFLAT-1. The EPS board is located at the back of the FlatSat to shorten the routes between the solar panels and the EPS. The transceiver is located towards the right of the satellite to allow it to be connected to the ADM, or GSE which requires coaxial cable connections.

3. Testing and Development

EIRFLAT-1 is used in three test campaigns prior to system assembly. The first of these is acceptance testing, during which components are installed on the FlatSat in isolation from other flight hardware and are tested using GSE to ensure that the components are operating according to their specifications. Once the components have been accepted, they are integrated with other components of their subsystem and tested at subsystem level. Some components are included in multiple subsystem test campaigns. For example, the solar panels are installed on the FlatSat for both the EPS tests (charging test, maximum power point tracking test) and the ADCS tests (magnetorquer and sun sensor tests). EIRSAT-1's OBC is installed on the FlatSat for many of these tests to test subsystem telemetry and telecommand. Following the subsystem functional testing, all of the components are added to EIRFLAT-1 and a system level functional test is conducted. This test verifies the functionality and requirements of the system and ensures that no unexpected errors arise due to the integration of the whole system.

This full cycle of testing has already been conducted for EIRSAT-1's EQM hardware, culminating in the flight configuration assembly of the EQM in November 2020 [8]. Currently, EIRFLAT-1 is being used for subsystem level testing of FM components of the satellite following a successful acceptance test campaign. In addition to these test activities, EIRFLAT-1 is used to assist in the development of flight software. During development periods, the OBC is installed on the FlatSat either on its own or with development models of the satellite's payloads for testing new software images. Moreover, software bugs are investigated and fixed using an OBC on EIRFLAT-1 while testing continues using the fully assembled satellite. This is to continue through-out EIRSAT-1's mission lifetime as EIRFLAT-1 is used to test new software images, new operations and for debugging of problems while EIRSAT-1 operates in space.

4. Discussion

EIRFLAT-1 has proven to be a vital resource during the development of the EIRSAT-1 CubeSat. The platform served as an excellent base to students working with flight hardware for the first time. The design has allowed for

DOI: 10.5821/conference-9788419184405.028

successful iterative payload development and robust testing which highlighted several issues which may have caused delays if they had gone unnoticed until the satellite had been assembled. Some of these issues included:

- Damaged I²C bus on the EQM OBC which had to be repaired. This issue was discovered during the OBC acceptance test campaign.
- Reversed polarity of the sun sensor on EIRSAT-1's custom solar panel when compared to the COTS panel. This issue was solved by a redesign of the flight harnessing system. This issue was discovered during the ADCS subsystem test.

The initial design of the EIRFLAT-1 platform, while useful, was not perfect. Improvements have been made to the system. One of the improvements is the addition of aluminium tape to the EIRFLAT-1 structure to ensure the solar panels and the other subsystems share an electrical ground as they would in flight configuration. Another is a change in the location of grounding points on the electrical interface boards. The importance of proper grounding procedures was highlighted during the acceptance test of the EQM transceiver on EIRFLAT-1 when an improperly grounded radio caused an overvoltage event on the transceiver which had to be sent for repairs. Systems to ensure that all satellite components and GSE are correctly grounded have been implemented to reduce the risk of a similar incident occurring in the future.

5. Conclusions

EIRFLAT-1, a FlatSat for the development and testing of the EIRSAT-1 satellite or other CubeSats which make use of the CubeSat kit standard, has proved to be an invaluable tool. The design of the FlatSat allows for the components of the satellite to be tested in isolation, at subsystem level and at system level, all while keeping the satellite interfaces accessible to test equipment. EIRFLAT-1 has uncovered several issues with the system which could have been costly had they not been discovered until the satellite was assembled in its flight configuration.

Acknowledgements

The authors acknowledge all students who have contributed to the EIRSAT-1 project. EIRSAT-1 is supported by ESA's Education Office under the FYS! 2 programme. JR acknowledges a scholarship from the UCD School of Physics. This study was supported by The European Space Agency's Science Programme under contract 4000104771/11/NL/CBi and by the European Space Agency's PRODEX Programme under contract number C 4000124425.

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Development of a Concurrent Engineering Tutorial as part of the "ESA_Lab@" initiative

Jennifer Hoffmann [1], *Marlon Deutsch*[2], *Reinhold Bertrand*[3]

Abstract

As part of the "ESA_Lab@" initiative, a Concurrent Engineering facility has been constructed at the Mechanical Engineering department of Technical University Darmstadt. Concurrent Engineering is a well-proven concept for designing complex space systems and missions in the pre-phase 0/A mission phase. The Concurrent Engineering methodology and processes are enabled by a multidisciplinary team and specific infrastructure in terms of both hardware and software, which generate an effective and time efficient design management system.

The university's "Concurrent Engineering Lab" provides an environment for both researchers and students to explore and apply the Concurrent Engineering approach in areas such as (model-based) systems engineering, Industry 4.0/ Space 4.0, and space traffic management. Furthermore, collaboration with the European Space Operations Centre – also located in Darmstadt – regarding the application of Concurrent Engineering for Ground Segment & Operations has been started.

The first addition to the university's curriculum centered around the Concurrent Engineering Lab will be a "Concurrent Engineering Tutorial", an opportunity to introduce the Concurrent Engineering methods and tools via hands-on experience to students of the newly established master's degree program "Aerospace Engineering". "Tutorials" are elective block courses of the degree program which offer practical learning experiences in many different fields, awarding 4 credit points upon successful completion.

Building on the lectures "Fundamentals of Space Systems" and "Space Systems and Space Operations", the week-long "Concurrent Engineering Tutorial" will challenge students to use their acquired knowledge to develop a preliminary design for a predefined CubeSat mission. This Tutorial will not only provide a closer understanding of the individual subsystems of the space segment of a mission, the Concurrent Engineering process and the relevant software "COMET" by RHEA Group but will also create a synergy with a student association of the university, as one of their projects is the development of a CubeSat.

This paper describes the background and approach to the development of the Tutorial, in particular the structure of the re-usable model architecture in "COMET", which was specifically derived and implemented for this purpose and validated via a pilot study.

Keywords

Concurrent Engineering, CubeSat, Space Systems Design, Tutorial

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Acronyms/Abbreviations

CDF	*Concurrent Design Facility*
CDS	*CubeSat Design Specification*
CE	*Concurrent Engineering*
CEL	*Concurrent Engineering Lab*
COTS	*Commercial off-the-shelf*
CSRM	*CubeSat System Reference Model*
DOE	*Domain of Expertise*
ECSS	*European Cooperation for Space Standardization*
ESA	*European Space Agency*
ESOC	*European Space Operations Centre*
GS&OPS	*Ground Segment and Operations*
IME	*Integrated Modeling Environment (COMET)*
INCOSE	*International Council on Systems Engineering*
OCDT	*Open Concurrent Design Tool*
OMG	*The Object Management Group*
SSEA	*Symposium on Space Educational Activities*
TBD	*To be determined*
TUDa	*Technical University Darmstadt*
TUDSaT	*TU Darmstadt Space and Technology e.V.*

1. Introduction

In 2019, the European Space Agency (ESA) and the Technical University Darmstadt (TUDa) signed a cooperation agreement ("Memorandum of Collaboration") with the aim of expanding and strengthening the cooperation between the two institutions and providing additional impetus along the entire innovation chain from basic research to space missions. [1]

Among other projects, this collaboration picks up the “ESA_Lab@” initiative, with the first core element at TUDa being a facility for concurrent engineering (CE), the “Concurrent Engineering Lab” (CEL), whose construction was completed in 2020.

CE is a well-proven concept for designing complex space systems and missions in the pre-phase 0/A. It relies on a multidisciplinary team of engineers and scientists as well as specifically tailored infrastructure to generate an effective and time efficient design management system.

The layout and infrastructure of the CEL is aligned with the ESTEC CDF [2] design, which provides an efficient environment as well as the necessary hardware and software tools for the CE process. Figure 1 shows the layout of the CEL from the front and back side.

Figure 1. Front and rear view of the CEL

Although numerous facilities exist (e.g., Concurrent Design Facility (CDF) [2] at ESTEC), the methodology is not yet fully established for GS&OPS design. [3] Therefore, one of the research activities in the context of ESA_Lab@TU Darmstadt is to define and tailor a design process, models, and tools to the more diversified requirements of GS&OPS conceptual design.

Regarding teaching activities at the CEL, the first addition to the curriculum will be a "hands on" experience in CE. Building on selected space lectures offered at TUDa, a “CE Tutorial” is currently being developed for this purpose, which will be integrated into the new master's degree programme "Aerospace Engineering".

This paper describes the development of the tutorial, with chapter 2 covering its basic structure. In chapter 3, the current state of the art of CE and CubeSats is briefly examined. Chapter 4 describes the methodology used to derive and implement a reference CubeSat mission architecture in the CE software “COMET”, while chapter 5 covers the pilot study which was held for validation purposes. Results are presented and discussed in chapter 6, with chapter 7 providing conclusions and an outlook.

2. Structure of the tutorial

2.1. Course content

The focus of the tutorial is the familiarization with CE processes and tools, not the teaching of space system design from the ground up. Therefore, before applying to the tutorial, aspiring participants must pass the exams of

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TUDa's lectures "Fundamentals of Space Systems" and "Space Systems and Space Operations".

After familiarizing with CE processes and basic functions of COMET, students will be presented with a CubeSat mission description from which they will derive their conceptual design. Participants will be graded via final presentations and short design reports of each subsystem.

2.2. Time structure

Adapting to the schedule of the prerequisite lectures mentioned above, the one or two weeks long (TBD) "block" part of the tutorial will take place in the lecture-free time between the winter and summer semester. Before this block part, students will be able to familiarize themselves with the software via remotely accessing a training model, guided by suitable instruction material.

The first day of the block course itself will serve to explore the "concurrent" part of the CE process, i.e., the near real-time and constant exchange of information and its utilization for the design process. Additionally, the mission description will be presented to students. Starting on the second day, students will derive requirements from the mission description and perform CE sessions, moderated by a scientific assistant as a systems engineer, in order to iteratively arrive at a conceptual CubeSat design. On the last day, final presentations of each subsystem will be held, while corresponding reports will be handed in later.

2.3. Preparation

The following elements have to be prepared for the first instance of the tutorial by the Institute of Flight Systems and Automated Control: a CubeSat mission description, which will change yearly, a re-usable CubeSat mission reference architecture in COMET, which is the focus of the remaining chapters, and suitable training material, which will be derived from the reference architecture.

3. State of the art

3.1. ECSS-E-TM-E-10-25A: The Foundation for European CE Software

The "Technical Memorandum for engineering design model data exchange" by the European Cooperation for Space Standardization, ECSS-E-TM-10-25A, is the foundation for CE Software such as ESA's "OCDT" and "COMET" by RHEA Group, which is deployed at TU Darmstadt's CEL and which will also supersede OCDT at ESA [4]. Intended to become a standard, ECSS-E-TM-E-10-25A "facilitates and promotes common data definitions and exchange" [5], including a definition of the decomposition of a system down to equipment level, shown in Figure 2.

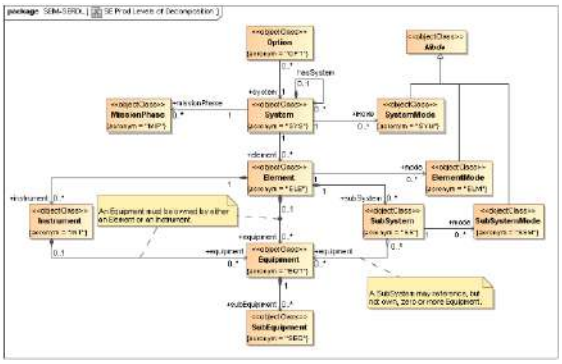

Figure 2: System decomposition as defined by ECSS-E-TM-E-10-25A [5]

An important part of this decomposition is that "a *SubSystem* is […] a *logical* grouping of *Equipment*, in contrast with the other decomposition object types that constitute a *physical* decomposition. Therefore, a *SubSystem* may refer to (but not own) a number of *Equipment*." [5] As noted in the diagram, "*Equipment* must be owned by either an *Element* or an *Instrument*". The technical memorandum notes that this presents a "limited way of decomposing systems that is considered adequate for the conceptual design phases 0 and A" [5], during which CE is applied most effectively.

3.2. CE Software "COMET" by RHEA Group

The open-source CE Software "COMET" by RHEA Group is used at TU Darmstadt's CEL. It is an implementation of ECSS-E-TM-10-25A and consists of three integral parts. A server application is responsible for storing models, users, reference data, etc. An add-in for Microsoft Excel is used for parameter calculations and analysis. Lastly, a stand-alone application, the "Integrated Modeling Environment" (IME), is particularly useful for administrative, preparatory, and organizational work. Regular synchronization of the client applications with the server enables near real-time collaboration.

3.3. The INCOSE CubeSat System Reference Model (CSRM)

Developed by the Space Systems Working Group of the International Council on Systems Engineering (INCOSE), the CubeSat System

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Reference Model (CSRM) is a SysML model with the following objectives [6]:

- "Demonstrate Model-Based Systems Engineering (MBSE) as applied to a CubeSat Mission"
- "Develop a CSRM that a university team can use as starting point for their mission-specific model"
- "Develop the CSRM as an Object Management Group (OMG) Specification"

Finalized in 2021, the CSRM is currently under review at OMG to become a standard [7]. In coordination with the responsible working group, an excerpt of the CSRM describing the reference hardware architecture of a CubeSat has been obtained to serve as a guideline for the Tutorial's model architecture in COMET.

According to the CSRM, the following 9 individual subsystems comprise a CubeSat system:

- Attitude Determination and Control
- Command and Data Handling
- Communications
- Guidance, Navigation and Control
- Mission Payload
- Power
- Propulsion
- Structures and Mechanisms
- Thermal

Furthermore, each CSRM subsystem contains "Components", as exemplified by the power subsystem in figure 3.

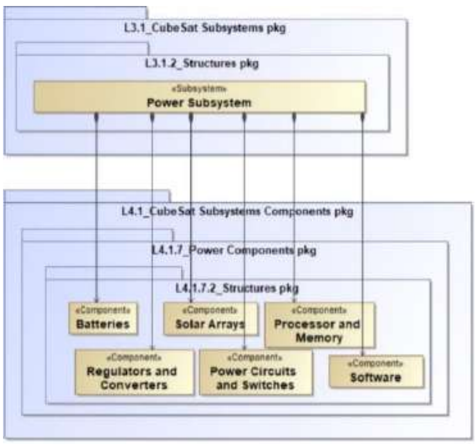

Figure 3. Example of "Components" contained within CSRM Subsystems – in this case, the Power Subsystem [7]

4. Methodology

4.1. Adaptation of the CSRM to comply with ECSS-E-TM-10-25A

As COMET implements ECSS-E-TM-10-25A, the CSRM structure, in particular the physical decomposition of subsystems into "Components", must be adapted to comply with the technical memorandum.

This has been achieved via the definition of element "Categories" within COMET which correspond to the CSRM "Components". Using the CSRM Component "Batteries" as an example, this adaptation is illustrated in figure 4.

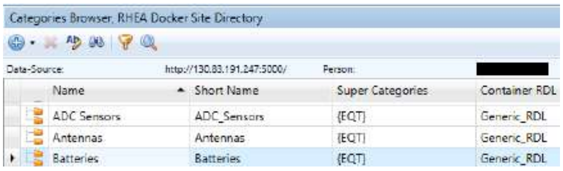

Figure 4. "Batteries" as an example of the CSRM adaptation to comply with ECSS-E-TM-10-25A via COMET "Categories"

The allocation of the "Super Category" "{EQT}" ("Equipment") provides the final link between the CSRM and the system decomposition defined by ECSS-E-TM-10-25A. The relation between a Category and a Super Category is defined as: "Every element of a 'Category' is also an element of the allocated 'Super Category', but not necessarily vice versa". Using again "Batteries" and "Equipment" as an example, this can be expressed more tangibly: "Every battery is a piece of equipment, but not every piece of equipment is a battery."

In this fashion, all physical Components of the CSRM Subsystems have been integrated into COMET. Categories are stored on the Site Directory level of the server and can be assigned to an element in a model.

4.2. Derivation and implementation of a re-usable CubeSat mission architecture in COMET

The following fundamental model architecture composed of three different model types has been envisioned for the tutorial.

- A "Template Model" serves as a generalized blueprint for a CubeSat mission. It represents the basic mission architecture, including the spacecraft's decomposition into subsystems. Details in section 4.2.1
- A "Model Catalogue" contains a database of CubeSat parts and equipment. Details in section 4.2.2

DOI: 10.5821/conference-9788419184405.029

- A "Study Model" will be created at the beginning of each tutorial. By selecting the "Template Model" as a "Source Model" during its setup, it mirrors the current state of the template.

4.2.1. The "Template Model"

To reflect the subsystems defined by the CSRM, corresponding "Domains of Expertise" (DOE) have been activated in the Template Model. The "System Engineering" DOE is also set to active and will be assigned to the scientific assistant who moderates the tutorial. With 10 students participating and only 9 subsystems defined by the CSRM, the "Payload" DOE will be assigned to two participants – one responsible for the payload instrument, one responsible for the mission trajectory.

In general, space missions consist of a "Space Segment", "Ground Segment", and "Launch Segment". Therefore, the top element of the template, defined as a generic "CubeSat Tutorial Mission" contains these segments, while the "Space Segment" contains a "CubeSat Spacecraft". This hierarchical structure is achieved via the "Element Usage" function of COMET and is represented in the model's "Product Tree", as shown in figure 6.

On the system and subsystem levels, applicable parameters have been assigned to the respective element definitions, without any values. Grouping of parameters improves readability. Depending on the parameter, different DOEs are responsible for its value, expressed by the parameter's "Owner" attribute. Examples of this parameter allocation are given in figure 5.

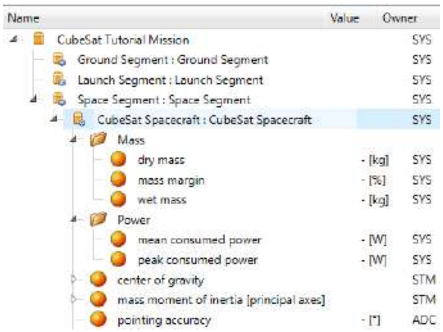

Figure 5. Product tree, showing the mission structure and parameter examples on the CubeSat system level

Reflecting ECSS-E-TM-10-25A, no physical equipment may be placed within a subsystem via the "Element Usage" function in a COMET model. As with parameters, the responsibility for an element, and thus the allocation of equipment to a subsystem, is expressed by its "Owner" attribute, irrespectively of the element's actual location in the model. The parameters assigned to a subsystem may refer to equipment that the respective DOE is responsible for. In this fashion, mass and power budgets for the individual subsystems can be created.

Different mission states, such as illuminated or eclipse phases of an orbital period, are an important design driving factor. In COMET, they are represented by "Finite State Lists", with the ability to define parameters as "state-dependent". To keep complexity at an appropriate level, an "Actual Finite State List" of 4 possible mission states has been defined for the Template Model, as seen in figure 6.

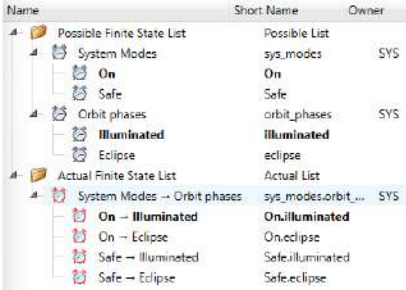

Figure 6. Finite states of the "CubeSat Tutorial Mission" template model

COMET also enables the integration and verification of requirements. The "CubeSat Design Specification Rev. 14" (CDS), currently available as a draft version [8], has been integrated into the Template Model.

An automated compliance check is possible after defining relationships between requirements and corresponding elements of the model, e.g., parameters. This is most easily achieved for requirements pertaining to numerical values, such as the maximum allowed mass per CubeSat Unit, etc.

With the official CDS serving as a starting point for any CubeSat project, students of the tutorial will also derive additional requirements from the mission description and link them to their model during the design process.

4.2.2. The "Model Catalogue"

The Model Catalogue serves as a database for CubeSat parts. It contains two types of elements:

- Specific COTS parts and assemblies from various manufacturers, with data sheets linked in the element definition
- "Generic" element definitions of various spacecraft equipment, including applicable parameters without values

DOI: 10.5821/conference-9788419184405.029

Both types are categorized according to the CSRM. Parameters are owned by the corresponding DOE and, if sensible, grouped. During the tutorial, elements of the Model Catalogue can be copied into the Study Model via simple “drag & drop”, assisting students in their design process.

5. Validation via pilot study

To validate the model architecture, a pilot study was conducted in the week of April 4th, 2022. A student association of TUDa, TUDSaT e.V., is currently in the preliminary design phase of a CubeSat mission and volunteered to participate, which allowed the testing of the model architecture regarding its usability by students and its applicability to CubeSat design, as well as the advancement of TUDSaT’s CubeSat project. The participating students answered multiple questionnaires during and after the study.

6. Results & Discussion

The evaluation of the pilot study yielded that the established COMET model architecture presents a solid and versatile environment for CubeSat design, adaptable to many different mission scenarios, including the one of TUDSaT. An excerpt of the questionnaire results is shown in figure 7, which shows the rating of the Template Model and the Model Catalogue on a scale from 1 to 5, with 5 being the highest possible rating.

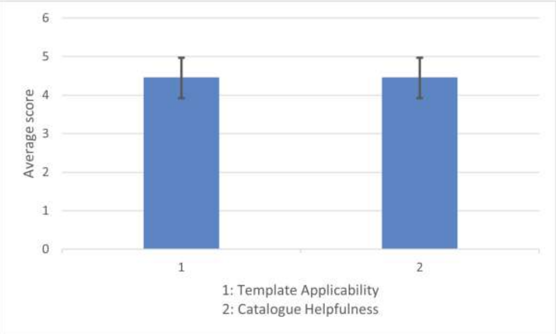

Figure 7. Excerpt of the pilot study evaluation. Results of Template Applicability and Catalogue Helpfulness on a scale from 1 (lowest rating) to 5 (highest rating).

7. Conclusions

With the presented COMET model architecture, the foundation for the future CE Tutorial at TUDa has been laid. Furthermore, via the definition of COMET “Categories” which correspond to CSRM subsystem “Components”, a semantic gap between the CSRM and ECSS-E-TM-10-25A has been bridged. In a broader context, this has the potential to enable general interoperability between the future OMG standard defined by the CSRM and the European standard that ECSS-E-TM-10-25A will eventually evolve into.

Acknowledgements

We would like to thank Mr. David Kaslow from the INCOSE Space Systems Working Group for providing the CSRM and Mr. Johan Vennekens from the European Space Agency for his insight about model architectures in COMET. Furthermore, we are grateful for the motivated participation of all TUDSaT members who were part of the pilot study.

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Spazio allo Spazio

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Abstract
“Spazio allo Spazio", active since 2010, involves students aged 5 to 20. This educational project was launched by a group of Italian teachers from the *Lower Secondary School Fermi* in Villasanta who believed Space exploration could be an efficient way to convey the idea that the extraordinary experience of the astronaut, who on the International Space Station must acquire new skills and be able to dominate a challenging and unpredictable context, similar to a disabled person's routine in daily life. This was a winning choice because gradually international institutions promoted similar initiatives. The central theme of space exploration is used to promote values of sustainability, equity and diversity, allowing students to become acquainted with the world of astronauts while facing subjects related to integration and disability. Several national and international universities and institutions, at the forefront of scientific research, have contributed to this project. The main topics of the project are: 1) Space exploration: the astronaut's experience is the starting point for lessons, cultural exchanges, lectures and interdisciplinary strategies to raise awareness about humans in space, the international cooperation for the International Space Station, physical training, technical, scientific and cultural preparation. 2) Career orientation: meetings with experts in different fields, from Science, Technology, Engineering, Mathematics to Arts and Physical Education, help students achieve better knowledge of themselves, their potential and limits acquiring skills in scientific research methodology in a multilingual environment. 3) Inclusion: as astronauts experience the limits of gravity and disability in Space, students can face their limits, through experiences of adapted physical activity, addressing issues related to the integration and insertion of people with different skills in school and society. 4) Team building: starting from the example of collaboration which takes place in space missions and scientific research, students are encouraged to experience teamwork. This is true for the teachers too, thanks to the strengthening of cooperative teaching, in the sharing of resources and good practices as well as in the implementation of innovative forms of communication and multimedia documentation. The project aims at making students able to face new and more advanced educational challenges and cognitive objectives, developing work strategies by transferring already tested approaches and processes to new situations. This is noticeable in the more self-conscious choices that former students have made about their future. An example is illustrated by an ex-student who directed his training path in the Science and Engineering field.

Keywords
Astronaut, Career orientation, Inclusion, Team building

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Acronyms/Abbreviations

OAVdA	Osservatorio Astronomico della Regione autonoma Valle d'Aosta
CNES	Centre National d'Études Spatiales
ESA	European Space Agency
EAC	European Astronaut Centre
DLR	Deutsches Zentrum für Luft und Raumfahrt
ASI	Agenzia Spaziale Italiana
ITU	International Telecommunication Union, Geneve
UNOG	United Nations Office in Geneva
ISP	Istituto Scienze Polari
CERN	European Organization for Nuclear Research
CNR	Consiglio Nazionale Delle Ricerche
ISMAR	Istituto di Scienze Marine
YOPP	Year of Polar Prediction
ENEA	Ente Nazionale per le nuove tecnologie, l'Energia e l'Ambiente
PNRA	Programma Nazionale di Ricerche in Antartide
ARISS	Amateur Radio on the International Space Station
STEAM	Science Technology Engineering Art Mathematics
STEM	Science Technology Engineering Mathematics
ESOC	European Space Operations Centre
DDI	Disabled Divers International

1. Introduction

Spazio allo Spazio is an educational project launched in 2010 by a group of Italian teachers from *Lower Secondary School Fermi* in Villasanta, a small town near Milan. It stems from an attentive school that wants to experience innovative teaching that enables the crossing of boundaries of individual subjects promoting transdisciplinary learning in a laboratorial way, oriented towards inclusion. These teachers believe Space exploration to be an efficient way to convey the idea that the extraordinary physical and psychological abilities of the astronaut have a surprising, unexpected similarity to the ones disabled people use in their daily life. [1] In fact, the astronaut, an excellence in the field of science and technology, while experiencing microgravity and weightlessness, must acquire new skills and be able to adapt to a challenging and unpredictable context, just like a disabled person does every day. Students learn through different experiences simulating theoretical and practical tasks on topics from the national curricula. They are required to handle various tests, to take responsibility, to face up to their own limits, including physical ones, and to assess their capabilities. Using the astronaut as an example in teaching, means setting challenging objectives, providing specific training, creating a synthesis of skills and knowledge to achieve abilities that can be used in any field in the present and the future.

2. Didactic aims

The aim of this project is to focus students' attention on topics connected with space exploration, inclusion, and career orientation through teamwork. The project pursues educational goals aimed at improving self-awareness and students' potential. It proposes the achievement of cognitive aims related to STEAM topics and to the other subjects through an interdisciplinary approach. In strengthening the skills and competences of each student, including those with special needs and disabilities, entrepreneurship is promoted as a proactive and creative attitude in order to be the protagonists of one's learning and not mere spectators of the teaching efforts of others.

Figure 1. CNR Arctic Station Dirigibile Italia 2021

3. Didactic approach

The different activities carried out within the project use different methodologies and tools, with the aim of making students the protagonists of their learning, stimulating their curiosity for knowledge and their desire to open new horizons on the world. Lessons, in presence or remotely, periodic video contacts with some international realities broadcast via streaming from the project's YouTube channel, allow the involvement of several classes at the same time and the participation of families in the educational activities proposed by the school for their children. Particularly significant for the development of students' oral skills, are the events dedicated to issues linked to the project, which see the direct involvement of students in the roles of presenters and in the exhibition of works which recount the different experiences they have lived. The use of their mother tongue and the foreign languages studied (English and French) makes it possible to communicate

DOI: 10.5821/conference-9788419184405.030

beyond the confines of school, to reach international realities of great educational importance. Over the years, these ties with foreign realities have made it possible to create a twinning collaboration with the *collège* "Pierre de Fermat" in Toulouse and to participate in numerous educational trips in Europe and in Italy (EAC in Cologne, CERN and ITU in Geneva, *Scuola Normale Superiore di Pisa* and others*).* Each experience of this kind is always preceded by a series of in-depth activities, conducted by the teachers in class. The scope of communication is relevant for the type of work linked to the project itself. The constant updating of the dedicated blog and the availability of videos on the YouTube channel allows for continuous use of the content covered and gives visibility to the work carried out by the students. Their involvement is also required in the graphic elaboration and design of the posters of the various events as also in the participation in creative competitions, during particular events such as, the European Day of Languages (competitions "Space for Words" and "The Lottery of Words") and the launch of weather balloons in Antarctica, with logos made by primary and secondary school pupils. More recent experiences such as "The Science Festival" have shown how the proposal of "contest" constitutes a highly challenging element for students and gives them the opportunity to express themselves, putting their personal skills and abilities into play. The personal re-elaboration of the contents dealt with takes place through the creation of "logbooks" that reflect and summarize the meaning of the activities carried out and collect the impressions and students' point of view.

4. Learning activities

4.1. Space exploration

Space and the astronaut's experience represent the common thread linking the different school subjects, becoming the starting point for lessons, cultural exchanges, lectures, and interdisciplinary strategies to raise awareness about humans in space, their physical training, technical, scientific, and cultural preparation.

Students learn Space topics by attending workshops and virtual planetarium shows, they observe the Sun in a Heliophysics laboratory and the sky with the naked eye using special telescopes in the Italian Starlight Stellar Park OAVdA. [2]

They visit European space centres (CNES, ESA, DLR), international agencies and organizations (ITU, CERN), a space theme park (Cité de l'Espace), and museums about the history of space exploration (ISMAR, the Science and Technology Museum in Milan).

They experience virtual reality space in a Cave Automatic Virtual Environment 3D (Virtual Immersions in Science - *Scuola Normale Superiore Pisa*). They improve their knowledge of the Earth's climate and become aware of the ongoing climate change, by taking part in school projects (#Volare#Beyond#YOPP, The Climate Detective School Project - ESA), visiting the marine research centre CNR-ISMAR in Bologna, having video conferences with the researchers of the CNR Arctic Station *Dirigibile Italia* and the Concordia Base in Antarctica (AUSDA - Adopt a School from Antarctica – ENEA/PNRA). These activities promote the development of STEM competences and skills, including scientific methodology, data collection, visualisation and analysis of the weather balloons data dedicated to our school, subsidised by Bicocca University and launched from different sites (Linate airport- Milan, Mario Zucchelli and Concordia Base in Antarctica).

Students are involved in lessons given by astronaut trainers in order to study the consequences of microgravity aboard the International Space Station. They train by simulating the experience of an astronaut in space through a practical lesson at the swimming pool, with the use of specific equipment provided by a highly specialised staff (Disabled Divers International - Italy) and on one occasion, they also flew in the indoor skydiving facility, Aero Gravity of Milan. They take part in nutrition workshops where they are taught healthy eating, correct food lifestyles, and wellness in general. They learn about what space food is and how it has changed in time (ARGOTEC, *COOP-Lombardy Italy*). Students meet, have videoconferences and lectures on scientific and technological topics with qualified space experts like university professors of astrophysics, astronomy, physics and engineering. In collaboration with the Amateurs Radio (ARISS), students had the opportunity of a radio contact with the astronauts Paolo Nespoli and Luca Parmitano while on the Space Station and in person on their return from their missions. They also met and spoke to astronauts Samantha Cristoforetti, Thomas Pesquet, Maurizio Cheli, Tim Peake, Walter Villadei, Franco Malerba, Scott Douglas Altman, Joe Acaba, Alexander Misurkin, Mark Vande Hei, Sergey Ryazansky, Randy Bresnik. These meetings heighten their awareness of the space programs and of their importance for modern society. All these space educational activities are meant to develop and reinforce the students' literacy and competence in STEAM-related subjects helping to stimulate their creativity, critical thinking and resourcefulness.

Figure 2. Samantha Cristoforetti, EAC 2012, Cologne Germany

4.2. Career orientation

At the heart of this project, there is the contribution to career orientation. Lower Secondary School, among its various missions, helps and guides students in their choice of high school, encouraging them to recognize personal aptitudes and to think about their future. Throughout the project experiences, students have the opportunity to learn about the different aspects of the experts' jobs. They gather valuable information on the personal experiences and training paths of the experts that have led them to their current jobs. A significant opportunity is represented by the meeting with renowned experts not only from the field of science and technology, but also from the fields of art, sport, literature, languages and music as well as representatives of the institutional world and international diplomacy. These interactions favour the acquisition of skills in the context of scientific research methodology and encourage the adoption of significant role models, leading to more conscious and responsible choices. Among significant experiences for career orientation, it is worth mentioning:

- the annual European Day of Languages event, which emphasizes the importance of multilingual learning as a tool for better intercultural understanding;
- the STEM International Day of Women and Girls in Science, which contributes to the reflection on science and gender equality, a goal included in the UN 2030 Agenda for Sustainable Development. [3] The testimonies of women protagonists in scientific fields, still perceived as male-dominated, are an inspiration to many girls in our school;
- the lectures given by leading figures from the world of academia and national and international research;
- meetings with experts during school trips to national and international study and research institutes, aerospace training centres (DLR, ESA, ASI, ISMAR, ISP, CNES, CERN, ITU, UNOG, INAF Centres, *Scuola Normale Superiore of Pisa*, Astronomical observatories, planetariums, museums, Cité de l'Espace);
- meetings at school and video conferences with illustrious personalities and representatives of the scientific, cultural and sports world (astrophysicists, astronomers, physicists, engineers, meteorologists, doctors, researchers, journalists, writers, interpreters and translators, Paralympic and Special Olympic athletes);
- collaboration offered by ex-students, who contribute to the preparation, implementation and running of initiatives linked to the project, for example organizing and presenting events, proposing lessons and peer-to-peer tutoring.

Figure 3. Andrea Accomazzo, ESA/ESOC 2018, Darmstadt Germany

4.3. Inclusion

Just as the astronaut, who needs special psychophysical requirements in microgravity conditions, to face new difficulties which require the ability to adapt to a different environment, so the students experience their own and other people's sensory, movement and language limitations. Trying to understand, help and include those who live them daily they also learn to activate functional compensatory strategies. The workshop methodological approach leads pupils with disabilities to work in more stimulating contexts, in which they are called upon to develop new processes of autonomy in the management of schoolwork and to collaborate with their peers in order to establish

DOI: 10.5821/conference-9788419184405.030

positive emotional relationships. Thus reducing the gap in the results obtained in the different activities as well as achieving all the educational and relational objectives set out in the Individual Education Plans of pupils with disabilities. Students experience real situations of disability through the various activities proposed; where they witness the impressive inner strength and willpower that is needed to face and deal with everyday hardships allowing them to enhance their strengths, reinforce their skills and develop human sensitivity capable of translating into concrete attitudes of help and support, which is pro-social behaviour. Examples of the activities are reported below.
At the Institute for the Blind of Milan, students have the possibility to experience “Dialogue in the dark” where they share a sensory enhancement workshop path by entering specifically designed darkened rooms that reproduce an environment from daily life and gain a completely new emotional point of view. Helped by a visually impaired guide, in a completely new perspective, they can’t see with their eyes, but must use their other senses. Thanks to this experience, a reversal of roles is created where the sighted become blind and the blind become sighted. They attend lessons in the Italian Sign Language, they do several adapted physical activities to allow them to develop cooperation and an attitude of acceptance of differences. They play sports related to the Blind Sports Federation (baseball, tennis, climbing, torball, showdown) and other adapted sports (wheelchair basketball, sitting volleyball, adapted swimming activities) in collaboration with the Italian Paralympic Committee, Disabled Divers International Italy, We Fly Team, Italian Alpine Club, other sports associations such as Vero Volley Monza, Aero Gravity Milan, Air Force sport centre and many others. They meet Paralympic and Special Olympic athletes who prove their worth both nationally and at the highest international level.

Figure 4. DDI Italy – Swimming Pool Vimercate Italy

4.4. Team building

Starting from the example of cooperation which takes place in space missions and scientific research, students are encouraged to experience teamwork, respecting their own and others’ diversity through collaborative practices. By accomplishing group tasks, students learn to get along with peers, to listen, trust and support each other, while developing life skills such as communication and collaboration. This is true for the teachers too, thanks to the strengthening of cooperative teaching, in the sharing of resources and good practices. The workshop activities that students undertake implicate teamwork, encouraging entrepreneurship, focusing on the value of cooperation and negotiation together with a communicative exchange in languages other than their mother tongue. Teachers propose many group activities using curricular learning units on orienteering, coding, robotics, physical resistance, nutrition and current relevant world issues.
As part of the *Spazio allo Spazio* project for example a learning unit on robotics and coding is held during Technology classes, allowing students to create simple computer programs that can control the actions of robotic devices. It is divided in theoretical lessons and practical lessons both in English, held by the teachers and external experts. The former students of the project, contribute to the lesson and coordinate the intervention of the guests and the questions of the younger learners. The students are divided into teams with different tasks but with the necessity of communication between the various groups, to be able to reach a positive outcome of the mission. In the end, the individual groups join and test the mission.

Figure 5. Robotic Lessons

5. Results

The results can be summarized in the enhancement of cooperative teaching, in the strengthening of curricular topics, in raising awareness on the issue of inclusion, in the experimentation of multi-lingual teaching, in the implementation of innovative forms of communication and in the sharing of multimedia documentation. Students have been able to grasp the importance of skills such as the ability to cooperate, to be enterprising, flexible and adaptable; they have recognized the strength of willpower and commitment, supported by passion, which has led them to carry out every work activity with competence and enthusiasm. Finally, they have come to understand the interdisciplinary, international and multicultural dimension in which they live as “Citizens of the World”.

The use of innovative communication technologies (interactive whiteboards, video conferences, dedicated platforms, blogs and the project website), well before the pandemic, compelled students and teachers to face the challenges of on-line teaching and learning with major confidence. This constituted an unexpected outcome, as if everyone was on a space mission directly in contact with the Control Centre on Earth.

Ludovico, one of the co-authors of this article, is a former student who has been participating in the project since the beginning of Lower Secondary School until today. Now he is enrolled in Aerospace Engineering at the *Politecnico di Milano*. His studies and life path are one of many examples of how the project has been able to pursue and achieve its educational and teaching goals. School orientation activities, especially the meetings with professionals enthusiastic about their work, have helped him recognize his aptitudes and have underlined the need to cultivate passions with commitment and dedication to transform them into talents. He has remained in contact with teachers and classmates learning the importance of friendship and inclusion.

6. Conclusions

The project is the expression of a school open to the world around it, in contact with other realities and contexts, which gives stimulating opportunities, that cares about the individuality of each person and values Science as the link to improve human relationships and commitment.

Acknowledgements

We would like to express our special thanks and gratitude to the large number of people who have contributed and supported us during these twelve years of project.

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[2] International Astronomical Union www.iau.org/administration/about/strategic_plan/ "Stimulate global development through the use of astronomy", pages 32-35
[3] United Nations: The 17 Sustainable Development Goals - https://sdgs.un.org/goals

Figure 6. Project Activities

SAR² - An Augmented-Reality App for Exploration of Principles of Synthetic Aperture Radar

Marcel Stefko[1], *Shiyi Li*[2], *Manuel Luck*[3], *Irena Hajnsek*[4]

Abstract

SAR² is a prototype educational simulation software for the Microsoft Hololens, developed by students as part of a geoinformatics course. The aim of this software is to provide a tool to introduce and explain the concept of synthetic aperture radar (SAR) to students, as well as the general public, by visualizing and interactively exploring the process of a SAR acquisition in a 3D virtual environment.

A distinctive feature of SAR² is that the SAR acquisition procedure is simulated in real time within a Unity Engine environment, using a set of algorithms which replicate the real-life SAR processing algorithms. While this provides a challenge due to the limited computational power available on the Microsoft HoloLens 1 device, it allows maximal freedom to the user in setting whatever configuration they would like to see. This would not have been possible if an approach using a pre-selected set of scenarios was chosen.

The augmented-reality (AR) app works in 3 phases:

- In the first step, the user is shown a terrain model, and a satellite model inspired by the TerraSAR-X. The user can adjust selected parameters of the acquisition by manipulating the satellite and model using intuitive AR controls (e.g. by physically grabbing and rotating the objects with their hands).
- After configuring the parameters, the user launches the acquisition and observes it in real time. The satellite model flies over the terrain, and the "flow" of the data into the storage is immediately visualized.
- After the acquisition is finished, the user can explore the focusing procedures that need to be applied to the data - namely the range and azimuth compression. Different geometrical effects (shadowing, layover) can also be explored at this stage.

The SAR² app used in concert with conventional educational approaches can reinforce the learned material, clarify misconceptions, and provide intuition for the complicated concepts of synthetic aperture radar.

Keywords
augmented reality, public outreach, synthetic aperture radar, visualization

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Acronyms/Abbreviations

AR	*Augmented Reality*
SAR	*Synthetic Aperture Radar*
SAR²	*Simulated Augmented-Reality Synthetic Aperture Radar*
VR	*Virtual Reality*

1. Introduction

Synthetic aperture radar (SAR) is a powerful method for monitoring of the Earth's surface using ground-, air- and space-borne sensors [1]. It can operate at any time of day, and in all weather conditions. Because of this, it has become one of the main sources of global-scale environmental data, with widespread socioeconomic impacts in areas of agriculture, disaster prevention/response, climate change monitoring and many others [2,3]. Due to these impacts, the method and its capabilities are often the subject of discussions between not only subject matter experts, but also policymakers, researchers from other fields, as well as students and members of the public. The method and its principles are however quite complex, making use of advanced signal processing algorithms. There thus exists a natural gap between the educational resources currently available (mainly university courses, demonstration videos, and webpages [1,4,5]), and the need for a relatively simple way to explain the principles of the method to non-experts. There is a temptation to use simplified explanations, which can however lead to misinterpretation of the method's capabilities and its limitations.

Education of SAR principles is challenging also due to absence of practical, small-scale educational models. Most SAR sensors are deployed on spaceborne or airborne platforms, and ground-based sensors remain costly and impractical for classroom or indoor demonstrations. There exist educational resources for building one's own low-cost SAR instruments [5], which is undoubtedly a very engaging pathway towards complete understanding of the SAR principles. However, the technical expertise and time investment necessary for such a project are too high for most members of the public. An alternative, less costly approach towards this challenge is use of virtual-reality (VR) or augmented-reality (AR) environments. Such an approach has been already used in other educational efforts [6-9]. This approach allows seamlessly downscaling SAR observations from hundreds of kilometers down to several meters. Furthermore, it imposes no additional hardware requirements besides the availability of a VR/AR device, and offers great flexibility in terms of preparation of specific demonstration scenarios, as well as repeating experiments.

SAR² (pronounced as "*SAR squared*," formerly HoloSAR) is an application for the AR device Microsoft HoloLens, which demonstrates SAR acquisitions on the human scale within a virtual environment. In order to maximize user freedom and verisimilitude of the simulation, it implements real-life SAR processing algorithms.

2. Development

SAR² was developed in 2020 as part of the ETH Zurich course GIS and Geoinformatics Lab. A key developmental decision was a complete implementation of a SAR acquisition simulation within the virtual environment of the Unity Engine, which computes the acquisition outcomes in real time while the application is being used. This allows for complete freedom in exploration of various acquisition configurations, and exploration of different phenomena which affect SAR acquisitions.

This developmental decision however imposed a performance bottleneck, since the simulation needs to be performed in real time on the Hololens device, which offers limited computational resources. Through use of graphics processing shaders, background processing, and parallelization [8], reasonable real-time performance was achieved. Processing of the data was implemented in a matter replicating the real-life SAR processing pipelines. Notably, azimuth compression – a key processing step for SAR data – is implemented using the real-life range migration algorithm [9].

3. Usage

The interaction of the user with the augmented-reality app can be roughly separated into three phases:

3.1. Setup

The user is shown a 3D environment with a SAR satellite model, a model of the Earth's terrain, and several basic shapes, which can serve as test targets. The user can manipulate (reposition, rotate, and scale) the models using the AR touch controls. Furthermore, the user can manipulate several settings of the SAR sensor, namely the start and end position of the acquisition, the look angle, and the antenna parameters (width, height, maximal range).

An interesting phenomenon to explore is the effect of the antenna dimension on the angular

DOI: 10.5821/conference-9788419184405.031

coverage of the resulting beam of radar waves. A demonstration of this phenomenon within SAR² is shown in Figure 1.

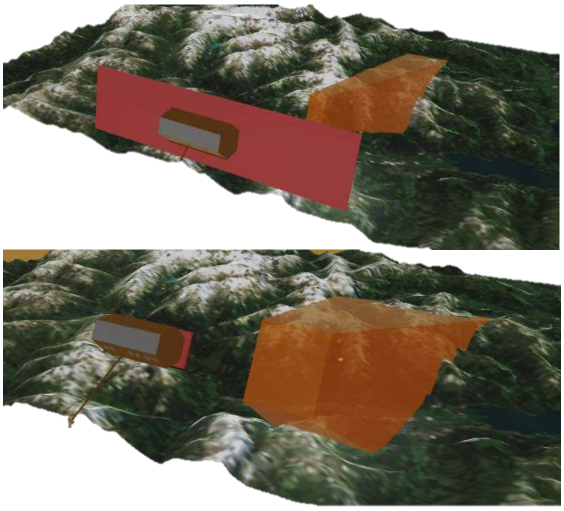

Figure 1: Demonstration of the effect of antenna size (visualized in red) on the resulting radar beam (visualized in orange). For narrower beam widths, which are desirable to achieve high resolution, an antenna with unpractically-large physical size is required (top image). Such antenna is not possible to operate on a spacecraft. This makes the synthetic-aperture approach attractive, since high resolution can be achieved also with smaller antennas (bottom image).

3.2. Acquisition

Once the user has configured the desired acquisition geometry, the acquisition is triggered with the push of a button. The satellite flies over the model of the terrain, and the line-by-line "flow" of the data is immediately visualized.

3.3. Evaluation

The acquired image is yet not compressed in the azimuth direction. The user can trigger the application of the range migration algorithm to compress the image, and retrieve the final single-look complex (SLC) image. This can be explored for features (such as shadowing, foreshortening, layover...), and also stored for later comparison.

The setup-acquisition-evaluation loop can be repeated several times in order to explore effects of different acquisition parameters on the final result. A demonstration video of the use of an earlier SAR² prototype can be viewed online [10].

4. Discussion

While SAR² was developed with use of the augmented-reality headset Microsoft Hololens in mind, owing to its implementation in Unity Engine, it can be quickly adapted to other platforms, such as Android phones or virtual reality headsets. Currently, only individual use of the application is possible (i.e. multiple users cannot share the same virtual environment). However, the HoloLens offers multi-user capabilities, which can be applied in the future in order to allow multi-user operation and facilitate further interaction between the educator and the audience.

The app, used in concert with conventional educational approaches, can reinforce the learned material, clarify misconceptions, and provide intuition for the complicated concepts of synthetic aperture radar. The availability of augmented-reality devices, and their track record in educational use [6,7,11,12], opens up opportunities of the approach for other topics related to space activities (e.g. orbital mechanics, interplanetary mission planning etc.). Development of such applications can also be an educational activity in itself and can be carried out as part of a university course, or a bachelor/master thesis -- students often already have experience with the needed development environments, and the process of development of the software would reinforce the student's understanding of the given concept.

5. Conclusions

SAR² can offer an alternative, engaging approach towards demonstration of synthetic aperture radar principles. It can be used as a public outreach tool in museums, science fairs, and similar environments. Furthermore, it can serve as a complementary tool to conventional, more rigorous explanatory methods in higher education remote sensing courses.

Acknowledgements

The authors would like to thank the GIS Lab at ETH Zurich for supporting the development of SAR², the ETH LET office for providing the hardware, and Pol Villalvilla and Philipp Bernhard for fruitful discussions regarding naming of the software.

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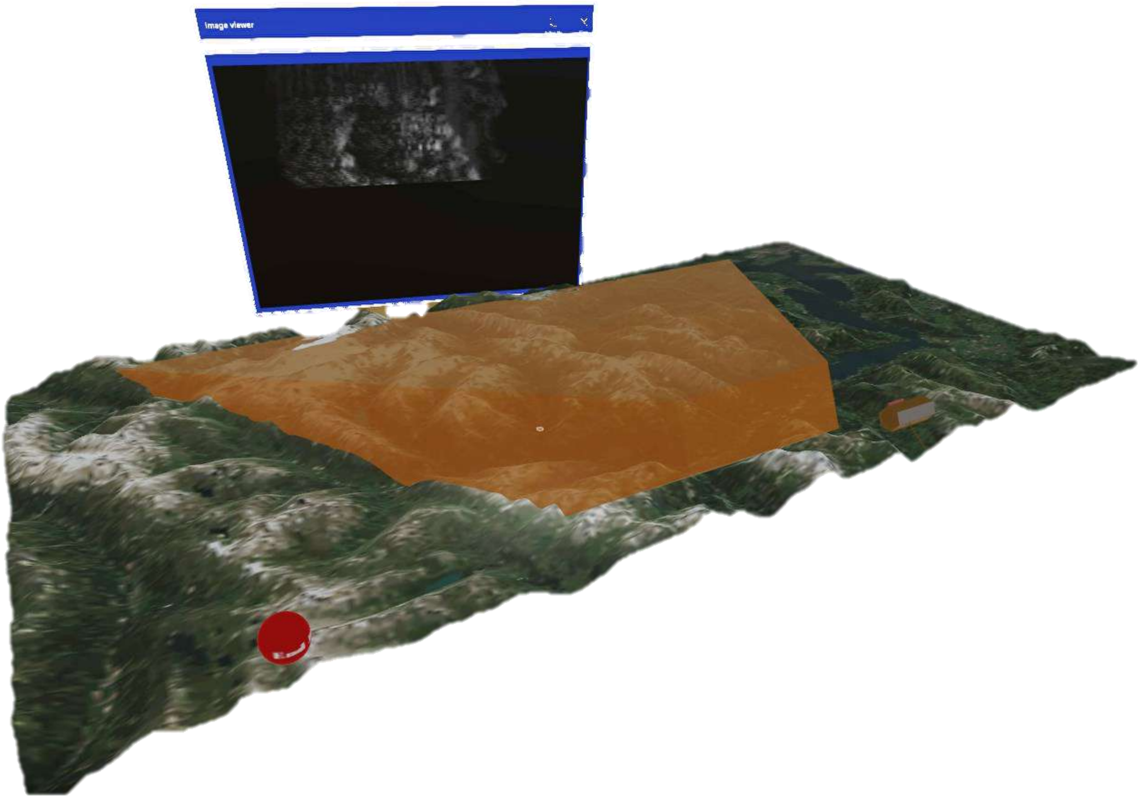

Figure 2: SAR² demonstrating an acquisition over a virtual terrain model of the St Gotthard region of the Swiss Alps. The acquired radar data is immediately visualized on the display panel in the top part of the figure.

DOI: 10.5821/conference-9788419184405.031

ATTITUDE CONTROL RESEARCH WITH EDUCATIONAL NANOSATELLITES

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Abstract

This paper introduces the three-axis attitude control of the ESAT platform. ESAT is a modular nanosatellite that implements the popular 10x10x10 cm CubeSat standard, designed for hands-on learning at different educational levels as well as professional training. ESAT features the full set of characteristic spacecraft subsystems (power, on-board data handling, attitude control, communications, and payload). The satellite can be disassembled to focus on each subsystem, one at a time, or used all together, and features a flexible ground segment. Courses using the ESAT platform are imparted in our university, as part of the last year of the master's degree in Aerospace engineering, and in other institutions like the ESA Academy. They cover aspects ranging from subsystems design to testing and spacecraft operations. In addition, the platform is used in master's thesis and research activities.

Although the version that is currently being used in the courses allows only one-axis attitude control, the ESAT is in continuous development and two prototypes of the satellite have already been developed that allow three-axis control based on reaction wheels and/or magnetorquers, which is essential for the testing and verification of attitude determination and control algorithms. For this purpose, the ground support equipment has also been updated to be able to carry out the turns in three axes, with the development of new testbeds and a complete magnetic field simulator. The present work aims to show the new three-axis platform designs and its main functionalities.

Keywords

Attitude control, Educational satellite, ESAT, Hands-on training, Nanosatellites.

Acronyms/Abbreviations

ADCS	*Attitude Determination and Control Subsystem*
E-USOC	*Spanish User Support and Operations Centre*
ESAT	*Educational SATellite*
HW	*Hardware*
IMU	*Inertial Measurement Unit*
PCB	*Printed Circuit Board*
PID	*Proportional, Integral, Derivative*
PWM	*Pulse Width Modulation*
SW	*Software*
TC/M	*TeleCommand/TeleMetry*
UPM	*Universidad Politécnica de Madrid*

1. Introduction

The application of active learning methods in engineering training has a huge positive impact [1–4] because of the important practical component of the education. In the context of aerospace engineering, the second cycle of degree and master's programs generally includes subjects with a very technological focus, where practical lessons are fundamental.

In the 2009-2010 academic year, the research group "Ciencias y Operaciones Espaciales", to which belongs the Spanish User Support and Operations Centre (E-USOC) [5], launched several educational innovation activities within the Aerospace engineering degree offered at Universidad Politécnica de Madrid (UPM), implementing practical sessions using benchmark demonstration satellites. At that time, there were few available models in the market and their design offered little flexibility for training activities. These limitations motivated the group to develop a self-designed satellite: the Educational SATellite (ESAT), developed by Theia Space [6], an initiative born at the E-USOC.

ESAT is a modular nanosatellite that implements the popular 10x10x10 cm CubeSat standard, designed for hands-on learning at different educational levels as well as professional training [7]. ESAT features the principal spacecraft subsystems: power, on-board data handling, communications, payload and attitude determination and control (ADCS) systems. The satellite can be disassembled, to focus on each subsystem or used all together, and includes a flexible ground segment. ESAT has been designed so that users can easily expand both its hardware (HW) and software (SW).

Nowadays, ESAT is used in different subjects of the space vehicles intensification of the master's degree in Aerospace engineering at UPM, and in training courses for other institutions like the ESA Academy [8], covering aspects that range from design to testing and spacecraft operations. In addition, the platform is used in master's thesis and research activities. All in all, around 70 ESATs are used in other universities and institutions around the world for teaching or research.

Although the current ESAT version allows only one-axis attitude control [9], the platform is in continuous development to improve its performance and capabilities. As part of this effort, several students have developed their bachelor's and master's degree projects working on the ADCS to achieve a full three-axis attitude control [10]. Two new prototypes have already been developed, offering three-axis attitude control based on reaction wheels and/or magnetorquers, and are being used for testing and verification of ADCS algorithms. These updates include new ground support equipment that allows to carry out the turns in three axes.

The present work aims to introduce the reader the design and main functionalities of the new three-axis ESAT. In section 2, we introduce the preliminary ADCS design. In section 3 and 4, the magnetic and reaction wheels-based prototypes are described, respectively. Section 5 presents the Earth magnetic field simulator and, finally, a brief discussion and conclusions are offered in section 6.

2. Preliminary three-axis control design

The preliminary study of a full three-axis ADCS in ESAT was carried out as part of a bachelor's degree project in 2016. The project focused on HW additions and the identification of required changes to fulfil a complete three-axis ADCS.

2.1. Hardware design and sizing

Since the one-axis version of ESAT already includes sensors to determine its attitude in three axes, the work focused on the design and sizing of the actuators, i.e., the reaction wheels and magnetorquers. We note that the one-axis ESAT controls its attitude around its Z axis, which is aligned with the local gravity vector, using one coaxial reaction wheel and two magnetorquers positioned in two perpendicular axes in a XY plane — a magnetorquer generates a torque perpendicular to its axis.

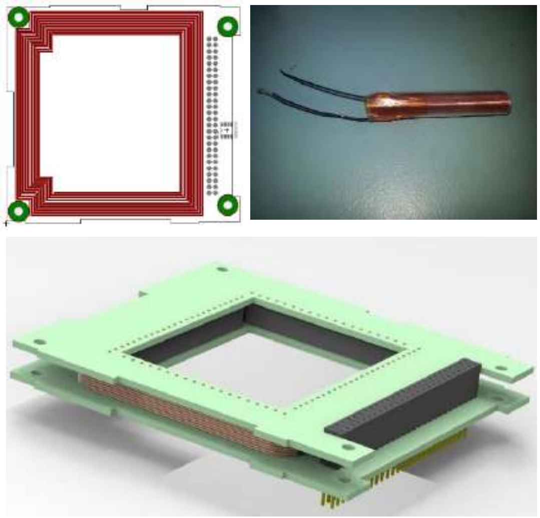

Figure 1. Embedded coil design (top left), manufactured torquerod prototype (top right), and combined air-core/embedded design (bottom).

Therefore, one magnetorquer and, at least, two reaction wheels had to be added.

Different types of magnetorquers: air-core, embedded coil and torquerod, as well as a combined design with air-core and embedded coils were studied; see Figure 1. A trade-off between these possibilities finally suggested that the best option for ESAT was the air-core solution.

Three reaction wheels were also designed to meet the requirements of a three-axis control, including the sizing and selection of Brush-Less Direct Current motors and tachometers.

2.2. Manufacturing, integration, and ground equipment

Different magnetorquers prototypes were manufactured and tested in this project. The integration process, on the other hand, must meet the geometric constraints of the 1U CubeSat and Printed Circuit Board (PCB)/104 standards, and provide a suitable mass distribution. Figure 2 shows two examples of integration proposals: the left optimizes the integration process and the right the mass and the prize.

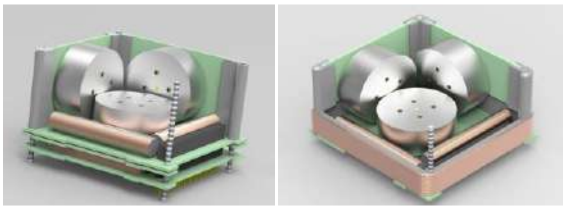

Figure 2. ADCS configurations with different HW.

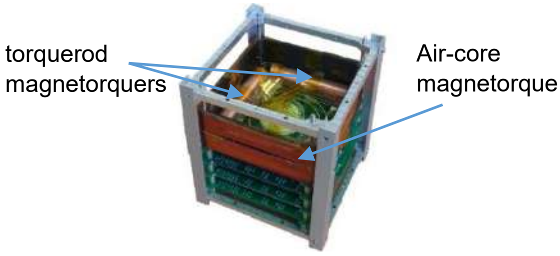

Figure 3. Three-axis magnetic controlled ESAT prototype.

The project was finished with a preliminary study of possible ways to develop a low-cost three-axis testbed for ground tests. This study has been continued in the following years and is still in development.

3. Magnetic three-axis ADCS implementation

With the preliminary design completed, the next step was the implementation of magnetic control and the materialization of the first three-axis controlled ESAT prototype. This prototype, developed during a master's thesis in 2018, added the third magnetorquer, an air core one, and relocated the other two due to geometrical constraints; see Figure 3.

To finalize the development, the complete determination and control cycle was implemented, including sensor reading, attitude estimation, error analysis, control laws definition and actuators commanding.

3.1. Attitude determination and sensors

This prototype was equipped with a three-axis gyroscope, an accelerometer, and a magnetometer. The signals were calibrated to eliminate the bias and a digital low pass filter was applied to reduce noise.

Considering the educational purpose of the satellite, different determination algorithms using different combinations of sensors were implemented: the TRIAD and Q-methods, and the integration of the gyroscopes [10]. In practical sessions, this allowed the student to discover when each method is more suitable, and the numerical problems associated with each of them.

3.2. Control laws

The magnetic three-axis prototype implemented a configuration based on a quaternion feedback schema and a Proportional, Integral, Derivative (PID) control law with the magnetorquers commanded through a Pulse Width Modulation (PWM) signal. Again, a detumbling B-dot

Figure 4. Three-axis magnetic-controlled ESAT and testbed prototype.

control law was also included for educational purposes.

3.3. Communications, ground segment and test facility

Telemetry (TM) and telecommand (TC) definitions followed industrial standards; TM and TC packages complied with the 'Consultative Committee for Space Data Systems' space packet protocol standard. Furthermore, the ground segment data base was defined through the 'eXtensible Markup Language Telemetric and Command Exchange' format.

The master's thesis also included some improvements in the three-axis testbed. In particular, the mass balancing system required to minimize the effect of gravity in ground tests incorporated more stable counterweights and rods; see Figure 4.

4. Three-axis ADCS implementation based on reaction wheels

As a natural extension of the work described above, a new reaction wheels-based ADCS was developed in a subsequent master's thesis.

4.1. Design

The first step of the process was to find the new components needed to achieve the desirable performance, constrained by the available space that ESAT provides to integrate them in its new configuration. In addition, a market search was carried out to study the state of the art and to check if there was any Commercial Off-The-Shelf platform that could be used. During this preliminary phase, simulations of the satellite on the testbed were implemented in

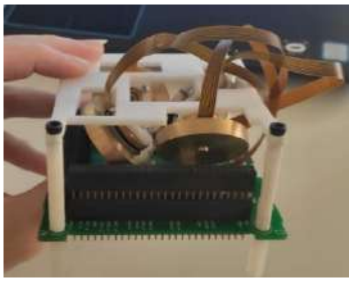

Figure 5. Reaction wheels based ADCS before being integrated in the ESAT.

MATLAB to have a first estimate of the main parameters that define the design.

The detailed design was divided according to HW and SW. The HW design consisted of choosing the motors as well as designing, manufacturing, and assembling a new PCB that included the electronic components for controlling these motors. It was also needed to design the reaction wheels, the wheel-motor coupling and the optimization of wheel's mass, inertia, and spatial arrangement. Figure 5 and Figure 6 show the new ADCS subsystem separately and integrated in the ESAT.

Regarding SW design, the QUEST attitude determination algorithm was added and a PID controller was implemented using modified Rodrigues parameters [11] as control variables. All TM and TC necessary for the satellite control were added, and a graphical user interface was designed.

4.2. Testbed

To analyze the behavior of the ADCS prototype, a new testbed was designed; see Figure 7. This testbed included automatic movement of the masses to reposition the center of gravity by means of stepper motors and an Inertial Measurement Unit (IMU) was added to facilitate the centering process.

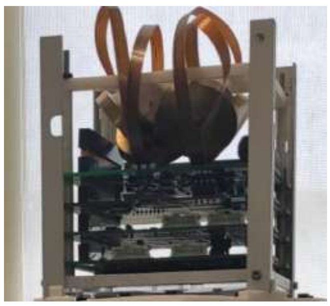

Figure 6. Reaction wheels based ADCS mounted on ESAT.

DOI: 10.5821/conference-9788419184405.032

Figure 7. Testbed with automatic reposition of the center of gravity.

This new equipment will also be the starting point for future work of other students. Improvements could be applied for a better location and reposition of the center of gravity as well as for the determination of the inertial matrix. The system could also be adapted to be mounted on an air bearing.

5. Earth magnetic field simulator

The development of new ground support equipment for ESAT also offers great opportunities for students. A complete magnetic field simulator was developed as a bachelor's degree project by using the Helmholtz Coils concept. A structure of three pairs of coils, one per coordinate axis, can generate an orientable magnetic field of adjustable intensity. This type of installation is popular in the space sector for satellite's testing, like the ESA's Magnetic Field Simulation Facility.

5.1. Design and manufacturing

The basic requirements for the simulator were its size and the strength of the magnetic field. The interior space had to fit the ESAT and the different testbeds that had been developed. Regarding the intensity of the magnetic field, it had to be strong enough so that the ESAT would be able to turn overcoming the friction of the turntable by using its magnetorquers.

Having this into account, a CAD program was used to develop the model that afterwards was manufactured using a CNC machine and a 3D-printer as main tools. The body of the coils was milled in wood because of being a non-ferromagnetic material while the joint parts where 3D-printed in PLA. This manufacturing technique makes it possible to design very specific and adaptable parts while the material is resistant enough and non-ferromagnetic.

5.2. Simulator control

The intensity and direction of the magnetic field were controlled using a PID algorithm implemented in an Arduino board. Each coil was connected to a driver that, depending on the PWM signal received, adjusted the power with which the coils were being fed. The setpoint of the system was sent to Arduino from MATLAB through serial communication. The actual magnetic field was measured using an IMU placed in the center of the simulator. This unit was mounted in a bigger board with other electronic components that interfere with the measurements, so calibrating it prior to installation was critical for the proper functioning of the system. With the setpoint and the real measurement, the controller calculated the PWM to be sent to the drivers to adjust the amperage of the coils to generate the desired magnetic field.

A MATLAB-based user interface app was also developed. This app allowed the user to monitor the simulator in real time, set fixed values or program variable magnetic fields as rotating ones and save all the data generated during trials.

5.3. Test and integration with ESAT

The uniformity of the magnetic field was studied by mapping its intensity when a fixed setpoint was commanded. It was proved that the central region of the simulator, where the ESAT would be placed, had a field with irregularities of less than 2.5% with respect to the commanded magnitude.

After several minutes on, the electric resistance of the coils starts to change because they heat up and this could cause undesired variations of the magnetic field. It was tested that the PID successfully counteracted this circumstance.

Once the quality of the magnetic field generated was ensured, the ESAT mounted on the one-axis turntable was tested in the simulator; see Figure 8. The satellite was commanded to keep a certain angle with the magnetic field, and, at the same time, the simulator was programmed to generate a magnetic field whose direction would rotate while being contained in a plane parallel to the ESAT turntable base. The result of the test was successful and the ESAT revolved around its axis following the magnetic field using its magnetorquers as actuators.

DOI: 10.5821/conference-9788419184405.032

Figure 8. ESAT inside the Earth magnetic field simulator on the one-axis turntable.

6. Discussion and conclusions

The new designs and prototypes of the three-axis ESAT platform and its ground support equipment have been presented. These improvements have been carried out by several students through bachelor's and master's degree projects.

These works have allowed students to be involved in real projects, applying basic engineering knowledge as design and manufacturing. They have acquired a very broad view of the different subsystems that compose the satellite and how they relate to each other. In addition, students have gained a better understanding on control algorithms and how the satellites use the magnetic field to move and orientate itself.

Acknowledgements

This work was supported by Theia Space, E-USOC and the Escuela Técnica Superior de Ingeniería Aeronáutica y del Espacio at UPM. We thank, in particular, the research group of 'Ciencias y Operaciones Aeroespaciales' for their invaluable efforts.

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Progress of the Development of a Two-Stage Supersonic Rocket within a Student's Association

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Abstract

The Ares mission is part of a student-led project with the aim of developing a two-stage supersonic amateur rocket. This paper discusses the progress since its foundation in 2016 and how it is planned to continue progressing to achieve this objective.

Currently, 4 rockets have been built and launched, evolving different aspects of the design and construction process in each one. From the Ares I, a two-stage rocket intended to test the electronics and the structure, the mission has evolved into designing the Phobos, a rocket whose aim is to compete in European Rocketry Challenges for universities. The final objective of the Ares Mission is to launch a two-stage supersonic rocket, the Ares III.

Keywords

Rocket, two-stage, supersonic, composite materials, 3D printing

Acronyms/Abbreviations

SSEA	*Symposium on Space Educational Activities*
UPCSP	*UPC Space Program*
ESEIAAT	*Escola Superior d’Enginyeries Industrial, Audiovisual i Aeroespacial de Terrassa*
EuRoC	*European Rocketry Challenge*

1. Introduction

The UPCSP project is part of the Euroavia Terrassa student Association, forming the most technical part of the set of activities that are developed within the aerospace field. The UPCSP project is a program fully formed by more than 80 students whose objective is to apply the knowledge acquired during the degrees of Industrial, Electronics, Mechanical and Aeronautical Engineering at Missions related to the aerospace field. Within the Program, 5 branches of missions are developed: stratospheric balloons, drones, robotics nanosatellites and rockets.

The Ares mission aims to design, manufacture and launch rockets inside the UPC Space Program. Since its beginning in 2016, the rocketry team has achieved four successful launches and aims to keep up and increase the pace in the coming years.

From the Ares I, a two-stage rocket intended to test the electronics and the structure, the mission has evolved into designing the Phobos, a rocket whose aim is to compete in European Rocketry Challenges for universities.

Figure 1. UPCSP (left) and Ares (right) logos

2. Ares I

The Ares I was the first rocket to be designed and launched. This two-stage rocket is intended to test the newly developed electronics and to test a simple structure with a low power launch that is capable of stage separation.

Figure 2. The first Ares members alongside the Ares I rocket

The rocket was launched on 18th November 2017, in Alcolea de Cinca, Spain. It reached a maximum altitude of 150 m. The team was able to recover the two rocket stages thanks to two deployable parachutes. This same system has been used to recover all the subsequent rockets.

The avionics system successfully registered and stored the flight data, thus validating the electronics in the rough environment of a rocket launch.

3. Deimos I

Afterwards, the Deimos I was built using a more advanced construction technique involving composite materials. The rocket presents high structural capabilities as it was designed following the traditional means of amateur rocketry provided by the Spanish amateur rocketry association. The aim of this launch was to test a more robust composite rocket structure to incorporate in bigger rockets.

The rocket was made using a cardboard tube as a work base for the structure. The cardboard tube was covered with two layers of fiberglass and epoxy resin. The epoxy excess was removed with a vacuum chamber, while the fiberglass was being cured. The fiberglass roughness was reduced by applying a layer of putty and polished by hand.

Meanwhile, the ogive geometry was extracted through the Open Rocket Software [1] and built by 3D printing. The 3D printing inconsistencies were also polished manually.

The Deimos I was launched with a G-class solid rocket motor.

DOI: 10.5821/conference-9788419184405.033

Figure 3. Ares members and Deimos I rocket after its second launch (September 7th, 2019)

In its first flight on the 13th of April 2019, the Deimos I recorded the launch thanks to a camera that the team placed in the small window that can be observed in the rocket (Figure 3). During this flight, the rocket registered a maximum altitude of 150 m.

As a result of its highly resistant structure, the Deimos I could be subsequently launched on the 7th of September 2019. The video of this flight could not be recovered due to issues during landing that damaged the camera.

In both flights, the electronics successfully registered flight data such as the altitude reached.

4. Ares II

The Ares II, being a two-stage rocket, incorporated several new features on top of the experience of its predecessors. In terms of design and construction, additive manufacturing polymers were introduced to the rocket structure, which led to more complex geometries in the insides of the rocket without sacrificing structural integrity. Moreover, the electronics evolved to a new board with more capabilities improving in its size and design.

The Ares II rocket was launched on the 7th of September 2019 to test the newly incorporated characteristics on top of verifying the integration with the already proven ones.

Unlike Ares I, the new design was built using additive manufacturing and composite materials. The structure of the fuselage was printed in nylon PA12 [2] and, in order to add structural integrity, covered with a layer of fiberglass and epoxy.

Figure 4a and 4b. The Ares rocket leaving the launch rail (September 7th, 2019). Successful ignition of the second stage of the Ares II (September 7th, 2019)

5. Deimos II

Furthermore, the last rocket to be built is the Deimos II, whose main objective is to allow the association to be certified in the use of level 1 engines (see Table 1).

It is designed to have the same structural design as the Deimos I while having the capability to use more powerful engines. Moreover, to have a smoother surface finish, the team implemented new manufacturing techniques, such as the use of a vacuum bag to ensure proper layer cohesion, and the use of a lathe to avoid epoxy dripping on one side.

The Deimos II is expected to be launched in May 2022.

DOI: 10.5821/conference-9788419184405.033

Figure 5. Deimos II rocket

Table 1. Solid motors classes and their requirements to be bought and launched. Tripoli Rocketry Association. [3] [4]

Class	Impulse (N·s)	Requirements
Micro	0–0,3125	No certification required for motors with less than 125g of propeller
1/4 A	0.3126–0.625	
1/2 A	0,626-1,25	
A	1,26-2,50	
B	2.51–5.00	
C	5.01-10.0	
D	10.01–20.0	
mi	20.01–40.0	
F	40.01–80.0	
G	80.01–160	
H	160.01–320	Level 1 certification required
I	320.01–640	
J	640,01–1,280	Level 2 certification required
K	1.280,01–2.560	
L	2.560,01–5.120	
M	5.120,01–10.240	Level 3 certification required
N	10,240–20,480	

6. Phobos

Finally, the mission has been designing the Phobos rocket. Its main objective is to participate in the EuRoC [5]. The Phobos is a single-stage rocket that, following the success of the Ares II structure, incorporates an optimized polymer structure paired with a fiberglass composite skin. It also features improved avionics capable of live data transmission as well as a more reliable recovery system.

Structurally, the main improvement is that the 3D printed fuselage is mass-optimized through generative design (see Figure 6).

The Phobos rocket is capable of deploying up to 5 CanSat-size experiments at a maximum altitude of 3000 m. This high altitude is reached with a class M solid rocket motor.

Figure 6. Optimized lattice structure for the Phobos rocket through Autodesk Inventor [6]

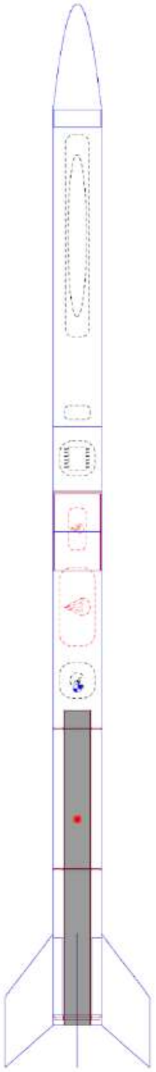

Figure 7. Phobos general configuration through Open Rocket design

7. Ares III

The Ares III rocket, which features a two-stage system, is in an early design phase pending the launch of the Phobos rocket to incorporate the tested structure. The Ares III aims to be the last rocket of the mission as it has been designed to reach supersonic speeds in a similar two-stage design as the Ares II.

This last proposed rocket marks, as we like to say between the student members of the UPCSP, the end of the beginning of the Ares mission, and after it, always aiming higher and beyond our possibilities. Thus, consolidating all our projects and becoming known among the rocketry associations nationwide and at an international level.

Figure 8. Generative design on the Ares III's motor section structure

Acknowledgements

This project would not have been possible without the help of UPC University, since the institution has founded the project as well as given appropriate facilities to work at. Moreover, HP's support has been crucial in order to be able to acquire such high-quality 3D printed parts. Furthermore, Resineco has also founded the project by providing the required materials. In terms of software, this project has been strongly supported by Valispace and Altair, which have allowed the team to perform various types of simulations. Likewise, both Tripoli Spain and Tripoli France have played an essential role in allowing the team to launch the different rockets, as well as to provide the necessary material and facilities. Last but not least, the UPCSP thanks the 4th SSEA22 [7] Scientific Board for giving young students the opportunity to present their projects and get in touch with the scientific community.

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Meteor observation with the SOURCE CubeSat – Developing a simulation to test on-board meteor detection algorithms

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Abstract

The scientific mission objectives of the Stuttgart Operated University Research CubeSat for Evaluation and Education are meteor observation, measurement of the lower Earth's atmosphere during re-entry as well as technology demonstrations. The meteor observation is done by pointing a camera towards Earth and continuously taking images during Eclipse. Since it is not possible to downlink all images, an on-board detection algorithm is necessary and mission critical. Therefore, this algorithm needs to be tested thoroughly. Realistic test data showing meteors from orbit is needed to properly develop and test the algorithm. Existing videos, provided by the Planetary Exploration Research Center, captured from the ISS are used as a baseline but are not sufficient to test the algorithm. The videos do not have the diversity of meteors needed and the meteor properties are not settable which makes it difficult to test the detection algorithm in as many scenarios as possible. Therefore, an artificial meteor program was developed to simulate meteors with given properties as perceived from a meteor observation system in a low Earth orbit. Here, we present the details of the artificial meteor program, its working principle and how we tested an algorithm for meteor detection.

The user can choose between different background videos, the existing ISS videos from PERC or the self-generated videos. Each different background is used to test a different aspect of the meteor detection algorithm. The ISS videos from PERC provide more diverse backgrounds than the self-generated videos with e.g., clouds and lightning. For these self-generated videos, a program is developed to take image sections of NASA's Black Marble and putting them frame by frame together into a video. These videos are more suitable for simulating satellite rotation and camera properties.

Independent of the background video, settable meteor properties contain important characteristics of a meteor like the light curve, brightness, speed, direction and shape. Additionally, the user can choose the meteor position in the video frame, in which frame it appears and which distance it covers. Furthermore, distortion settings can be applied which contain airplanes with adjustable parameters and scalable noise.

Only a properly working meteor detection algorithm leads to a success of a mission critical part of the SOURCE CubeSat. Therefore, the development of this artificial meteor generation program is crucial. Furthermore, this technology demonstration of developing and especially testing a meteor detection algorithm will enable future space-based missions for meteor observations.

Keywords

Meteor simulation, Detection algorithm, On-board processing, Earth observation

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Nomenclature

d_{TV}	*selectable distance between camera and screen*
I_{curr}	*current pixel brightness*
I_{max}	*maximum pixel brightness*
S_{screen}	*screen size*
$Screen_{res}$	*screen resolution*
$Sensor_{res}$	*sensor resolution*
z_{total}	*total frames for visible meteor*
z	*current frame number*

Acronyms/Abbreviations

ArtMESS	*Artificial Meteorvideo Simulation Software*
MeSHCam	*Meteor, Star and Horizon tracking Camera*
PLOC	*Payload On-board Computer*
PERC	*Planetary Exploration Research Center*
SOURCE	*Stuttgart Operated University Research CubeSat for Evaluation and Education*

1. Introduction

This paper describes the working principle and results of developing a meteor simulation named Artificial Meteorvideo Simulation Software (ArtMESS). The task of ArtMESS is to create videos, showing meteors entering Earth's atmosphere as seen from orbit. Those videos are needed to test space-based meteor detection algorithms. ArtMESS can generate a variety of different, realistic meteors which allows systematic testing. Its use case include testing and optimizing a detection algorithm for the Stuttgart Operated University Research CubeSat for Evaluation and Education (SOURCE) satellite on ground using realistic data. The SOURCE satellite is a 3U+ CubeSat developed by KSat e.V. and the Institute of Space Systems at the University of Stuttgart and is part of ESA's *Fly your Satellite!* program [1]. Its mission objectives are education, technology demonstrations, re-entry science and meteor observation during eclipse. A visual camera is used for meteor observation. The observation generates a high amount of image data. This leads to the necessity of onboard processing since the downlink capacity is constrained. Due to the limited processing power and the absence of suitable detection algorithms, one must be developed and tested on ground. The camera used onboard the satellite is called Meteor, Star and Horizon tracking Camera (MeSHCam) (see Table 1).

Table 1. Details of the MeSHCam

Parameter	***Value***
Camera	GenieNano M1920
Sensor resolution	1936 px × 1216 px
Pixel size	5.86 µm
Lens	Schneider-Kreuznach Cinegon
Focal length	12 mm
Field of view	31° × 48°

For the testing campaign and algorithm development a testbed is setup and calibrated in the IRS cleanroom. The testbed consists of the MeSHCam that is imaging a TV screen showing videos of meteors as seen from orbit. These images are saved and can be processed later or live using the PLOC. The algorithm then returns the positions and frames of the detected meteors.

2. Meteor Simulation ArtMESS

The meteor simulation is a Python based program. Fundamentally, it takes provided background videos, for example captured videos from the ISS by the Planetary Exploration Research Center (PERC) [2] and adds artificial meteors to provide suitable test data for an onboard detection algorithm. The following chapters will go into more depth on the three main parts of the program which are the used backgrounds, the meteor image generation itself and the implementation of several distortions (e.g., camera noise) that can occur observing meteors from a satellite.

2.1. General Principle

ArtMESS reads in a selected background video and saves each video as an individual image. Next, the meteor images are generated. Therefore, the number of images from the background video is counted. For each background image a mask image containing the meteor is generated, all other pixel values are set to 0. The mask images are combined into a three-dimensional array. Axes one and two of the array represent one mask image with the dimensions of the video (e.g., 1920 x 1080). The meteor pixel brightness is set according to adjustable parameters. The third axis represents the temporal progression. The length of the third axis is set by the number of background frames. Afterwords, the array is also divided into frames and saved as individual images. These mask images are then further adjusted for distortions like camera noise. In a final step, both the initial background images and the mask images are put together into joint image frames and in the end into to the final test video. All parameters set by the user or chosen randomly are written to a csv-file along with the assigned video name to allow for later review. This also includes the frame number and position in the frame of the implemented meteor. Thus, automated evaluation is enabled by comparing the meteor positions detected by the detection algorithm and the actual positions of the meteors. ArtMESS is also capable of operating in three different modes. Int the first mode a single video is generated, the second one generates a whole test set which varies meteor parameters for systematic testing. Finally. the third mode allows to read parameters of a previous run and change some parameters (e.g., implementing the same meteor but using a different background).

2.2. Backgrounds

The used backgrounds can be divided into three categories: A black background, self-generated background videos from NASA's Black Marble [3] and ISS videos from PERC [2].

The black background is used to create baseline videos for testing. They can be used to test the algorithms general capability of detecting meteors. The self-generated background videos are used to test the algorithms' ability to distinguish city lights from meteors. The background videos are based on the black marble images and are generated using an additional small script using the sliding window method. For this method sections of NASA's Black Marble image [3], which shows the Earth at night, are used: A sliding window moves across the image plane, generating a series of frames that are put together in a video. This imitates a satellites movement while observing Earth. This is possible due to the large resolutions of the black marble images. Finally, ISS videos provided by PERC [2] are used. These offer a lot of variety for example lightning, clouds, real meteors, or image errors like noise.

2.3. Meteor image generation

The detection algorithm determines areas that are not moving in the main direction caused by satellite movement. Hence the following parameters can influence the result of a successful detection (see [4] and [5] for more details on the algorithm).

Brightness: Brightness is an important factor not only influenced by the absolute brightness but also by the light curve itself. The light curve of a meteor represents the variation in brightness as it burns up in the atmosphere. For a realistic result it is necessary to consider this property of a meteor. Therefore, a brightness function is used, which gives the current pixel brightness (l_{curr}) of the meteor depending on the duration of the meteor (z_{total}) and its maximum brightness (l_{max}). The currently implemented functions is orientated on actual light curves measured [3]. It is implemented as shown in Eq. 1, where z is the current time step.

$$l_{curr} = l_{max} - \frac{4}{z_{total}^2 * l_{max}} * \left(\frac{z - z_{total}}{2}\right)^2 \qquad (1)$$

For a more realistic depiction in the final video, each pixel brightness is multiplied by a random factor between 0.8 and 1.2. This simulates the burn up of the meteor in the atmosphere and considers the fact, that the meteor has not the same brightness of its spatial extension.

Speed and angle: Furthermore, speed and angle play a key role in the simulation. A similar meteor and satellite movement makes it harder for the algorithm to detect the meteor. Suitable and realistic values for speed have been found to be 1.5 to 7 pixels of meteor movement between two frames. A meteor is considered easy to detect when the angle between satellite and meteor movement is 180° +- 45° while 0° +- 45° are the hardest to detect. In this case the meteor moves almost in the same direction as the satellite.

Trail: The final parameter is the length of the meteor trail. It is used to further diversify the available test cases. The longer the trail the easier the algorithm recognizes the meteors due to their larger size. Values between 100 pixels to 500 pixels are good and realistic values.

It is important that the motion of the meteor is realistic with respect to background. Therefore, an optical flow is calculated for the background videos and is used to correct the movement of the meteor between frames.

2.4. Distortions

During space-based meteor observation, a variety of distortions can occur. The algorithm needs to deal with those. Radiation and camera noise can complicate detection and are therefore considered in the simulation. Implemented are e.g., gaussian noise, salt and pepper noise or hot pixel to name a few. The noise is layered over the final video frames, as one of the last steps.

Additionally, to the noise, the algorithm also needs to deal with limitations of the attitude control system: The satellite may rotate around the optical axis during observation. This effects the algorithm and needs to be considered during testing and development. Thus, the ArtMESS allows to generate videos with a settable rotation. It is implemented by using a bigger sliding window on NASA's Black Marble images [3]. This results in a larger background video with higher aspect ratio. After generating the meteor images and combining them with the background, the final video images are cut out and rotated by a few pixels each frame. This results in a rotation around the optical axis.

3. Testbed setup

As mentioned above, the testbed is used to display and image the generated videos using the meteor detection camera MeSHCam. The images taken by the camera are either processed with the meteor detection algorithm in real time or stored for later processing. This allows to test the camera, the control software as well as to optimize the algorithm by using realistic data: The images are acquired with the same camera and significant camera settings effecting the algorithm as planned for the orbital observations. Before describing the required calibration, a short overview of the testbed design is given.

3.1. *Testbed Design*

The testbed consists of a large OLED screen mounted on an aluminum frame. The camera is mounted on an optical rail to allow horizontal and vertical adjustments as well as providing a fixed and defined position.

When conducting measurements, the complete setup is covered in blackout curtain to prevent stray light from entering the setup as you can see in Figure 1.

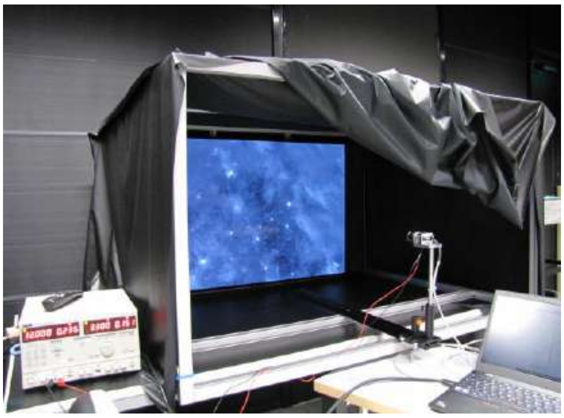

Figure 1: The testbed setup during algorithm testing in the clean room with MeSHCam and a generated video displayed.

3.2. *Optical design*

An OLED screen is chosen as the basis for the testbed, since pretests showed that screens using a backlight (e.g., LCD) cannot be used. This is due to the fact, that the backlight emits light even for complete dark parts of a video (high black level). The light is imaged by the camera and results in unrealistic images. Moreover, the issue is worsened due to the uneven distribution of the light generated by the screen. An OLED screen uses individual LEDs for each pixel, thus in black parts of the video the LEDs are turned off resulting in a superior black level.

Two aspects are considered when designing the testbed:

1) The size of the screen must be large enough to cover the complete FOV of the camera at a useful distance. A useful distance is defined as large enough that the camera still can be focused (614mm for the used lens) but small enough to keep the setup at reasonable dimensions (not larger than 1.3m).

2) At the chosen camera distance, the screen resolution should be large enough. This means, one pixel of the camera image should image more than one screen pixel.

The screen size can be derived from basic geometry using the FOV and selectable distance between camera and screen (d_{TV}).

$$S_{screen,v} = tan(FOV_v/2) * 2 * d_{TV} \qquad (2)$$

The vertical FOV is used since it reaches the edge of the screen first, therefore limiting the distance. This is due to the higher screen ratio (16:9=1.77) compared to the image sensor ratio (1936px/1216px=1.6). Using the screen ratio and calculated vertical screen size, the screen diagonal can be calculated.

At the time of the testbed design, only one affordable OLED screen (LG OLED55B8LLA) was available with a diagonal of 55 inch. This means, the maximum distance is about 1.2m, before the FOV expands over the screen. The actual distance used is 1m to keep the setup smaller.

The second aspect, number of screen pixels imaged on one camera pixel, is calculated with the resolution of the screen (3840px*2160px) and camera (1936px*1216px). At the given distance of 1m the size of the screen imaged is determined by using Eq. 3. Next, the number of screen pixels imaged is calculated. Finally, the pixel density can be determined using the number of screen pixels imaged and camera resolution.

DOI: 10.5821/conference-9788419184405.034

$$Pixel\ Density = \frac{Screen_{res,x}}{Sensor_{res,x}} \qquad (3)$$

For a distance of 1m, the pixel density is sufficient with 1.46 screen pixels per camera pixel.

3.3. Testbed Calibration

The testbed can only represent a proper environment if the settings of the hardware and the input images are adjusted accordingly. This will ensure that the images the MeSHCam outputs are resembling the view of an Earth observing satellite to test the detection algorithm. The calibration mainly counters the specific brightness curve of the TV screen: Instead of a linear relation between input pixel value and output pixel value, a quadratic relation was observed as can be seen in Figure 2. This is an effect of the screen because the output pixel values of MeSHCam are scaling linear with the received irradiance.

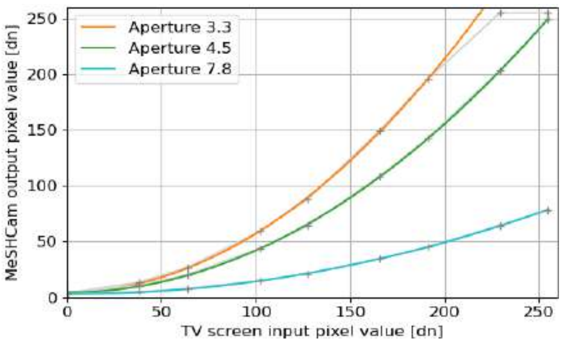

Figure 2: Output pixel of MeSHCam plotted over input pixel to the TV screen at different apertures.

3.3.1. Relative Brightness Calibration

To assure consistency between tests, specific TV screen settings were fixed. The settings were chosen in a way that leaves little to no room for the screen to modify the input. For example, OLED-Light and Dynamic Contrast were shut off. The brightness and contrast settings were selected because their specific combination resulted in the least curved input pixel value vs output brightness relation.

The next step of the brightness calibration is to determine a specific lens aperture. To use the screen to the maximum extent, a displayed pixel of maximum brightness should produce a pixel close to maximum brightness in the image the camera outputs. To achieve this, an array of 8 images with different luminosities (0 to 255) was shown on the screen and imaged by MeSHCam with different apertures in the range from 1.4 to 11. The results provided the best fitting aperture as well as enough data points to calculate the regression curve of all possible pixel values shown in Figure 2. In our case, aperture 4.5 was chosen because it met the earlier specified criteria best. The regression curve can now be used to predict the output pixel values in the camera given the input pixel values of the screen. Through reversing the curve, it is possible to determine the input needed for a specific output. In the meteor simulation, a Python function creates a lookup table and then swaps all pixel values in an input frame. If a modified frame is imaged by the MeSHCam, the brightness in the resulting image will be almost identical compared to the original input frame as can be seen in Figure 3.

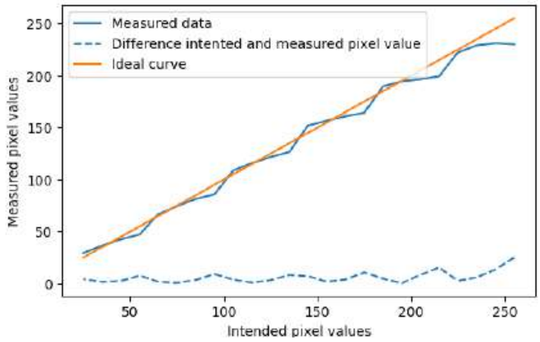

Figure 3: Comparison of pixel values after the calibration's adjustment.

3.3.2. Geometric Calibration

Automated test evaluation using the known meteor position in the video and the detected meteor position determined by the algorithm improves the development speed of the algorithm significantly. It is achieved by mapping pixel positions on the screen to pixel coordinates in the camera image. This requires a fixed camera: The camera must be centred and rotationally aligned with the screen. In order to take into account small inaccuracies in camera alignment between individual tests, a chequerboard-style image is imaged by the MeSHCam. The corners of the squares can be automatically read out, thus creating a rough map. Finally, interpolation between coordinates allows the mapping of all coordinates from the taken image back to the original frame. If the algorithm detects a meteor at a specific position in the image, the position can be mapped to coordinates in the original image. Since the meteor position in the original video is known from ArtMESS, it can be checked whether the meteor was identified correctly.

4. Results

The meteor simulation works and is used to develop and improve the detection algorithm.

4.1. Application of the simulation

In the scope of a master thesis, the simulation was used to develop and improve the algorithm

[4]. Therefore, a systematic set of test videos was generated. This test set contains videos with different backgrounds, each is used for a different purpose: The black background is used to evaluate the effect of algorithm parameters on the detectability of meteors with different properties (e.g., speed and brightness). The black marble backgrounds [2] are used the determine the effect of a moving background and adapt the parameters accordingly. Various videos taken from the ISS [2] are used to consider clouds and lightning.

All in all, the simulation was crucial for testing, improving and setting parameters for the algorithm. Furthermore, the export of the meteor position in the generated videos allows for an automatic evaluation of the results since the algorithm also exports the meteor position and time of detection. Using a Python script to automatically evaluate the detection performance significantly reduces the development time.

4.2. Comparison of artificial and real meteor

To validate the simulation and assure realistic data is generated, the videos and implemented meteors were compared to the meteor videos taken from by PERC from the ISS. As can be seen in Figure 4, the artificially generated meteor looks similar to a real meteor. Thus, the generated videos can be used for further development.

Figure 4: This image shows two meteors. On the left you can see an artificial meteor and on the right is a real meteor for comparison. [3]

5. Discussion / Conclusion

As outlined in the previous section, ArtMESS is a crucial tool in the development of the novel space-based onboard meteor detection algorithm for the SOURCE mission. Therefore, the development of the detection algorithm and testing it with ArtMESS is mission critical. ArtMESS will be used to further improve the detection algorithm and will also be further developed. For example, the formula for the light curve can be improved and adapted to represent a more realistic meteor burn up. Since other space-based meteor observations missions are planned and each of them relies on a working detection algorithm, we decided to publish ArtMESS under an open-source license. ArtMESS will be published this year on the Institutes Software Repository[4].

Acknowledgments

A special thanks goes to all students who have been and are working onwards a successful SOURCE mission. Additional thanks go to the academic personnel at the IRS and students of KSat who supported us with their time and expertise. We also want to thank ESA for their support with the *Fly your satellite!* program and all sponsors of SOURCE without their help the realization of such a project would not be possible.

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A Flexible CubeSat Education Platform Combining Software Development and Hardware Engineering

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Abstract

While many secondary schools offer courses or extracurricular activities that focus on satellite engineering, e.g. CanSats or the assembly of ground stations, these projects usually stay close to ground. With SpaceTeamSat1, the TU Wien Space Team wants to enhance this approach and tackle the challenge to perform various experiments in space, enabling students to participate in a space mission that actually orbits our planet. Therefore, our goal is to develop a 1U CubeSat platform, which allows students at secondary schools to access a set of different sensors connected to a Raspberry Pi. Consequently, students can write their own software experiments in Python and exploit the possibilities of sensors in space.

In this context, participation happens at different stages: For one, students are getting in contact with Python, which also allows an easy step into software engineering paradigms. Moreover, our team will pose some challenges, such as re-doing an earlier satellite mission and giving impressions about how CubeSats can be used, e.g. to combat climate change. To complete these challenges, the CubeSat is equipped with various sensors such as temperature sensors, gyrometers, magnetometers, as well as two cameras. Moreover, the participating students also have the possibility to design their own experiments independently to leave room for creativity.

Further enhancing this educational mission, participating students are also invited to work on hardware topics. This is mainly aimed at engineering schools, which are encouraged to assemble Raspberry Pi HATs which contain the actual mission sensors, as well as a SatNOGS ground station, which also enables students to get an insight on satellite communication. It needs to be considered that the educational mission follows a modular setup since the combination of all individual tasks is not realizable within a single school year. Thus, schools are also able to individually select appropriate tasks.

In the past we were already collaborating with the European Space Education Resource Office as we are acting as launch provider of CanSats for ESERO's Austrian CanSat competition. In this sense, STS1 shall be an extension to the space educational program in Austria. Based on that, we believe that the STS1 mission has a high potential to bring something that is currently out of reach for most people, outer space, closer to a demographic with a lot of talent and enthusiasm for engineering and potential future engineers.

Keywords

CubeSat, Python, Raspberry Pi, SatNOGS, software engineering

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Acronyms/Abbreviations

COBC	*Communication module and on-board computer*
EDU	*Education module*
EPS	*Electrical power system*
ESA	*European Space Agency*
ESERO	*European Space Education Resource Office*
FW	*Firmware*
GS	*Ground station*
HAT	*Hardware attached on top*
LNA	*Low noise amplifier*
PCB	*Printed circuit board*
RBF	*Remove-Before-Flight (pin)*
RF	*Radio frequency*
RTOS	*Real time operating system*
RODOS	*Realtime Onboard Dependable Operating System*
ROS	*Robotics Operating System*
SatNOGS	*Satellite Networked Open Ground Station*
SBC	*Single board computer*
SDR	*Software defined receiver*
SPI	*Serial peripheral interface*
STS1	*SpaceTeamSat1*
TUST	*TU Wien Space Team*
UART	*Universal asynchronous receiver / transmitter*
UCI	*Umbilical cord interface*

1. Introduction

The TU Wien Space Team (TUST) is constantly expanding their breadth of topics, and since we are already working with students to some extent via ESA's CanSat competition in Austria, we are planning on an extension of the CanSat mission by launching an educational CubeSat mission dedicated for Austrian high schools. While there are many educational missions, e.g. Astro Pi,[1] deep insights from an educational point of view on space missions are still elusive. Therefore, the primary goal is to build and operate a self-developed CubeSat, and to enable students at secondary schools to run own-developed software on our satellite. Moreover, the space mission design shall also incorporate students to a certain extent and thus, students shall gain insights on the operation of such a mission. This combination shall help students to get a deeper knowledge on space technology as well as software engineering. The idea is also inspired by the increasing popularity of platforms such as Arduino[2] or Raspberry Pi[3], which a lot of students are already familiar with. Consequently, we started developing a satellite around the idea of a Raspberry Pi that can run programs using various instruments on board. For example, cameras, temperature sensors or magnetometers will be implemented to gain various insights. To further involve students, a pilot school supports us in selecting appropriate sensors. For ground communication, we are implementing a ground station based on the SatNOGS[4] stack, including a transmitter. This shall even deepen the understanding of space technology by actually getting in contact with space RF communication. Furthermore, students of technical high schools are invited to build and operate their own SatNOGS ground station.

The paper is structured as follows:

In Section 2 the structure as well as the utilized subsystems of the satellite are outlined and described. Section 3 discusses the education aspect and describes its high variety. In Section 4, a self-developed game, the dataflow game, is presented. This topic is also of high importance from an educational point of view as it shows how to find errors in a CubeSat design and outlines a way on how to add additional functionality to subsystems. This tool shall also be presented to students, as it depicts a way to overcome complex issues and paves an understandable way to define software architectures. This tool shall also be presented to pupils, as it depicts a way to overcome complex issues and paves an understandable way to define software architectures. In Section 5, the current results given by our prototype are presented and the impact this mission has is discussed. Finally, Section 6 concludes the discussed topics and gives an outlook.

2. Subsystems

2.1. System Architecture

Our 1U CubeSat is divided into multiple subsystems, each performing different tasks that can be combined under a common theme. Here, we use a combined communication module and on-board computer (COBC), an electrical power system (EPS), and an

DOI: 10.5821/conference-9788419184405.035

education module (EDU). The following diagram shows the subsystems and its communication interfaces.

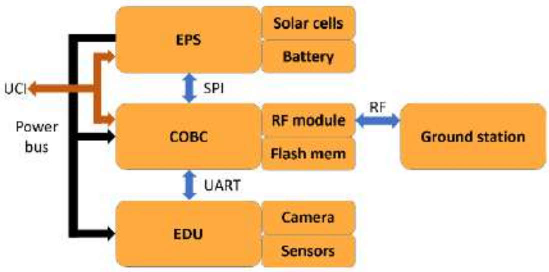

Figure 1. System architecture of STS1.

The EPS distributes power to the COBC and EDU via the power bus while also being capable of charging its batteries with solar cells. The COBC gets housekeeping data from the EPS via a serial peripheral interface (SPI), and it uses the universal asynchronous receiver / transmitter (UART) protocol to communicate with the EDU. Importantly, the COBC acts as the master and merely operates the EDU on command as a slave. However, educational software as well as results are managed and stored on the flash memory integrated on the COBC. Lastly, radio frequency (RF) communication is used to send data from and to the ground station. Additionally, STS1 features an umbilical cord interface (UCI), that is mainly used to charge the batteries (EPS) and program the microcontroller used on the COBC.

2.2. Electrical Power System (EPS)

The EPS distributes power to the subsystems and contains the system level safety features. We use a Remove-Before-Flight (RBF) pin, deployment switches, and a deployment timer, which shall prevent a premature activation of the CubeSat. In general, the satellite is powered by solar cells, which are also capable of charging a battery which is used to power the subsystems in parts of the orbit without light incidence. Importantly, no microcontroller is used, ensuring highly reliable operation. To further increase reliability only a single voltage is supplied by the EPS.

2.3. Communication Module and On-board Computer (COBC)

While other missions might separate communication modules and the on-board computer into distinct subsystems, we decided to combine both areas into a single subsystem. Here, the combination is possible since experiments are performed respectively executed merely on the education module (EDU).

On the on-board computer we use an STM32F411RE microcontroller in conjunction with a real time operating system (RTOS) called RODOS, which was developed especially for space applications where a high dependability is needed.[5] This operating system is also used by the German Aerospace Center[6], as well as in other satellite missions such as TechnoSat[7] launched by TU Berlin. The COBC will be responsible for receiving and transmitting data via a RF module, managing memory access, deploying the antenna, and managing the Python files as well as the result files to respectively from the EDU. Furthermore, it collects housekeeping data, which is then combined into a beacon and sent to earth periodically.

The commercial off-the-shelf RF module transmits data at 434 MHz band, which is an amateur radio band. Again, from an educational point of view this shall envision students the possibilities of amateur radio technology.

2.4. Education Module (EDU)

The EDU handles the educational task apart from developing and operating a satellite from scratch. It contains a Raspberry Pi Compute Module 3+ which enables students to perform their own experiments in space. Students are able to submit Python programs which can use an array of sensors and a camera to collect data and take pictures. The resulting data is stored and transmitted back to earth, where further analysis and evaluation can happen. Ambitious students may also use the Raspberry Pi on-board the CubeSat for pre-evaluations and further decision making in their Python software experiment.

For the execution of the student software, we are using the Robotics Operating System (ROS).[8] This allows us to easily handle sensor data via a publisher-subscriber pattern. Moreover, it can be used seamlessly with Python.

2.5. Ground Station

The primary ground station handles all uplink commands as well as is capable of receiving downlinked data. To further increase downlink capabilities, we also include SatNOGS, which is an open-source satellite ground station network, striving to build a free to use receive-only network of ground stations around the globe.[4] Importantly, these ground stations are easy to build and are an extension to our educational mission, as schools shall be encouraged to build and operate their own SatNOGS stations.

DOI: 10.5821/conference-9788419184405.035

It consists of a helical antenna for the 70 cm satellite RF band, rotatable using an antenna rotor. The signal is amplified using a low noise amplifier (LNA) and then fed into a HackRF-One[9] software defined receiver (SDR). The software for satellite tracking as well as data handling is controlled by a Raspberry Pi 4 single board computer (SBC).

As a RF uplink for our satellite is also required, we plan on extending the capabilities of the standard SatNOGS software stack with transmission capabilities. Therefore, a simple solution is to add a power amplifier to the HackRF-One's transmission output. By doing so, legal aspects also need to be considered. A diagram of the data flow between the ground station and the CubeSat STS1 is shown in Figure 2.

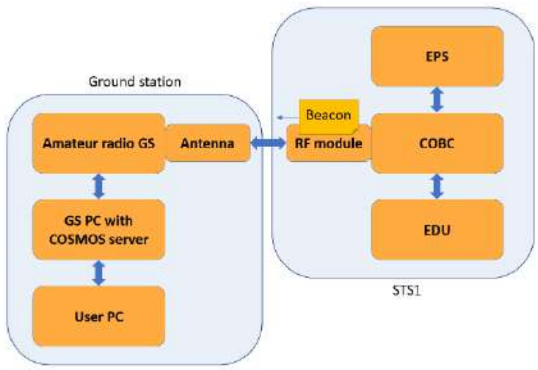

Figure 2. Data flow interfaces of the ground station and the CubeSat STS1.

While our SatNOGS ground station has up- and downlink capabilities, we also plan for students to build their own receive-only SatNOGS ground station. Furthermore, Figure 2 also symbolizes part of our design process that we want participating students to use, dataflow games. It works by people acting as subsystems and giving data notes to recipient subsystems, as demonstrated with the "Beacon" note. A person acting as the COBC, for example, will thereby assemble a data packet (beacon) from housekeeping data by creating a note and then drag it to the RF module, where the next person performs the steps necessary to send it to the ground station.

3. Education

3.1. Educational Mission

Figure 3 shows various aspects of the educational mission, where the CubeSat educational mission stands in the center of the mission. Our educational mission can be split into three types of objectives: scientific objectives, software objectives, and hardware objectives.

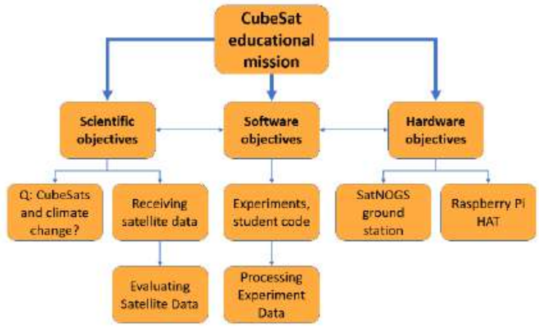

Figure 3. Modular approach of the educational mission.

We realize that working on topics of all objectives is not feasible for most students within one school year. Therefore, a modular approach is proposed. This will mostly affect the hardware topics, as they may be difficult to approach for students that do not attend engineering schools with the necessary teaching staff and equipment. Those groups will receive pre-assembled development hardware (Raspberry Pi HATs with the missions sensors) and the satellite communication will run entirely through the TUST. However, students are encouraged to focus on scientific topics and the design of their experiment instead, as this is a perfect opportunity to write their final thesis. Students from engineering schools on the other hand can also work on hardware challenges. This includes assembling the PCBs for their development hardware and most importantly, building a SatNOGS ground station. While transmissions to the satellite will still be operated by the TUST, this enables students to receive satellite data on their own, which also includes other satellites registered in the SatNOGS network. As with the final thesis before, students from engineering schools can easily use their work with STS1 as a final year project.

3.2. Predefined Challenges

Moreover, while we want students to express their creativity with this project, we will also pose some mandatory and optional challenges. Those challenges include topics such as climate change, which is something that we believe should be part of the project, or recreating an older satellite mission. This has the added benefit of creating a guided path, which offers an easier start for beginners. Additionally, students gain experience for new experiments. Lastly, it also allows the TUST to offer more appropriate support in the case problems arise.

4. Dataflow Games

Dataflow games are one of our most important tools to find flaws in the satellite design. As mentioned before, it is based on the idea of people acting out subsystems or even just parts of a subsystem. One starts out by choosing a scenario to run through, such as sending a Python file to the COBC for storage and further execution on the EDU. Within the scenario, every actor will act out the steps that their subsystem would take, e.g. the ground station is responsible for encoding and signing the file, then transmitting it at a certain time stamp, when the CubeSat is in sight. Utilizing this tool also helps to understand the challenges and requirements for satellite missions. Therefore, our dataflow game is also part of the educational objective for students. In a general introduction at the beginning of the actual mission, this game will be played in a simplified manner with students to introduce them to the delicate and fascinating topic of CubeSat mission design.

The TUST used an online whiteboard tool for documentation. Therefore, we can keep track of messages and the system state by putting notes with relevant information into the relevant place, for example a beacon getting sent down will be modeled as a note that gets passed down from subsystem to subsystem until it has reached its destination, as seen in Figure 4. Memory contents, such as Firmware (FW), that stay the same for some time are also depicted with notes. An example is shown in Figure 4.

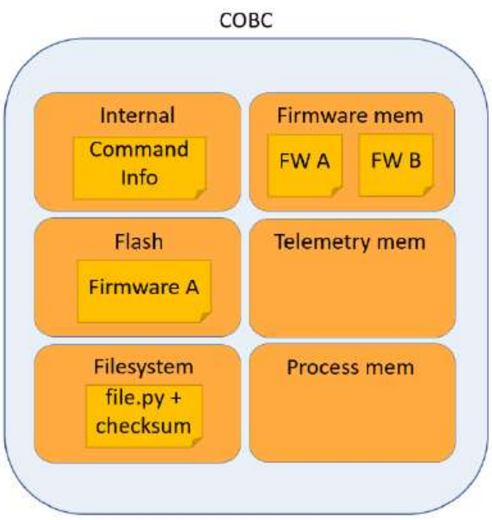

Figure 4. An example of COBC memory states at a certain time within the dataflow game.

For more complex processes within a subsystem, the use of flowcharts is more appropriate. This approach made it possible to flesh out the subsystems before submitting our design to external reviewers. We will also encourage students to use this approach, as it shows flaws in the design and the processes very quickly. Therefore, it can teach beginners how to work on complex projects and derive software and hardware architectures from specified behavior.

5. Results & Discussion

Our results so far are considerable. Before constructing the actual CubeSat, we are working on a prototype board which shall have the same functionality as STS1, but all the subsystems are mounted on an easily accessible PCB. At the time of writing, we could verify that the design is operational, and we are running a demonstration project. This includes sending simple commands to the COBC via UART and performing tasks such as reading the reset counter from a backup register or controlling the EDU from the COBC and receiving its data.

With other space education programs getting traction and STS1 already generating much interest from schools we can see that projects like ours are in demand by students. Even at this stage we are cooperating with a pilot school that has committed to participate in an extensive capacity, aiming to work on all topics, including the SatNOGS ground station. This is not surprising, as space is a topic that has always been popular among every age group, as demonstrated by the number of students participating in ESERO's CanSat competition every year, for which the TUST launches the rockets in Austria. We believe that giving students hands-on experience has the potential to make an impact on their future field of study or profession. Since the TUST can only work with a limited number of groups within Austria, we encourage other university engineering teams to think about developing their own educational projects.

6. Conclusions

We believe that our CubeSat mission is very promising, further enhancing the scope of space education. Due to its modular approach with different tasks, it allows us to bring space education to the next step. Consequently, we are not merely constructing a working prototype with a demonstration program. Moreover, we already received feedback from schools, which are interested in participating. We designed a satellite system from scratch and employed dataflow games successfully to debug our design. The first pilot school has also already received a demonstration of the prototype and their students are given the opportunity to write their diploma theses on their involvement with the STS1 project.

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DOI: 10.5821/conference-9788419184405.035

An example of Space Engineering Education in Spain: a master in space based on Project-Based Learning (PBL)

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Abstract

This work describes the successful education experience for five years of space engineering education at the *Universidad Politécnica de Madrid* (UPM), Madrid, Spain. The MSc. in Space Systems (MUSE, *Máster Universitario en Sistemas Espaciales*) is a 2-year and 120-ECTS (European Credit Transfer and Accumulation System) master program organized by the Microgravity Institute 'Ignacio Da Riva' (IDR/UPM), a research institute of UPM with extensive experience in the space sector. The teaching methodology is oriented to Project Based Learning (PBL), taking advantage of the IDR/UPM Institute experience. The main purposes are to share the IDR/UPM knowledge with the students and promote their collaboration with several space scientific institutions, both national and international. In the present work, the most relevant characteristics of this master program are described, highlighting the importance of the student's participation in actual missions.

In addition, to offer practical cases in all aspects of satellite development, the IDR/UPM decided to create its own satellite development program, the UPMSats. The latest, the UPMSat-2, is an educational, scientific, and in-orbit technological demonstration microsatellite (50 kg-class) that was launched in September 2020 on-board a Vega launcher (VV-16 flight). MUSE students have participated in all phases of the mission, from design to integration, calibration, and testing, and (at present) in-orbit operation. The construction of a microsatellite, although it exceeds in time the academic duration of the master, has proven to be a very interesting and versatile tool for PBL education, since it provides practical cases at all levels of development. Furthermore, the continuity of the project encourages graduated students to continue their education with a Ph.D. and the collaboration of master and doctoral students. These reasons have made MUSE one of the most successful academic programs in space systems engineering in Spain, with high employment rates in the most prestigious space engineering institutions.

Keywords

Space Systems, Master, Education, Project Based Learning

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Acronyms/Abbreviations

ADCS	*Attitude Determination and Control System*
CE	*Concurrent Engineering*
CD	*Concurrent Design*
CDF	*Concurrent Design Facility*
ECSS	*European Cooperation for Space Standardization*
ECTS	*European Credit Transfer and Accumulation System*
ESA	*European Space Agency*
IDR	*Instituto 'Ignacio Da Riva'*
MUSE	*Máster Universitario en Sistemas Espaciales*
PBL	*Project-Based Learning*
SSEA	*Symposium on Space Educational Activities*
UPM	*Universidad Politécnica de Madrid*

1. Introduction

Spanish universities have entailed a profound renewal in recent years to adapt their study programs as results of the implementation of the European Space for Higher Education. In the case of the *Universidad Politécnica de Madrid* (UPM), this change led to the possibility of developing new official master's degrees.

One of these new master's programs, initiated in 2014, is the MSc. in Space Systems (MUSE, *Máster Universitario en Sistemas Espaciales*), fully devoted to space systems engineering and focused on the space industry needs. MUSE is promoted, organized, and implemented by the Microgravity Institute '*Ignacio Da Riva*' (IDR/UPM), a research and technological center of the UPM named after its founder, Professor Da Riva.

IDR/UPM has a quite large heritage in space systems engineering that started in the late 70s of the 20th century with research on liquid bridges under microgravity conditions. Since then, the IDR/UPM institute has been very present in the aerospace sector, participating in a significant number of activities and missions. Some examples are the CPLM payload for the MINISAT mission [1], the thermal control of the OSIRIS instrument for ROSETTA [2], the thermal control of the balloon-borne telescope SUNRISE [3], the thermal analysis of the NOMAD payload in ExoMars [4, 5], SO/PHI and EPDS in Solar Orbiter [6, 7], or the MEDA sensors in Mars 2020 mission [8].

In addition, in 1995, IDR/UPM initiated its own microsatellite development program. The first one, the UPMSat-1 was launched in 1995 and successfully operated for one year. This spacecraft was the first 100% Spanish satellite and, according to reference [9] is 12th in the ranking of the 272 university-class satellite missions. The second one, the UPMSat-2, was launched on September 2020 in the Vega launcher VV-16 flight and is still operational. The UPMSat-3 is currently under development.

In this context, the wide experience in space systems of the IDR/UPM Institute was organized as a master program within the period 2010 and 2014, and in September 2014 the first lessons of MUSE were given to a selected group of students at the Aerospace Engineering School of UPM. Since then, the main purpose of MUSE [10, 11] has been focused on sharing with students the IDR/UPM institute experience in space research/technology, make them part of the microsatellites development program and other missions, as well as promoting collaboration with several space scientific institutions and companies.

The aim of the present work is to describe the academic design of MUSE and to emphasize the usefulness of using PBL methodologies to train master students. In addition, some insights on the way the development of the UPMSat-2 and other missions have improved the program of MUSE are presented. On the one hand, this project represents a unique framework in which students can participate in actual projects using the skills learned in the master program. On the other hand, the program of many subjects has been modified by the coordinators due to their work on different missions and projects [12].

2. Project-Based Learning applied to master programs on Space Engineering and Technology

Today, there is an increasing interest in the development of new teaching methodologies. These techniques shall be focused on the students learning, making them co-creators of their own education. The idea is to prepare students not only with academic knowledge, but also with some specific skills, such as curiosity, creativity, and collaboration, to prepare them for future success. In this context, Project-Based Learning (PBL) has emerged as an innovative educational technique that offers students the opportunity to gain knowledge and skills by participating for an extended period in real-world challenges, questions, or problems.

Applying a PBL methodology is in general a big challenge for educators, traditionally more focused on the concept of lectures rather than in applying student-centered learning. At universities where professors usually dedicate

DOI: 10.5821/conference-9788419184405.036

a part of their workload to research, PBL could be a powerful tool to involve students in the research process. This could give students the opportunity to plan their own research, propose solutions, communicate, discuss their ideas, and evaluate their own progress. Therefore, professors became guides of the learning process, but the motivation is at the students' own.

The application of PBL is especially interesting for master students, who have already acquired a solid theoretical foundation during their degree's studies. In this way, students gain professional experience in actual projects at the same time they learn.

3. Master in Space Systems (MUSE)

The Master in Space Systems of the UPM is a 120 ECTS (European Credit Transfer and Accumulation System) master program designed to provide a practical, updated, and professional approach to space technology. It is fully harmonized according to the UPM regulations regarding admission of students, organization boards, transfer credits from other university programs, Erasmus program, quality procedures, etc.

The academic load of MUSE was designed considering two major guidelines: (1) be focused on a multidisciplinary approach and (2) the use of Project-Based Learning as main learning methodology. Both aspects represent a key factor in engineering education, as students trained within this roadmap seem to be capable of better solutions when compared to students from mono-disciplinary approach programs [13]. This is especially important in space engineering, where PBL has proven to be the best way to combine academic requirements with industry needs.

Regarding general competencies and learning objectives, the MUSE academic program was designed to allow students to gain skills such as: being able to develop original ideas to solve problems in professional contexts; using the acquired knowledge to solve problems in multidisciplinary and less familiar contexts; being able to integrate different knowledge to draw conclusions from a limited amount of information, preserving social and ethical responsibilities; communicating conclusions to specialized and non-specialized audiences; predict and control the evolution of complex situations within a multidisciplinary context related to space systems developing new technologies; be familiar with the quality control systems applied to spacecraft and space engineering, particularly the European Cooperation for Space Standardization (ECSS) standards; and be able to work in group, leading it when required.

The subjects included in MUSE's academic program are shown in Table 1. They are classified in three categories, depending on the learning methodology: (1) Traditional learning (i.e., mono-disciplinary approach based on lectures); (2) Combination of a Multi-disciplinary approach (MA) and PBL; and (3) PBL.

The academic load distribution, in terms of ECTS, is also indicated in Table 1. As it can be noted, an 85% of MUSE academic load is PBL-oriented, with different levels of implementation depending on the subject.

Table 1. Subjects included in the Master in Space Systems (MUSE) of UPM, classified by learning methodology. T: Traditional learning (mono-disciplinary); M: Multi-disciplinary approach; PBL: Project-Based Learning.

Learning methodology	Subjects	ECTS
T	Advanced Mathematics (I, II), quality assurance, space industry seminars	18 (15%)
T+PBL	High velocity aerodynamics, vibrations and aeroacoustics, production, and propulsion and launchers	18 (15%)
MA+PBL	Project management, system engineering, structures, orbital dynamics and ADCS, communications, data housekeeping, power systems, test and verification, space environment, thermal control, space materials, and graphic engineering	52.5 (44%)
PBL	Case Studies (I, II, III) and Master Thesis	31.5 (26%)

In addition, four subjects are specifically oriented to PBL: Case Study I, II, III, and the final project (i.e., master thesis), in which students are encouraged to work in a space engineering project, sometimes carried out in national and international aerospace companies and institutions. These subjects, that are distributed along the 2-year program (Case study I in the 2nd semester; Case Study II in the 3rd; Case Study III and final project in the

4th), are focused on increasingly detailed aspects of the design of space systems. Therefore, they provide students with the opportunity to delve into a specific topic: from acquiring a global vision of a space system and its development process, to focusing on the preliminary design of some relevant subsystems or even going into detailed design.

The next section describes the applications of PBL to MUSE subjects. Although only a few examples are presented, they represent well what is carried out in almost every subject of the master program.

4. Examples of PBL application in the MUSE subjects

4.1. Space Systems Engineering and Project Management (1st semester)

Within the subject Space Systems Engineering and Project Management, concepts related to the new trends in space mission pre-design and feasibility phases have been included [16]. Between these concepts, the Concurrent Engineering (CE) or Concurrent Design (CD) is emphasized, which can be defined according to the European Space Agency (ESA) as "a systematic approach to integrate product development that emphasizes the response to customer expectations".

The IDR/UPM Institute has its own Concurrent Design Facility (CDF), which includes the technology and resources needed to perform parametric studies with the objective of finding a mission solution that fulfils a set of technical requirements. Through this subject, students are guided in a Concurrent Design process within the CDF [17] (see Figure 1). A mission is proposed each year, depending on ongoing projects, so a preliminary design is requested as a result of the work. The students are divided into two or three teams, each one of them performing the same mission design. This makes it possible to do a comparison exercise between the different solutions proposed by the teams when the design process has ended.

In this context, students of MUSE have participated in different missions and challenges. As some examples, they participated in the 1st ESA Academy Concurrent Engineering Challenge in 2017, with excellent results, performing a phase 0/A design for a lunar mission (Figure 1). In addition, some mission designs have also been performed within the NANOSTAR project [18], funded by INTERREG-SUDOE through the European Regional Development Fund (ERDF). NANOSTAR aims to develop a collaborative platform in Europe for hands-on nanosatellite education and training in space engineering. The mission designs are articulated as challenges between international universities, so students have the opportunity, not only to be trained in practical aspects of Concurrent Engineering discipline, but to interact with international students and share their knowledge and experiences.

Figure 1. MUSE students and professors in the IDR/UPM CDF during their participation in the 1st ESA Academy Concurrent Engineering Challenge.

4.2. Space Structures (2nd semester)

The UPMSat-2 structural design [19] is presented as a case study in the practical lessons of the subject Space Structures. In this subject, students are trained in the use of usual structural analysis tools (such as Nastran/Patran© or ESI's VAOne software) to then apply the acquired knowledge to a practical case.

They must design a 50-kg finite element method model of the UPMSat-2, as is shown in Figure 2, that can meet the specified structural requirements. Each group must decide between different configuration options such as: material, geometry and thickness of primary and secondary structures, dimensions, quantity, and placement of internal and external stiffeners, etc. The design is then iterated to develop an optimized design in terms of mass.

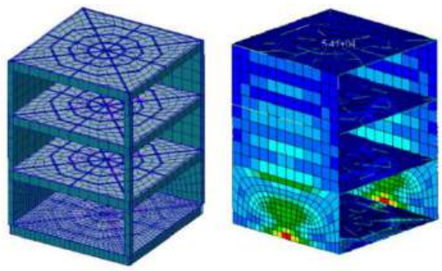

Figure 2. Finite element method model of the UPMSat-2 and structural analysis results obtained by MUSE students.

DOI: 10.5821/conference-9788419184405.036

The developed models are analysed under the same load levels as those used for the calculations carried out in the UPMSat-2 development to verify that the structure will be able to endure the vibrations and noise produced during launch.

4.3. Orbital Dynamics and Attitude Control (3rd semester)

The subject Orbital Dynamics and Attitude Control introduces the most relevant aspects of the orbital dynamics needed for the understanding of the functionality of the orbit and attitude control subsystems in a space vehicle. The IDR/UPM Institute has a wide experience in the development of ADCS simulators, including:

- Models of environment and ephemerides.
- Orbit propagators, attitude perturbations.
- Different sensors and actuators models.
- OBC models, including control laws and attitude determination.

The UPMSat-2 ADCS model [20] is used as a basis for teaching students the different parts of an attitude simulator, so that they can test different attitude controls.

As project for the course, students are encouraged to build in small groups a functional Arduino-based attitude control capable of orienting a CubeSat-like platform towards a light source (see Figure 3). Hardware provided to students includes an Arduino UNO kit (with resistors, wires, board, etc), photodiodes and photoresistors as sensors and a servo motor as actuator.

Figure 3. One of the satellites built by the students in the 2021-2022 academic year

Students must model and characterize the various control components, choose their type, quantity and placement, and build the satellite platform (many groups opt for 3D printing). Finally, they design and implement the control law in the Arduino and demonstrate the ability of the satellite to measure the direction of an incident light and orient itself towards it.

5. Discussion and Conclusions

Space science and technology is a field in constant evolution and subjected to the development of new techniques and concepts. This fact should be transferred to universities, updating their teaching models accordingly. The UPM is focusing their effort on the development and use of new and innovative educational tools and programs, in a search for improvements of their student's qualification. Since the end of 2014, the IDR/UPM institute, through the development of its Master in Space System's (MUSE) program, has been using PBL has main learning technique. The academic results obtained during this 7-year period have been very good and the conclusions extracted from students interviews and surveys have shown great student satisfaction. In addition, almost 100% of MUSE students show a high motivation during their participation in the different proposals and projects. Some positive aspects have been identified:

- A significant percentage of MUSE students are interested in or have begun their Ph.D. studies.
- Many students from MUSE are receiving fellowships from departments of other universities.
- A high number of MUSE students have been contacted by companies from space sector even before finishing their master studies.

Acknowledgements

This research has been partially supported by the project 478 Y2020/NMT-6427 OAPES from the program "Sinérgicos 2020" from Comunidad de Madrid (Spain). The authors are indebted to the Horizon 2020 IOD/IOV Programme of the European Union that funded UPMSat-2 launch.

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Potential application of a measurement tool for quality assurance of E-Learning content to a new MSc in Aerospace Engineering

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Abstract

While witnessing how rapidly and frequently the human life-sustaining structure of society has changed from the past to modern times, the effects of the Covid-19 pandemic presented us a unique challenge, moving a considerable part of our life more than ever online and showing us the signs that a new era has begun. While the access to information is enormous, there is a lack of proper skills in selecting the best options available to upgrade one's educational status. Considering how fast education tools are evolving, it has become important to carry out new studies in order to increase and boost the Quality Assurance for E-learning processes in Education.

In this context, recently in Malta a new Aerospace Programme kicked off through an MSc in Aerospace Engineering. This Master's has been structured as part-time and online, aiming to attract undergraduates and professionals in aeronautics from Europe, Asia and Africa, providing the skills required by national and international aerospace companies. For these reasons, the course has been chosen as a test case for the potential application of a measurement tool for its E-Learning content quality assurance.

This paper describes the preliminary analysis to assess the main Quality Measurement parameter. An uncertainty parameter will be associated with the measurement, which will be improved with the increasing size of the statistical sample and iterations. The uncertainty parameter includes measurement errors, sampling errors, variability, use of surrogate data and the combined effect of assumptions that will be necessary to do in the preliminary phase due to the novelty of the study.

Projections suggest that in the proposed study case of the MSc in Aerospace Engineering, the Quality Measurement parameter value will increase in the next few years, thanks to continuous investments, the sharpening of teaching and learning tools, and the growth of interest from the Maltese aerospace sector; it is expected that the uncertainty of the model will similarly decrease.

Keywords

Measurement tools in Education, MSc in Aerospace Engineering, Quality assurance of E-Learning

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Nomenclature

Ui *Uncertainty parameter*

Acronyms/Abbreviations

Au *Auditory*

Ks *Kinesthetic*

MCAST *The Malta College of Arts, Science and Technology*

QM *Quality Measurement*

Vi *Visual*

1. Introduction

Throughout the years, the education systems have seen many developments and improvements [1]. Despite the fact that many innovations were introduced, this is an area that needs continuous renewal [2].
Several socio-economic, historical, cultural, and political events have influenced the education systems and their content and have impacted the trajectory of people's learning paths [3]. Technology has advanced in ways that we could never have imagined until a few years ago. Its contribution to the learning process improved techniques and accelerated the teaching and learning processes.
Despite significant advancements in online Education, institutions have always prioritized traditional classrooms as the major learning method [4], improvements in this field are always considered as a backup plan [5]. Also, due to this mindset, it was impossible to properly train lecturers on how to teach online, use Edtech tools successfully, design and implement quality assurance requirements for online learning, data protection, consent details, and other related topics.

Nowadays, there are remarkable developments in the educational technology (EdTech) sector, which provides users with high-end technologic tools, such as:

- Grading Apps & Platforms,
- E-books,
- Virtual workshops,
- Learning Management Systems,
- Tools to create video content,
- Educational games,
- VR Technologies,
- Formative assessment tools,
- Learning Apps, Blogs, Forums.

The list above represents potential access to a massive amount of information to comprehend, absorb, apply, and teach.
Therefore, one crucial aspect to consider is how long it takes for education participants to get to the level where they are comfortable using these tools in their regular practices. Other points that need to be clarified, for example, are the success probability of being able to track inventions in a world where technology advances too quick to be easily followed; and the accuracy of structuring the participants' responsibilities while these changes are happening and further updates on the Curriculum and quality assurance standards.
Unfortunately, with the advent of the Covid-19 pandemic into everyone's life, the education system had to face an unprecedented situation in contemporary learning systems.
The fact that students, teachers, and administrators made such a quick transition to entirely online or hybrid education during this period brought to the fore the added issues of adaptability and process management [6]. This can be taken as an excellent opportunity for the entire education system to have a major change. There is a need to carry out more studies to fill the gaps in this field to achieve the best possible results.

The current state of the art in the field shows the following main issues [7]:

- Methodologies are outdated; thus, they do not consider the effects of the Covid-19 global pandemic [8].
- Data analysis was carried out before important technological changes, such as Virtual Reality and Artificial Intelligence [9].
- Quality Assurance is based mainly on qualitative parameters and not quantitative, which is mandatory for the development of a proper measurement tool [10].

From the analysis of the studies in the field [11], it emerges that in the present-day scenario, the main parameters for quality assurance of e-Learning are different in terms of:

- Statistical sample available,
- Boundary conditions, e.g. a very high number of students having e-learning solutions as their only choice,
- Technology improvement, e.g. software and hardware available,
- Social impact of a global pandemic,

The motivation behind this study is related to the fact that the personal and professional development opportunities are virtually unlimited, and the benefits of online training are more significant today than ever before. As a result, schools that embrace E-learning technologies are ahead of schools that still rely

DOI: 10.5821/conference-9788419184405.037

exclusively on traditional approaches to learning.

The human brain is thought to be capable of remembering and relating to what is seen and heard in moving pictures or films. In addition to maintaining the student's attention, visuals have been discovered to be kept by the brain for extended lengths of time [12].
The brain is made up of a variety of networks that help to learn. Some people learn better by seeing, others by hearing, and others require action to discover new knowledge. The term "learning style" was first recorded in 334 BC by Aristotle; he said that "each child possessed specific talents and skills" [13]. The concept of learning styles has evolved ever since with invaluable research in this field [14,15].
Neil Fleming introduced an inventory called the VARK model in 1987 that was designed to help students and others to learn more about their individual learning preferences [16], more in detail:

- Visual learning (pictures, movies, diagrams)
- Auditory learning (music, discussion, lectures)
- Reading and writing (making lists, reading textbooks, taking notes)
- Kinesthetic learning (movement, experiments, hands-on activities)

This most accepted learning styles model was first developed as VAK; Visual, Auditory and Kinesthetic. Fleming later splits the Visual dimension into two parts, symbolic as Visual (V) and text as Read/write (R). This preliminary study will focus on 3 main styles.

Many interpretations of the Learning Styles hypothesis claim that teaching individuals using approaches that are tailored to their 'Learning Style' would result in improved learning [17]. According to neurolinguistics expert Michael Grinder, states that "In the first group of thirty students, about twenty people are able to learn quite effectively by means of visual, auditory, and kinetic so they do not need special attention" [18].

This shows that learning through the VAK approach can help students better understand the material that will be taught. Of course, the knowledge acquisition will be more enjoyable and more meaningful for students. Given that mirroring the learning styles in course content is advantageous to students' learning development, researchers recognize that using e-learning tools to create course content that appeals to all learning styles will move the institutions forward in Education.
With these main considerations, it became essential to develop a tool, i.e. a methodology, to measure the quality of E-modules applied in different contexts.

This paper will focus on the relation between the students' learning experience and materials used in the Aerodynamics and Measurements for Aerospace units of MSc in Aerospace Engineering course. The survey prepared for this focus group aims to have preliminary results on the course material used. A quantitative assessment was done on the material used to have the total numbers of how many pictures, slides, videos, texts, etc., are used in each unit to compare the students' replies based on these numbers. This research will serve as the first guide for teachers to evaluate their teaching materials and identify areas for improvement. Education facilities will have a numerical reference parameter value to demonstrate that they are supplying high-quality standards. Finally, this will provide students with assurances in their course selection.

2. Methodology overview

The proposed study's main methodology aims to measure the quality standards for online courses at MCAST and, potentially, of other higher education institutions. The previous research in this area mainly focused on qualitative results, but in this case the definition of quantitative results will be key for the research process.

The methodology will use techniques such as:

- Conceptual mapping: To design the measuring tool settings, the feedback of teachers and students will be evaluated. Analyzing the comments and surveys is a qualitative process, but measuring the quality with those parameters provides a quantifiable outcome.
- Parametric checklist definition: The material quality will be determined at this step. A list of the materials will be compiled, and the most effective settings will be checked.
- Mixed–method, which combines the qualitative and quantitative methods: The data from the case study will be reviewed to see the correlation between the teaching materials used in the lecture and the students' learning style to build the core of the measurement tool.

3. Case study – MCAST MSc in Aerospace Engineering

The MCAST MSc in Aerospace Engineering aims to allow candidates to deepen their knowledge to be able to design and implement aerospace projects, dealing with the highest standards using environmentally friendly technologies taking into consideration safety and social responsibility. The course provides students with intense knowledge to develop the skills needed to conquer three highly sought-after fields: Structures and Measurements for Aerospace, Aerodynamics, and Space Technologies. The course has core units such as Aircraft Propulsion, Aerospace Structures, Aviation Maintenance Management and Law, Aerodynamics, and Measurements for Aerospace. While the global pandemic is still affecting our lives, MCAST decided to move courses online more than ever, including this course. This Master's has been structured purposely for part-time and online delivery, aiming to give an opportunity to students in Europe, Asia, and Africa.

For these reasons, the course has been targeted for a preliminary study to develop the fundamentals of the measurement tool. The collected data is analyzed to see how effective the MSc is at providing knowledge to understudies in a course that aims to prepare students for various disciplines using e-learning tools.

1.1. Measurement parameters definition

In this study, the starting point considers the QM parameters measurable as a function of 3 main parameters; Vi, Au, Ks.

This tool will measure how the course uses the technology to adapt the content to the three learning styles to maximize the students' learning potential and allow organizations to improve their educational success rate.

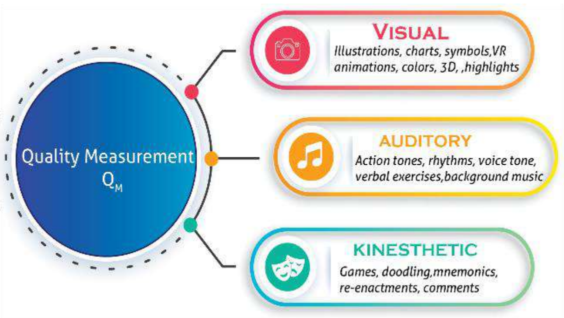


Figure 1. Overview of the measurement parameters for Q_M methodology.

Once assessed the value of the main QM parameter for a given E-learning course content, an Ui will be associated with the measurement, which will be improved with the increasing size of the statistical sample and iterations in the process. The uncertainty parameter includes measurement errors, sampling errors, variability, use of surrogate data, and the combined effect of assumptions necessary to do in the preliminary phase, due to the study's novelty.

1.2. Analysis procedure

Based on the previous measurement parameters described, a first analysis has been defined, based on the following steps:

- Quantitative analysis design of the teaching material: Materials have been categorized to address three learning styles, and total numbers and percentages for each lesson were identified.
- Survey design and implementation: The survey has been structured with 30 questions for two units of the MSc and with an anonymous online format.
- A first assessment of the parameters to measure has been performed.
- The first feedback to start the development of the measurement model has been retrieved.

The two selected units are Measurements for Aerospace and Aerodynamics 1, carried out during the first semester of the MSc, for the first intake of students.
Figure 2 provides an overview of the parameters assessed, while Figure 3 shows a sample of the online survey.

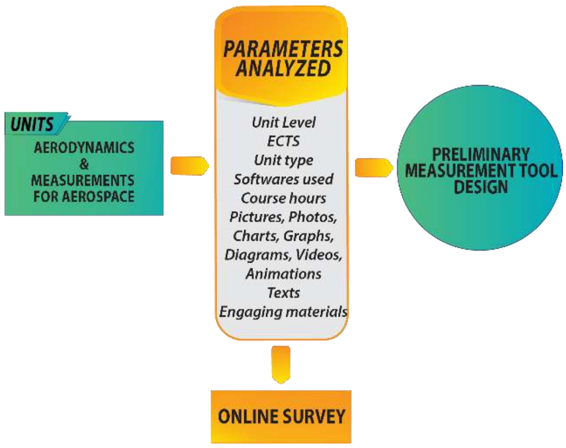
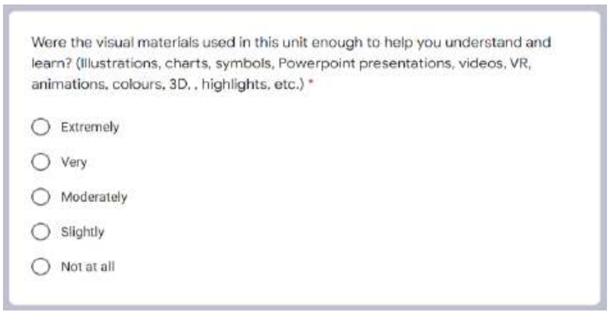


Figure 2. Overview of the analysis performed


Were the visual materials used in this unit enough to help you understand and learn? (Illustrations, charts, symbols, Powerpoint presentations, videos, VR, animations, colours, 3D, , highlights, etc.) *

- Extremely
- Very
- Moderately
- Slightly
- Not at all

Figure 3. Sample of the online survey

1.3. *Data analysis*

This paragraph presents the analysis carried out on the preliminary set of data retrieved.
Being the first time this procedure has been applied, the focus has been on the development of the tool itself and the design of the measurement parameter for future study iterations.

With reference to Figure 2, the two sets of parameters assessed and the survey results have been correlated with the aim of describing the dependent variable Qm as a function of the three independent variables Vi, Au, Ki. The reference polynomial model selected as the starting point is the one of Eq. 1.

$$y = ax_1 + bx_2 + cx_3 \quad (1)$$

With:

- X_1 (Visual content);
- X_2 (Auditory content);
- X_3 (Kinesthetic content).

The two sets of data were analyzed thanks to Matlab™ software for curve fitting of data, using regression techniques. For each parameter the standard deviation was also evaluated. Moreover, the overall R-squared (R2) was calculated. R2 is a statistical measure representing the proportion of the variance for a dependent variable explained by an independent variable.

Finally, usually standard relations from literature, the Qm function was determined with its associated Ui, the design stage uncertainty analysis, that provides an estimate of the minimum uncertainty based on method chosen, according to the relation of Eq. 2.

$$Y = Y_{\text{measured}} \pm U_i \ (P\%) \quad (2)$$

4. Results

The first outcome in applying the described procedure shows that the course meets the requisites to pass the acceptance criteria, the value being 6 on a scale from 1 to 10, and that there is still a good margin for improvement.

The final Qm equation results to be, Eq.3:

$$Qm = 0.4Vi + 0.3Au + 0.1Ki \quad (3)$$

The evaluation of Ui provided: Ui=1.53.

The final relation for Qm results is to be:

$$Qm = 6.34 \pm 1.53 \ (95\%)$$

The 3d plot done in Figure 4 shows the correlation between the three parameters and their relative weight for Qm.

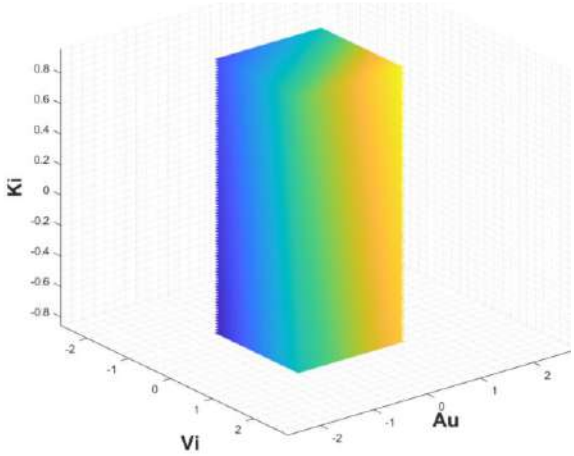


Figure 4. Qm= Quality measurement parameter

5. Conclusions

This study shows that the initial parameters for quality assurance measurement for e-learning content have been defined.
Following a process similar to the continuous improvement of the Lean methodology, over the years, the technique will be refined, and the statistical pool will be significantly more prominent, and it is reasonable to imagine that the same course will achieve better results. This will be considered an accepted "plateau" limit in the improvement curve of the course, where the course is considered to be at a very high level and where a higher QM value will be considered not feasible from an economic point of view, in the evaluations done by the educational institution providing the course. It is important to highlight that this methodology is scalable, modular and can be improved iteration after iteration.

The research has met its primary objective to contribute to a study to develop a measurement tool for the quality assurance of e-learning content.
The conceptual mapping on the parameters that will be used to develop the measurement tool has been defined. This study offers an example of the course material evaluation process based on the learning style.

The case study, MCAST MSc in Aerospace Engineering, has been selected for being an online course providing specific and intense content. The first promising results show that the development of a measurement tool for e-learning content is feasible.

The next stage will assess the quality of each material used under these three topics and conduct a quantitative analysis to determine the most effective settings to utilize. After this stage, more surveys will be carried out with more extensive samples to develop the complete checklist with the parameters evaluated in detail.

Acknowledgements

This research was supported by Dr Leonardo Barilaro and Dr Lorenzo Olivieri. The Authors are immensely grateful to these brilliant scientists for their time and work put into this research.

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Moon Rover Challenge. An educational space robotics resource to teach programming and promote space careers at secondary education levels

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Abstract

Nowadays, space educational activities are essential in schools, in order to show the importance of space research and exploration in our daily and future life. Space related activities provides teachers tools and a fascinating context to get students involved in different disciplines which are 'difficult' for them. In addition, programming is one of the most important skills in technological areas. Space technology is full of programming, algorithms, and code. However, students' perception is different because they think coding is difficult and they will not be able to program a satellite or a rover, so they are not very interested and motivated to learn to program.

A widely useful tool to motivate students to learn programming is educational robotics, which uses physical robots and block-based programming interfaces to attract their attention. However, these robots are not accessible for all schools, and it is difficult to use robots in the online environment created by COVID-19. Therefore, online tools are becoming more and more important in education, because they make activities more flexible and accessible for schools and students.

In this paper, we show an educational resource that used space robotics as a context achieving two main objectives: to promote space careers and teach and motivate high school students to learn how to program. We also show our conclusions and lessons learned, after implementing this project in two different situations. The students' challenge is to control a Moon rover, which is on the Moon surface in order to fulfil a space mission. The activities can be performed completely online using an online simulation tool and block-based programming language.

We tested the educational material in an online event with many high school pupils and also in a face-to-face lesson with pupils studying a technical module. The experiences and feedbacks were positive and allowed us to improve the initial activities. Moreover, the results show students are more interested in space careers after completing the challenge. Space robotics give us a perfect opportunity to introduce subjects such as programming, robotics, and technology to students. These areas will be essential in the future and we have to change perception of the space industry because it is fundamental for the development of space exploration and our society.

Keywords

Block-based programming, Educational resources, Outreach activities, Robotics, Space context.

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Acronyms/Abbreviations

ESA	*European Space Agency*
ESERO	*European Space Education Resource Office*
STEAM	*Science, Technology, Engineering, Arts and Mathematics*
ORL	*Open Roberta Lab*

1. Introduction

Space industry and exploration are essential for the technological and scientific development of our society. For most people, to work in the space industry just means being an astronaut, but behind a space mission there is a lot of work and different specialists who work as a team: programmers, engineers, astronomers, mechanics, doctors, welders, etc.

The Space industry involves technical disciplines which seem as 'difficult', such as coding, robotics, technology and electronics. Young people have the perception that these disciplines are very complicated. For this reason, teaching these subjects to primary and secondary pupils using an educational context is essential. Students are more easily involved and engaged if the learning activities are set within an interesting context [1]. That is because they are more interested in learning when they can relate the theory to the real world [2].

The European Space Education Resource Office (ESERO) provides a direct link between the European Space Agency (ESA) and teachers [3]. The ESA Space Missions are multidisciplinary as they involve programming, simulating, engineering, etc. As a result, school activities based on ESA's Missions allow students to interact with STEAM (Science, Technology, Engineering, Arts and Mathematics) disciplines in the classroom [4]. In accordance with this, ESERO offices have developed a long list of educational resources, based on ESA's Missions, called "Teach With Space collection" [5], for teachers. These resources use space as a context, to engage students to be more motivated to study disciplines like physics, biology and science.

Educational robotics is commonly used as a multidisciplinary tool to teach programming, because it materializes the abstract behaviour of algorithms [6]. The clearest example is LEGO Mindstorms [7]. Another important fact is most educational robots have a programming interface which uses block-based programming language, interactive structures and graphics to catch students' attention. This is due to the fact that programming with blocks permits students to forget the technical problems and they can focus on the structures and logist [8]. Students who programme in blocks are not quicker learners, however they have the perception that it is less complex [9], and this is directly related to the learning context.

So, one question is clear: learning coding in a real context attracts students to technology and programming, because it changes the perception and makes coding more interesting for students [6]. Also, the context plays a determining role in girls' perception of programming. Girls, who are often not interested in traditional approaches to robotics and programming, become motivated when programming activities are introduced as a story or connected with other subjects and areas of interest [10]. Space robotics is the union of two great backgrounds, robotics and space, and it involves motivation, programming, space careers and a long list of multidisciplinary disciplines.

Despite the fact that space robotics is a fantastic context, it is not always possible to have a robot to program and a table simulating Moon surface in the classroom. Educational robots are usually a bit expensive and schools cannot afford them for all students. Moreover, programming a robot in an online class is not possible. In 2020 and 2021, the educational system became to totally online because of COVID-19. Online tools have been essential to help learning in this situation and makes it more accessible.

In this paper, we present an educational resource for secondary education levels. The main goals are to teach programming and to promote space careers, taking advantage of block-based programming language and Space robotics as a context. Presenting the learning activity as a Space robotics Mission, motivates students to consider a Space career as a good career choice. At the same time, using block-based programming tools makes coding more attractive for them. Moreover, we used an online tool to program and simulate robot movements, so we do not need a physical robot to do the activities. Students can easily see if the robot is performing well, doing the simulation. Furthermore, performing simulations is one of the most important phases in a technological project development. In any space mission, millions of simulations are carried out before the spacecraft is tested [4], especially if it is manned.

The challenge is based on the ESA 'teach with space' resource 'Mission to the Moon' [11], which is contextualized in the ESA Heracles robotic mission. Students work as ESA programmers who are developing a program to remotely control a Moon rover. Our rover goal is to take some surface samples and bring them to the Earth. Students have to complete a set of activities to fulfil the challenge.

All educational materials developed have been tested in two learning situation involving secondary school students. We did these activities in the framework on ESERO Spain. In both cases, resources were easily adaptable to the situations, learning rates and classroom formats. More than 80 % of students showed more interest in space careers and coding after completing the challenge. In addition, using a totally online platform made it possible to forget all problems associated with the use of physical materials and software installation.

2. Methodology

The software we used to complete the activities is Open Roberta Lab (ORL) [12]. This online tool has a block-based programming language and allows robots' movement simulation in a configurable online environment.

ORL is an open-source platform to programming and simulating robots. It was developed by Fraunhofer Institute for Intelligent Analysis and Information Systems and financed by Google Germany inside the initiative 'Roberta- Learning with robots' [13]. It is so easy to use, through any web browser. In the main interface you can see the programming area and the simulation tab. The simulation environment makes it possible personalizing the backgrounds, color areas and obstacles [Figure 1]. This is essential to keep the space context all the time, because the robot will stay on the Moon surface all the time.

The educational resources we have developed include all the materials that teachers need to complete the challenge in their classroom: a teacher's guide, taking into account curricular contents, with all important aspects in the educational planning, and practical guides for students using a scaffold-type methodology. This implies instructions to complete little milestones, in order to achieve the final challenge.

The title of the first mission is 'Back to the base!' where students have to program the robot to go to the base camp. Students have to use action programming blocks and calculate the angle to turn. This mission has lots of solutions. The second Mission is 'Searching Moon surface samples!' The robot has to take four samples, which are spread over the entire surface. Students have to use colour sensor and action blocks. The last Mission is 'Let's race on the moon!', where students have to program a Rover to follow a line. They have to use loops and sentences to fulfil the mission.

Apart from performing simulations, ORL is prepared to load programs in different educational robots and development boards. Moreover, it allows account configuration options, save programs, share programs and manage user groups.

3. Results and Discussion

All educational materials developed have been verified in two learning events involving secondary school students [Table 1]. These activities are part of the ESERO Spain awareness-raising events during the year 2021.

Table 1. Experiences Summary

	Engineering fair	Technical module
Date	21 April 2021	26 May 2021
Students	291	10
Time	1 hour	2 hours
Format	Online	Face-to-face

We designed a simple form with two questions to get some feedback from students:

- Question 1: after doing these activities, do you think space careers are more interesting?
- Question 2: Would you like to work at the European Space Agency?

Also, we asked them how many missions had been completed [Table 2].

3.1. Engineering Fair

We developed the first version of our resources to do an outreach activity in the engineering fair

DOI: 10.5821/conference-9788419184405.038

2021, so the material we used to participate in this event, was the first draft of the challenge, and it can be seen in the platform with the other activities [14]. The first edition of this fair was in 2019. In the year 2021, due to the pandemic situation, this event became online and it was in April.

Table 2. Students form Results Summary (percentages)

		Engineering fair	Technical module
Q1	Yes	82	74
	No	12.8	17.6
	DK	5.2	8.4
Q2	Yes	88.4	90.8
	No	8.8	4.8
	DK	2.8	4.4
Percentage of students who have completed the mission	M1	97.5	100
	M2	62	90
	M2	31.5	70

The Engineering fair is an event organised by the University of Granada. The objective is to introduce engineering areas to secondary school pupils and its professional outings. This programme is especially for girls, to show them engineering is for everyone and they are as capable as boys of studying a technological degree. During one-week, different schools visit university laboratories and equipment to do different activities like workshops, talks, experiments, etc.

The format was a live online connection with schools [Figure 2]. Classrooms from six different secondary schools connected to do the workshop simultaneously, in total 291 students and 13 teachers. Results were as good as we expected, more than 88 % would like to work at ESA. Moreover, during the workshop students were enthusiastic to get to know the next challenge.

After this experience we realised the activities were so useful, flexible and engaged students in programming and knowing more about the Moon and space exploration. However, only 31.5 % of the students finished the third mission. As a result, we have developed new introductory activities to help students to fulfil this last challenge.

3.2. Technical module

In this case, the format was face-to face with pupils who were specializing in microcomputer systems and networks module. These students are usually not motivated to learn, and they do not have any future expectations regarding becoming programmers, engineers or workers of a big company like ESA. They did not have any experience in programming,

For this time, we had the updated material, with two more introductory activities to program loops and sentences. We had two hours instead of one as well. All these facts helped students to complete all the challenges. As they did not have any experience in programming, 70 % completed the last mission.

The space context was the key to catch their attention. Space robotics motivated them to do the activities and they showed a lot of interest in space missions and exploration rovers. 'How many rovers are there in space? Who designs the rovers? How can I apply to work at ESA?' were some of their questions. 90.8 % of them wanted to work at ESA in the future.

4. Conclusions

We have developed a space educational resource which puts three key elements into practice: space robotics as a context, block-based programming language and online simulation tool. Contextualizing activities inside space robotics which seems 'unreachable' from the outside, is a way to change this perception and show that anyone can be a space programmer.

In both cases we obtained the similar results, the interest for space careers and industry were higher after completing the challenge. From our point of view and experience, girls have some 'fear' of technological areas, and it is necessary to change this. Introducing activities with the mysterious space context can help to attract them and increase their motivation. We have improved the material, including more activities and taking into account the students' feedback. Also, we plan to put this challenge into practice again with new modifications and improvements.

Education is the base of a society and teachers are essential in this process. They teach us to develop our skills, to know our environment, its characteristics and possibilities, and this knowledge makes us free to choose our future.

Apart from the main goals of this challenge, we wanted to show with this educational resource that the limits are only in our minds and the space industry is waiting for the new generation.

Acknowledgements

The authors wish to thank ESERO for developing incredibly inspiring resources for teachers. Also, to the University of Granada to let us to put this resource into practice at the engineering fair, and Padre Suarez secondary school for giving us the opportunity to implement our activity in their professional classroom.

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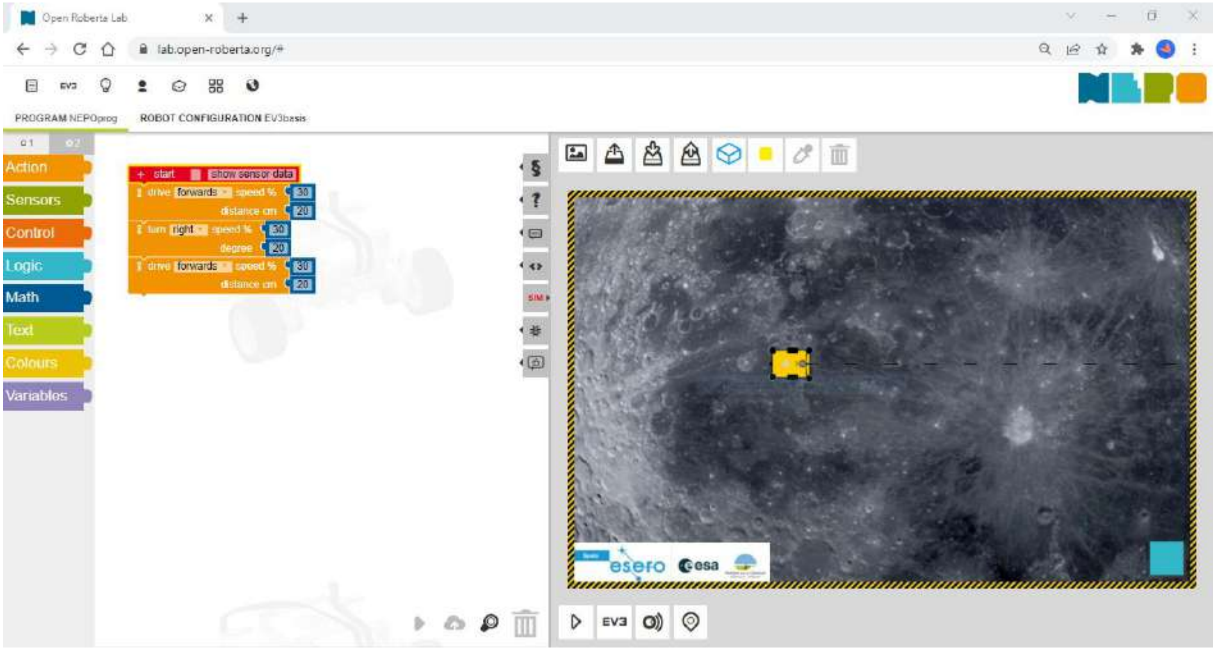

Figure 1. Open Roberta Lab environment with Moon surface simulation background [12]

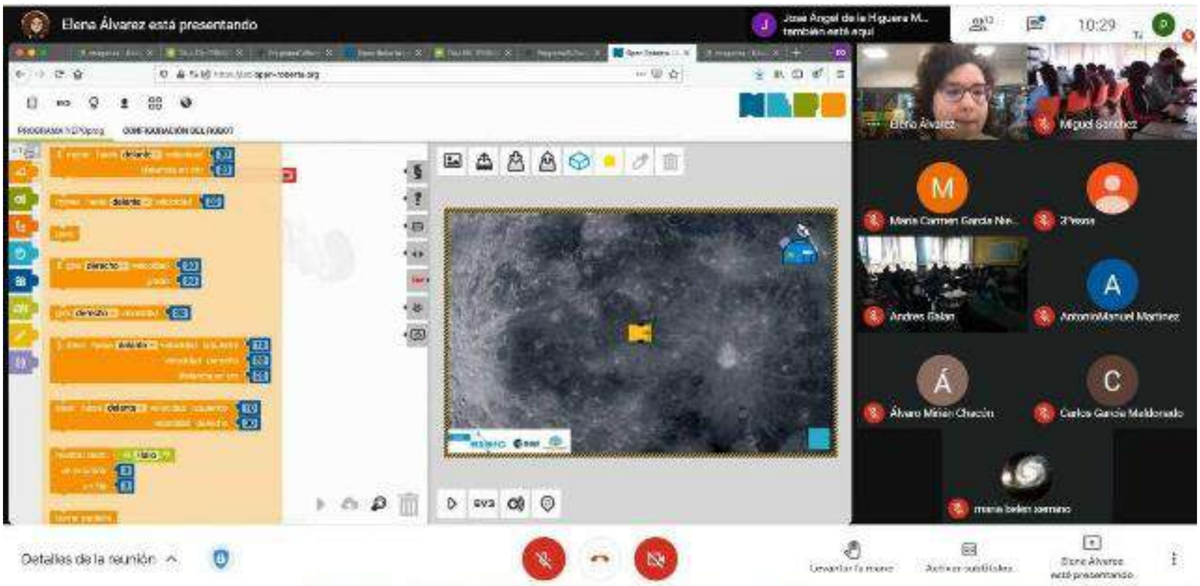

Figure 2. Live connection at engineering fair (21/04/2021)

Suborbital Autorotation Landing Demonstrator on REXUS 29

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Abstract

Current developments in the aerospace industry point towards more frequent interplanetary travel in the future. However, the main focus of developments is on launcher technology, yet the descent of interplanetary probes is of high importance for the success of future missions. Additionally, to the present landing approaches using either a powered descent requiring fuel or a combination of different parachutes, a third method is investigated in this project. The chosen approach is called autorotation and is commonly used in helicopters. When a helicopter suffers a loss of power, it can still land and even choose its landing site without the utilization of an engine. Similar to parachutes, the presented technology can be applied to various atmospheric conditions by modification of rotor and control parameters. Moreover, a rotor in autorotation can provide directional control and thus the choice of a landing site, which is not feasible using a parachute. All these factors make autorotation an interesting option as an entry descent and landing (EDL) technology for interplanetary missions. Our project, Daedalus 2 implements the autorotation landing strategy as part of the REXUS student project campaign under DLR / ESA / SNSA supervision. Since 2018 we are developing the SpaceSeed Mk.2, a technology demonstrator that incorporates a rotor and all necessary technological means to perform an autorotation EDL maneuver from an apogee of 80 km. The mission concept is laid out within the presented paper. This includes the main challenges like miniaturization of the SpaceSeed v2 due to the size constraints of the REXUS rocket or the used sensors for height and position determination. The importance of a technology demonstrator tested on a sounding rocket to prove the feasibility of our presented system is laid out in our publication. Furthermore, the custom development of electrical, mechanical and software sub systems is discussed. Additionally, the planned mission profile will be explained, including flight phases and different activities conducted by the SpaceSeeds during flight. Moreover, the main differences and improvements to Daedalus 1 are being discussed.

Keywords

Reentry, Landing, Autorotation, Parachutes, Rotors

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1. Introduction

Daedalus 2 is a student project that investigates alternatives to parachutes. Since 2018 roughly 40 students are working on the mission. In contrast to telescopic or inflatable rotors we decided to use a tiltable rotor system. This adds to the scientific knowledge base about rotor systems in space applications. The main focus of this paper is the mechanical setup of the implemented system. It will shine light onto the general layout as well as significant implantation details. Special attention will be payed to the tilting mechanism of the rotor as it is the most complex mechanical subsystem.

2. State of the art

The Technology Readiness Level (TRL) of autorotation in the context of space flight is comparably low. However, the idea is not novel. Multiple studies have investigated the topic. The most prominent examples shall be introduced in the following sections.

2.1. KRC-6

The KRC-6 represents one of the earliest developments for autorotation vehicles. In the 1960s Karman Aerospace and the US Airforce tried to build cargo deployment vehicles based on autorotation. They quickly realised that this technology could be used for space. This was followed by the campaign that built and improved the KRC-6. A total of 12 vehicles were built and tested. Good results were achieved, however, the campaign was discontinued due to unknown reasons. It could be due to the idea being way ahead of its time. The KRC-6 was remote controlled and used mechanical gyros due to the lack of advanced micro electronics which are available now. [1]

2.2. Auto-Rotation in Martian Descent and Landing (AMDL)

In 2009 EADS (now Airbus) performed a study for autorotation landers geared towards Martian missions. The prevalent problem on Mars is the low atmospheric density. This implies that a comparably high rotor radius is needed. AMDL chose to investigate the solution that employs inflatable rotors. They found that it is possible to deploy such a rotor and save a lot of weight and space. However, the low rigidity of the rotor was a problem that could not be overcome in the initial study. A further study to investigate this problem was suggested but seems to have never been implemented. [2]

2.3. ARMADA

ARMADA represents another study that investigated the use of rotors for EDL on Mars. In 2009 they studied a similar issue to AMDL but decided to use a telescopic rotor. Compared to AMDL the rigidity of a telescopic rotor blade is clearly superior to an inflatable rotor. The study showed significantly better results. They stated that other celestial bodies might be more suited for a near term mission, due to the higher atmospheric density. [3]

2.4. SpaceSeed

The predecessor SpaceSeed Mk.1 in the Project Daedalus 1 is also an important element of the state of the art. Launched in 2019 the vehicle built a foundation for the next mission. It was a technologically simple prototype for evaluating the concept design space. There was no controllability and the rotor was locked to the vehicle. During the flight it only showed moderate stability and in some flight zones it even showed significant instabilities. The learning of Daedalus 1 were very important for the development of Daedalus 2. An image of the SpaceSeed Mk.1 can be seen in Figure 1. [4]

Figure 1. Flight hardware SpaceSeed Mk.1 for Daedalus 1 [4].

3. Approach

This section describes the general setup of the Daedalus 2 mission. Daedalus 2 is a project carried out in the framework of the DLR / ESA / SSA joint venture program REXUS/BEXUS. Here, European students are given the opportunity to design, build and operate their own experiment on a sounding rocket. Daedalus 2, which is participating in the current cycle on REXUS rocket No. 29, comes from the student spaceflight association WueSpace.

3.1. Daedalus 2

The primary goal of the Daedalus 2 experiment is to demonstrate full re-entry and landing based on rotor pitch actuation only. As is common in conventional helicopter emergency landings, a maneuver known as an autorotation landing can be performed to achieve a safe and smooth landing without any type of propulsion. The concept will be tested from a drop altitude of 70 km to evaluate the system at reasonably high re-entry speeds.

Mechanically, the experiment consists of an ejection mechanism mounted on the launch vehicle, and two ejectable re-entry capsules, the so-called "space seeds". Beginning with ejection at apogee of flight, the two SpaceSeeds operate autonomously on their way back to the surface. During descent, rotor speed, ambient pressure, GNSS position and lidar distance to the ground are continuously measured and used to control the angle of attack of the main rotor. Key information is transmitted at a low rate to the ground station via the IRIDIUM satellite network. The transmitted data includes the GNSS position and the current estimated altitude, to provide an approximate estimate of the landing zone for subsequent recovery. To prove the feasibility of autorotation-based re-entry from space and have a record of mission success, high frequency data will be stored on the spacecraft's internal memory.

4. Implementation

Figure 2. SpaceSeed with fully tilted rotor blades.

Besides the basic structure, three fundamental mechanical decisions were the implementation of the swashplate mechanism, the accommodation of the rotor inside the REXUS rocket and how to avoid instabilities during the descent. This section describes the mechanical setup of the SpaceSeeds with a focus on the elements that address these problems. A cut through the whole SpaceSeed can be seen in Figure 3.

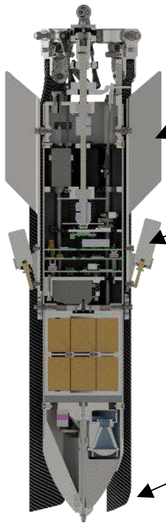

Figure 3. Cut view of the SpaceSeed.

4.1. Inner Structure

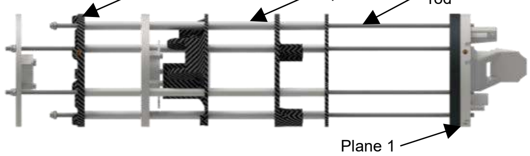

Figure 4. Skeletal Structure of the SpaceSeed.

The skeletal structure of the SpaceSeed, pictured in Figure 4, is composed of four threaded rods and seven planes, that are separated with spacers.

4.1.1. LiDAR

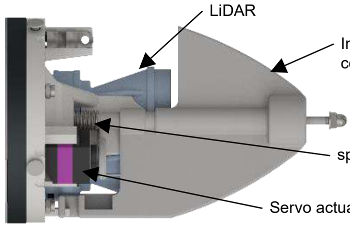

Figure 5. Opening mechanism of the nose cone.

Starting at the nose cone, the first plane accommodates the LIDAR that is used for height measurement during the landing phase. To protect it until the final phase of the flight and to retain the aerodynamic profile during re-entry, the LIDAR is covered by an inner nose cone. Just before measurement begins, a servo actuator releases a spring mechanism that rotates the inner nose cone out of the field of view of the LIDAR. The servo actuator, the spring and all other parts of the mechanism are also mounted on this plane.

4.1.2. Battery Compartment

Between the first and the second plane the battery compartment is fixated (Figure 6). The six batteries that power the SpaceSeed are put into cartridges, connecting them to two plugs. These cartridges can be slid into the compartment, where the plugs connect to the corresponding jacks. This allows for battery replacement without the need to disassemble the SpaceSeed.

4.1.3. Fins Actuators and PCB Stack

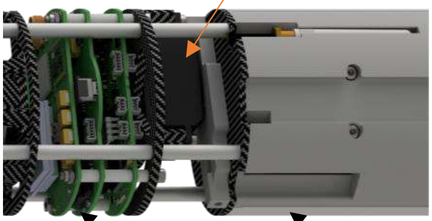

Figure 6. PCB Stack, Fins Actuator and Battery Compartment.

Between the second and third plane the servo actuator for the fins is placed. The fins mechanism will be discussed further in chapter 4.3.

On the third plane the PCB stack is mounted, consisting of three boards stacked upon each other.

4.1.4. Slit Wheel, Camera and Ball Bearings

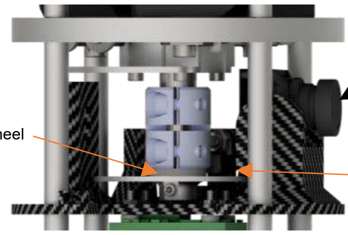

Figure 7. Camera, slit wheel and optical switches.

A camera for gathering in flight footage of the descent is placed on the fourth structural plane. A hole within the outer shell allows for a sideways look.

The plane also contains two optical switches. In combination with the slit wheel fixated on the rotor shaft, that ends in this area, they enable the measurement of the rotational speed of the rotor.

The next plane contains one of the two ball bearings that support the rotor shaft. The second ball bearing is placed in the last plane. While all other planes are 3D printed, these two planes are made out of aluminium, as they are expected to experience larger strain

4.1.5. Servo Actuators

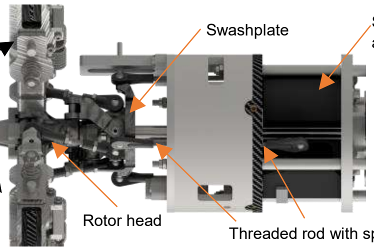

Figure 8. Rotor head with swashplate connected to servo actuators.

The three servo actuators, that control the swashplate and thereby the pitch of the rotor blades are fixated between the fifth and sixth plane.

The area between the servo actuators and the seventh and last plane serves as space between the swashplate and the servos. Additionally the seventh plane holds a USB-C socket to connect the Seed to the Rocket Board Computer before ejection.

4.2. Rotor System

As main part of the rotor system a standard RC helicopter rotor head with its corresponding swash plate is used, which is connected to the three servo actuators by threaded rods and spherical heads (Figure 8). This setup would be suitable for cyclic pitch, but only collective pitch is used in the Daedalus 2 project. The rotor blades, with a length of 470mm, are standard RC helicopter parts as well. They are made out of carbon fibre.

4.2.1. Tilt Mechanism

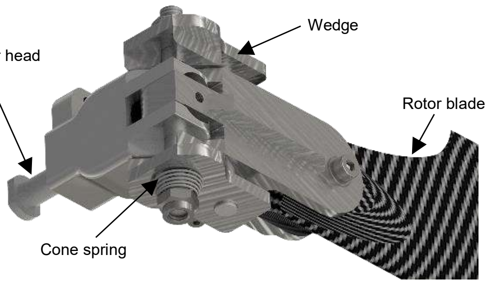

Figure 9. Rotor joint topside in tilted position.

As the SpaceSeed has to fit into the REXUS rocket no standard blade mounts come into consideration. Instead a specially designed tilt mechanism is used. The mechanism can be seen in the tilted position in Figure 9 and in the opened position in Figure 10.

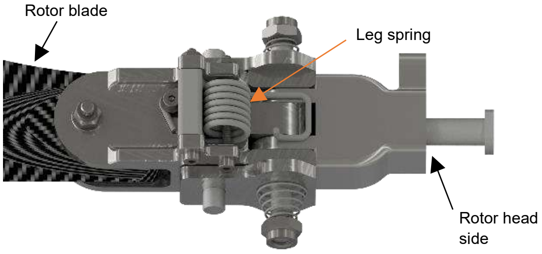

Figure 10. Rotor joint bottom in opened position.

During the ascent of the REXUS rocket, the rotor blades are kept in the fully tilted position by a tube mounted on the rocket. As soon as the SpaceSeed is ejected, the wings are free and a leg spring forces the mounts into the open position. To ensure, that the joint stays open, even if sudden shocks occur, a wedge is placed on both side. When the joint is fully extended, both are pushed into the matching cut-outs in the mount by a cone spring, which arrests the tilt mechanism.

4.3. Fins

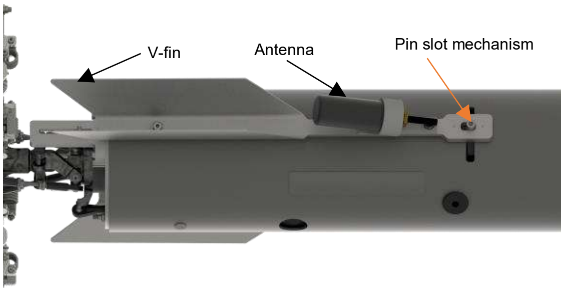

Figure 11. V-fin in middle position.

On the outside of the SpaceSeed two V-shaped aluminium fins are attached. They are pivoted between the sixth and seventh plane. Between the second and the third plane they are connected to one servo actuator via a pin slot mechanism. For this on both sides a ballhead is connected to the servo, that can slide through a low friction 3D printed part inside the fins and thereby enables the fins to tilt in both directions. On the one hand the fins contribute to the overall stability of the SpaceSeed and on the other hand the mechanism enables the minimization of the body rotation.

5. Outlook and future work

The two SpaceSeeds used as flight hardware for the REXUS rocket launch and two additional spare instances are already assembled as described in this paper. Wind tunnel tests indicate, that the structure withstands the high rotational speeds of the rotor, the SpaceSeeds will experience during the flight. The actual rocket launch and thereby the prove of concept of the project is scheduled for April 2023. After this the results will be analysed to understand the existing future challenges.

A first possibility would be to test the concept for different scales. This would be needed to use it as landing mechanism for payloads, as the free space in the Daedalus 2 Space Seed is very limited. With these results a comparison to other rotational landing mechanisms, like the concepts with the inflatable or the telescopic rotor blades mentioned in chapters 2.2 and 2.3 would be feasible. In a future revision another technological enhancement of the SpaceSeed could be to use the cyclic pitch to control the flight direction and thereby influence the landing position.

Acknowledgements

There are a lot of people and institutions that helped us in various ways throughout the project and who deserve our gratitude and a mentioning here. Regarding institutions, we begin with thanking the German Aerospace Centre DLR [5], the Swedish National Space Agency SNSA [6] and the European Space Agency ESA [7] as the main organizers of the REXUS/BEXUS programme. In addition, the campaign would not be possible without the Swedish Space Corporation SSC [8]. The Centre of Applied Space Technology and Microgravity ZARM [9] also deserves special thanks for constantly helping the team to improve and successfully conclude the project cycle.

Further we want to thank the Julius-Maximilians-University Wuerzburg, especially the Chair for Aerospace Information Technology [10], represented by Prof. Hakan Kayal.

The Daedalus 2 team is grateful to all the sponsors who made the project possible: Atomstreet, Mouser Electronics, Carbonteam Shop, Hacker Brushless Motors, MathWorks, Siemens, ublox, VDI, Breunig Aerospace, Airbus, Ansys, Hirsch KG, PCB Arts, Vogel Stiftung, MÄDLER, WÜRTH ELEKRTONIK, PartsBox, molex, LRT Automotive, ZFT, Iridium, TELESPAZIO and ARCTIC. An overview of all helpers and sponsors can be found in [11]

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Mubody, an astrodynamics open-source Python library focused on libration points

Juan Bermejo-Ballesteros[1], *José María Vergara Pérez*[2], *Alejandro Fernández-Soler*[2], *Javier Cubas*[2]

Abstract

Mubody is an astrodynamics open-source Python library focused on the libration points. Such points result from the equilibrium of the gravitational forces between two massive bodies as the Sun and Earth, for example. The library is mainly intended for the generation of orbits in these regions, which is not a straightforward process, specially if perturbations are considered. Currently, the library allows to generate Lissajous orbits in the second Lagrange point of the Sun-Earth system under the influence of perturbations such as the Earth orbit eccentricity. The next milestone, as a result of a master student work, is the incorporation of Halo orbits and the expansion to all three collinear libration points from any two massive bodies of the Solar System. This tool has been developed as part of a PhD, motivated by the need of performing mission analysis in libration point regions. Nevertheless, since its creation it has also proven to be an excellent academic tool for both enhancing the library itself and using its results for further studies (collision risk, thermal analysis, formation flight control, etc). As a result, the tool has rapidly evolved, building onto the knowledge and experience that the students gather while working on their academic projects (bachelor's degree dissertations, master theses, subjects, internships). The participation on the library development provides students with experience in orbital mechanics, software design, version control and it compels them to ensure that their work can be readily used by others as it is properly documented. The project is hosted in GitLab under a MIT licence.

Keywords

Astrodynamics, Libration Points, Python, mission analysis, education, open-source

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Nomenclature

Δv	*Delta-v of maneuvers*
μ	*CRTBP mass parameter*
ρ_i	*Distance to primary i*
G	*Gravitational constant*
m_i	*Mass of the celestial body i*
r_i	*Position vector to celestial body i*
U	*Pseudo-potential function*

Acronyms/Abbreviations

CRTBP	*Circular Restricted Three Body Problem*
ERTBP	*Elliptical Restricted Three Body Problem*
ETM	*Equitime targeting method*
FETBP	*Full Ephemeris Three Body Problem*
GMAT	*General Mission Analysis Tool*
IDR	*Instituto Universitario "Ignacio Da Riva"*
IFCA	*Instituto de Física de Cantabria*
MUSE	*Máster Universitario en Sistemas Espaciales*
OTM	*Optimized targeting method*
TBD	*To be done*
UPM	*Universidad Politécnica de Madrid*
WIP	*Work in progress*

1. Introduction

Mubody is an astrodynamics open-source Python library focused on the libration points [1]. Such points result from the equilibrium of the gravitational forces between two massive bodies, e.g., the Sun and Earth. The library is mainly intended for the generation of orbits in these regions, which is not a straightforward process, specially if perturbations are taken into account [2,3].

The interest in these regions has increased in the recent years, with the consequent increment in the scientific research activity focused on this topic on multiple fields as orbit dynamics, trajectory control, spacecraft formations and navigation [4,5]. One of the most common destinations for libration point missions is the L2 point of the Sun-Earth system, which presents ideal conditions for deep space observation due to its stable thermal environment and its distance from near Earth perturbations. The most recent example is the James Webb Space Telescope mission, which successfully deployed in its target Halo orbit [6] in January 2022. Nevertheless, other libration points have been and will be destination of many other missions: the L1 point of Sun-Earth system has been used for several space weather control missions [7,8], the L2 from Earth-Moon was selected by China to place a communication relay satellite for their mission to the dark side of the Moon [9] and the L1 from the same system will be the destination for the future Gateway mission of NASA [10].

Within this scientific topic, the Instituto Universitario "Ignacio Da Riva" from Universidad Politécnica de Madrid (IDR/UPM) participated along the Instituto de Física de Cantabria (IFCA) on a research project of a calibration satellite for CMB telescopes located in L2 [11,12,13]. Mubody originated from this project and started as a script developed by a master student to compute the nominal orbits for the calibration satellite and the telescope. The script was expanded progressively as part of a PhD, motivated by the need of performing mission analysis in libration point regions, until becoming an open-source library with multiple functionalities and oriented to be used and improved by students.

Since its creation, Mubody (its icon is shown in Figure 1) has proven to be an excellent academic tool for both enhancing the library itself and using its results for further studies (collision risk, thermal analysis, formation flight control, etc). As a result, the tool has rapidly evolved, building onto the knowledge and experience that the students gather while working on their academic projects (bachelor's degree dissertations, master theses, subjects, internships). The participation on the library development provides students with experience in orbital mechanics, software design, version control and it compels them to ensure that their work can be readily used by others as it is properly documented.

Figure 1. Mubody icon

This paper presents an overview of the library current structure, models and its main capabilities (Section 2), followed by a description of the student involvement (Section 3), and the discussion of the experience results

DOI: 10.5821/conference-9788419184405.040

(Section 4). Finally, the conclusions of this work are presented.

2. Mubody library

Mubody is an acronym for multi-body dynamics, which refers to the dynamics of the gravitational environment created by two or more massive bodies. The library focuses on the three-body problem, which studies the motion of three bodies under their mutual gravitational fields. When there are no restrictions in terms of the bodies masses and initial conditions, it is called the general three body problem. Such problem does not present a closed solution as the two-body problem does. In fact, in most cases the solution is chaotic. Diverse simplifying assumptions lead to interesting cases. The most known are the so-called restricted three body problems [14], where the mass of one of the bodies is negligible when compared to the other two, which are called primaries. Thus, the motion of the primaries is not affected by the third body, and it can be considered as a two-body problem. In the CRTBP the primaries have circular orbits.

The equations of the CRTBP model present 5 equilibrium points, the so-called Lagrange point or libration points, whose locations are shown in Figure 2. The collinear points (L1, L2 and L3) are unstable and if not controlled, any orbit around them will end up scaping from the libration point region and entering an orbit around one of the primaries. Conversely, the equilateral points (L4 and L5) are stable.

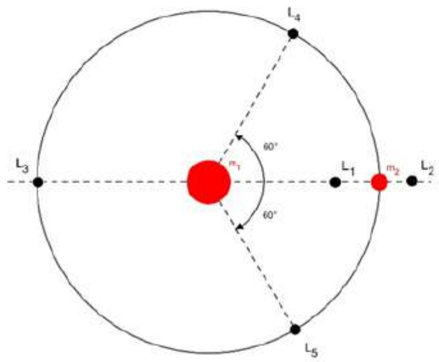

Figure 2. Location of the 5 libration points

The CRTBP model contains many types of different orbits which revolve around the libration points, called libration point orbits (LPO), and they are usually classified into periodic orbits and quasi-periodic orbits. As the CRTBP has not analytical solution, the orbits must be calculated by combining successive approximations with differential correction methods.

The origin of Mubody is in 2018, as a single Matlab script to generate Lissajous orbits (a type of quasiperiodic orbit) in L2 point of the system Sun-Earth. The script contained the analytic solutions for this type of orbits that the linearized equations of the CRTBP model provides [2]. As the project in which it was being used progressed, the script expanded incorporating new functionalities as orbit control and orbit refinement algorithms [15].

Such enhancements were also made by students from both bachelor's degree and masters. All these features accumulated in the same script, which could only analyse one case at the same time.

With the start of a PhD focused on mission analysis of flight formations in L2, it was decided to create the Mubody library as such, switching to Python, establishing a version control through Git [16] and opening a repository in GitLab [17] under a MIT license. These actions were intended to:

- Create a research tool to perform detailed orbital design and analysis.
- Make the tool accessible to others, allowing to reproduce the research results without requiring a paid licence.
- Facilitate the participation of several people in the project at the same time.

With this new approach, the development of the library became faster and easier, implementing an object-oriented structure, following official Python code recommendations, and benefiting from the active Python community online.

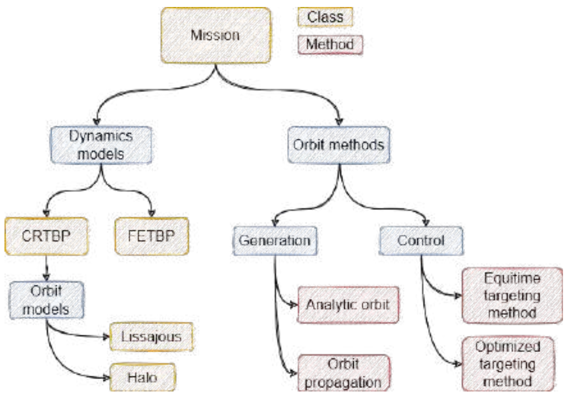

Figure 3: Mubody code diagram

The core of Mubody is the top-level object called *Mission,* where all the data (constants, celestial bodies ephemeris, orbit trajectory, physics models, etc) and methods (generating orbits, refine orbits, plotting, etc) are stored and from which they can be called by the user. The library allows to generate a reference orbit (Lissajous/Halo) using the analytic solution from

DOI: 10.5821/conference-9788419184405.040

the linearized CRTBP equations. Such orbit is unstable and direct propagation from any point along it will end up diverging. Thus, it can be controlled (computing the maneuvers required to keep the satellite in such orbit) o refined (reducing the Δv required in the control maneuvers). The refinement can be performed using the CRTBP model or the FETBP model. In the Figure 3, a scheme of Mubody structure is shown.

2.1. *CRTBP*

The study of this problem is simplified by using a synodic reference frame and normalizing the equations of motion. The synodic reference system is centred in the primaries barycenter, with the X-axis passing through the primaries and oriented to the least massive, and the XY-plane coincides with the primaries orbital plane.

Under these considerations, the equations of motion are:

$$\ddot{x} - 2\dot{y} = \frac{\partial U}{\partial x} \qquad (1)$$

$$\ddot{y} + 2\dot{x} = \frac{\partial U}{\partial y} \qquad (2)$$

$$\ddot{z} = \frac{\partial U}{\partial z} \qquad (3)$$

where U is a pseudo-potential function defined as:

$$U = \frac{1}{2}(x^2 + y^2) + \frac{1-\mu}{\rho_1} + \frac{\mu}{\rho_2} \qquad (4)$$

and $\mu = m_2/(m_1+m_2)$, the mass ratio between the primaries, which must not be mistaken with the standard gravitational parameter. ρ_1 and ρ_2 are the distances from the primaries to the third body.

If the Eqs.1-3 are linearized, analytic expression for Lissajous and Halo orbits can be found [15,18]. In Figure 4, an example of a family of Halo orbits for Earth-Moon L2 obtained with Mubody is shown.

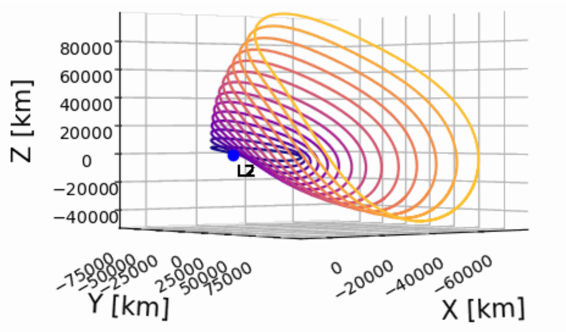

Figure 4. Family of Halo orbits in L2 from Earth-Moon system generated with Mubody

2.2. *FETBP*

In this model, the motion equation is directly the gravity law, expressed in the EME2000 coordinate system:

$$\ddot{\boldsymbol{r}} = -\frac{Gm_1\boldsymbol{r_1}}{|\boldsymbol{r_1}|^3} - \frac{Gm_2\boldsymbol{r_2}}{|\boldsymbol{r_2}|^3} - \sum_{n}^{i=1} \frac{Gm_i\boldsymbol{r_i}}{|\boldsymbol{r_i}|^3} \qquad (5)$$

where $\boldsymbol{r_1}$ and $\boldsymbol{r_2}$ are the position vector from the primaries to the third body and $\boldsymbol{r_i}$ and m_i the position vector to the third body and mass of each of the celestial bodies considered as perturbations.

2.3. *Orbit control and refinement*

Currently, Mubody implements one method for orbit control, ETM, and a method to refine the orbit, called OTM, both from [15]. An example of application is shown in Figure 5.

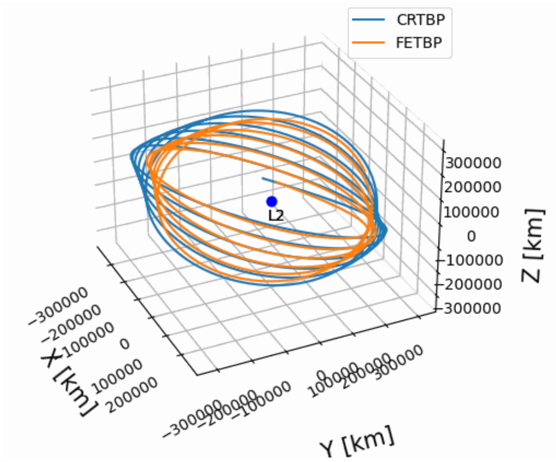

Figure 5. Comparison of refined Lissajous orbit in CRTBP and FETBP

2.4. *Summary of capabilities*

In Table 1, a summary of the present and planned capabilities of Mubody is shown.

Table 1. Mubody capabilities status

Function	Implemented
N-body propagation	Yes
Halo orbits (CRTPB/FETBP)	Yes
Lissajous orbits (CRTBP/FETBP)	Yes
Sun/any planet/Moon as primaries	Yes
Solar wind perturbation	WIP
Formations	TBD
Transferences to Earth/Moon L2	WIP
Documentation/Examples	Yes
Basic plotting	Yes

Currently, Mubody allows direct propagation of an orbit under the influence of several bodies gravity. By default, all Solar System planets, the Sun, and the Moon are available for this operation as well as to be used as primaries.

3. Students involvement

The capabilities/functionalities of the library have been developed motivated by three factors: one, the engineering projects handled by the IDR/UPM, second, the research performed as part of one of the authors PhD, third, the educational activities in which the library has been used. Although different, these three branches of activities are connected. The engineering projects constitute the source of the questions that the PhD research intends to answer. As these activities are developed within an academic environment at the university, they interact with bachelor and master students through their final dissertations, and cases of study, through which work cases are proposed to the students, with a limited scope, allowing them to participate in a real engineering and research activity as an integrated activity of they academic curriculum [19].

The proposed projects are normally focused on incorporating a new functionality to the library and then use such functionality, together with the rest of the library, to analyse or study a given aspect of a mission. The students are provided with basic bibliography of the topic, which they use as a starting point for a more extensive bibliography research. They are given some basic issues to solve so they familiarize with the library structure, Python language and Git use. Then, they are asked to elaborate a proposal of how they would implement the new functionality.

This approach requires certain degree of independent work by the student, but weekly follow-up and doubts resolution facilitates progress and avoids stalling in minor issues. After implementation, the inclusion of testing and documentation is required. Besides the mandatory dissertation or report, their contribution in the library must be documented, tested, and used in some example cases. Their work will be also included in the repository, with an indication to the used version of Mubody, so their work can be freely used and reproduced, even after the library keeps on developing and changing.

In Figure 6, a scheme is shown of how the Git version control is used to incorporate the changes of a new feature while other contributions are made to the library. This allows to parallelize the library development and avoid the risk of causing a failure on projects using Mubody.

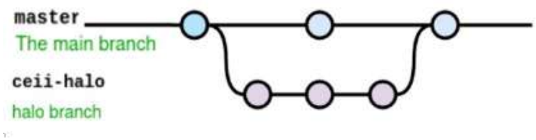

Figure 6. Scheme of Git version control

4. Discussion

The numerical propagation of Mubody has been validated against GMAT, an open-source mission analysis software from NASA. This validation will be automatized in the future so it can be run in each new version of the library.

The educational experience has produced positive results. It is a hands-on project, in an astrodynamics area different from what it is usually taught in aerospace related bachelor and masters syllabus. Students can contribute to something that outlast them and will be used by others. The library has been developed much further than it would have without student collaboration.

The main disadvantage of this approach is that normally students lack experience with version control and object-oriented programming, with the consequent learning curve. Ultimately, this disadvantage is easily overcome by considering an initial period of learning and taking it into account when setting the goals for the project.

Thanks to projects proposed each year as case of study in the MUSE master taught by IDR/UPM, there are multiple opportunities to keep developing the library, with enhancing-oriented projects o with projects focused on libration points that require orbital data that Mubody can provide.

The participation is open to anyone who wants to collaborate, improving the library or using it, specially for students who want to use it in any type of academic work.

5. Conclusions

The development of the library has increased the IDR/UPM know-how in astrodynamics, software development and libration point mission analysis.

Such knowledge has been built in collaboration with bachelor, masters, and PhD students, allowing them to acquire real experience in engineering and research.

All this work is open-source and can be accessed and used freely, which makes research more transparent and facilitates its reproducibility.

The development of the library will continue, focused on orbit design, transference to libration points and formation analysis.

Acknowledgements

Mubody has been developed thanks to the contribution, both direct and indirect, of many people, but especially the students Álvaro Martínez, Leonardo Ruo, Luis García, Ismael Embarek, David Pérez, and Esther Bastida. The authors would also like to thank Francisco Casas and Enrique Martínez for coming to us with the idea of L2-CalSat.

This research has been partially supported by the project 478 Y2020/NMT-6427 OAPES from the program "Sinérgicos 2020" from Comunidad de Madrid (Spain).

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Further evidence of the long-term thermospheric density variation using 1U CubeSats

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Abstract

Faculty members, undergraduate and graduate students of the School of Communication and Aerospace Engineering (Polytechnical University of Catalonia) are participating in a series of studies to determine the thermospheric density. These studies involve planning a space mission, designing and constructing small satellites, and performing related data analysis. This article presents a method for determining the thermospheric density and summarises the academic context in which we develop our work.

Several studies have reported the existence of a downtrend in thermospheric density, with relative values ranging from –2% to –7% per decade. Although it is well known that solar and geomagnetic activity are the main drivers of the variations of the thermospheric density, this downtrend was reported to be caused by the rise of greenhouse gases. We present an update of this progression, considering the last solar cycle (2009-2021) and using Two-Line Elements sets (TLE) of 1U CubeSats and the spherical satellites *ANDE*-2. TLEs were used to propagate the orbits numerically using SGP4 (Simplified General Perturbations), and then compute the average density between two consecutive TLEs by integrating the appropriate differential equation. Then, using the NRLMSISE-00 (Picone 2002) and JB2008 (Bowman 2008) atmospheric models, we calculated an average density deviation per year.

We built a comprehensive time series of the thermospheric density values, ranging from 1967 to the present. We merged Emmert (2015) thermospheric density data and our results computed both with NRLMSISE-00 and with JB2008. A linear regression on the combined dataset yields a decreasing trend of –5.1% per decade. We also studied the geomagnetic and solar activity to isolate the possible greenhouse gasses effect during the considered period. Our results show a strong correlation between geomagnetic activity and density deviation near the solar minima, and we propose that the cause of the previously reported long-term density deviation could be a poor adjustment of the effects of geomagnetic activity. Finally, we proved that orbital information from small satellites could be efficiently used to assess the evolution of thermospheric density variations. Additional data obtained from future missions (as the one proposed by our group) will eventually allow a better characterisation of the atmospheric density and help disentangle the possible greenhouse gasses effects on its variations.

Keywords

Thermosphere, Femtosatellite, Space Climate

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1. Introduction

The lower thermosphere (between 100 and 300 km above sea level) remains poorly known due to the scarcity of operational satellites in this region. Accurate knowledge of the thermosphere is a requirement for efficient operation in Very Low Earth Orbit (VLEO) as exemplified by the catastrophic demise of 40 out of 49 *Starlink* satellites due to a geomagnetic storm in early 2022 [1]. Furthermore, in the era of megaconstellations, space situational awareness will also require a very accurate knowledge of the thermosphere and its variations due to solar and geomagnetic activity, among other possible effects.

Greenhouse gases emissions due to human activities have led to an increase in the global air temperature in the troposphere and lower stratosphere. However, these gases (mainly CO_2) have a cooling effect in the upper layers of the atmosphere [2]. Then, carbon dioxide migrating from the troposphere to the high atmosphere will lead to a decrease in its density.

At the UPC, we have started a research group devoted to the study of the physics of the atmosphere beyond the von Kármán line (100 km). Realizing that this is a topic of profound interest to students, we decided to propose a series of academic works to provide our pupils a first exposure to actual research. This experience has resulted in 11 BEng Degree Thesis, 6 MSc Thesis and one PhD (in development). The subjects have ranged from astrodynamics to small spacecraft design and mission analysis. The first MT along this line dates from 2015.

It should be noted that students of all levels (from undergraduates to PhD candidates) have been involved in the development of this project during all its phases, thus having an outstanding opportunity to demonstrate and apply the knowledge acquired during their bachelor in a real-life research project.

Students and researchers from the EETAC propose a mission based on a swarm of spherical femtosatellites (each with a total mass of about 100 g) in order to determine the density of the lower thermosphere.

Femtosatellites are particularly suitable for our purposes for several reasons. Their reduced cost would allow us to launch a large number of them, permitting in this way a study of the thermosphere as a whole. On the other hand, this low cost is an essential property in other respect: the lifetime in orbit, in the best case, is limited to 100 days, and so inexpensive satellites are the only suitable choice. Lastly, their tiny size and (relative) simplicity makes femtosatellites a very powerful educational tool.

Furthermore, as a preparation and test for the required numerical tools, we have used the TLEs of 1U CubeSats in order to determine the thermospheric density. The results of a Final Degree Thesis by one of the authors (AM) form the core of this communication.

This paper is organised as follows. In Section 2 we describe two possible designs of femtosatellites to improve the data gathering. Section 3 provides a description of the methodology and data used to perform the study of the orbital evolution of 1U CubeSats. In section 4 we discuss the results obtained analysing the time series from 1967 to the present using NRLMSISE-00 (Naval Research Laboratory's Mass-Spectrometer Incoherent-Scatter model) [3] and JB2008 [4]. Moreover, an analysis is done to study the reasons for this downtrend in the thermospheric density. Finally, we draw our conclusions.

2. Femtosatellite configuration

Our overall goal consists of determining, with as high an accuracy as possible, the density of the lower thermosphere. To do so, we have designed two spherical femtosatellites, one with a MEMS (Micro-ElectroMechanical System) accelerometer as payload and a GNSS (to provide the position and time of the measurement), and the second with a MEMS GNSS receiver. With the accelerometer we plan to measure the deceleration caused by drag, and then infer the local value of the density; this approach is limited by the accelerometer accuracy to altitudes below ~250 km. In the other design, a GNSS will provide the state vector ($\vec{r}$ and $\vec{v}$) from which we will be able to solve the orbit and assess the aggregated effect of atmospheric drag; in this way we would obtain an along-orbit average of the density.

In both cases, our designs call for a spherical satellite with a diameter of 10 cm and a mass around 100 grams, which will yield a small ballistic coefficient. The femtosatellite will be affected by the drag with the remaining atmosphere:

$$\vec{D} = -\frac{1}{2}\rho v^2 S C_D \hat{v} \qquad (1)$$

where $\vec{\boldsymbol{D}}$ is the atmospheric drag, $\vec{\boldsymbol{v}}$ the satellite's velocity with regard to the atmosphere, $\hat{\boldsymbol{v}}$ the unit vector in the direction of the velocity, $\boldsymbol{S}$ the cross-section of the satellite, $\boldsymbol{C_D}$ the drag coefficient, and $\boldsymbol{\rho}$ the thermospheric density, our scientific target. The spherical shape implies that the drag coefficient and the cross-section are independent of the satellite's attitude.

This drag causes a deceleration, which can be measured by means of a high-accuracy MEMS accelerometer and, subsequently, the local thermospheric density could be inferred from it. Therefore, the resulting data would be exempt from biases except for the drag coefficient, which is specially complicated to determine as it depends on the geometry and size of the satellite as well as on the solar and geomagnetic conditions.

In the case of the GNSS-based femtosatellite, the state vector would be used to perform an accurate orbit reconstruction. Then, determining the variation of the orbital parameters we would be able to obtain average values of the density.

In both cases, to obtain a holistic vision of the thermosphere it would be necessary to send hundreds of femtosatellites, in different orbital alleys, which would provide determinations of the thermospheric density simultaneously over the whole Earth at multiple altitudes. To achieve complete coverage of the Earth, the orbits will be near-polar ($\boldsymbol{i \approx 90°}$) and distributed in several orbital planes. As an added benefit, high inclination will also result in improved downlinking provided high latitude ground stations are used. Given the low altitude and large ballistic coefficient of the femtosatellites, the risk posed to third-party satellites by this swarm would be negligible.

In addition to the accelerometer, a GNSS receiver capable of solving the navigation message will be added in order to assign accurate position and time tags to each density determination. In the event of failure of the nominal mission with the accelerometers, the GNSS receiver would be used as a backup method in order to determine the along-orbit average density. In addition, if the two above-mentioned methods fail, an orbit reconstruction method, whose input data are Two-Line Element (TLE) sets, would be used in order to determine average thermospheric density values. We expect the latter to be the least accurate of these three methods.

All the electronic components that constitute the designs of our femtosatellites are commercial off-the-shelf devices. The femtosatellites will consist of three single-axis, high-accuracy MEMS accelerometers (in our first design), a GNSS receiver (in both designs, on the second design being the payload), an on-board computer, an SD card, a transmitter (with an omnidirectional antenna), and a primary battery (with a high energy density) for the design using accelerometers, or a combination of solar cells and secondary batteries in the femtosatellite carrying a GNSS as main payload.

The satellite's bus will be embedded in a sphere of a suitable plastic to simplify the drag coefficient as well as to protect it from the space environment, such as the effects of the highly reactive atomic oxygen. Thermal control will be completely passive due to power and size limitations. ADCS can also be absent or be based on passive magnetic systems.

3. Density determination: methodology

In order to study the long-term thermospheric density variation, two different approaches have been used. On the one hand, some studies have performed simulations using climate models to infer the thermospheric conditions (e.g., [5]); on the other hand, researchers have studied the orbits of LEO satellites to deduce the thermospheric density. These studies have yielded results indicating that the density of the thermosphere decreases in the range from –2% to –7% per decade. Among these works, some of them pointed out the increase of CO_2 concentrations as the main cause for this density decrease. However, the causes of this long-term trend are still under discussion.

We derive long-term variation trends in the density of the thermosphere by studying orbits of LEO satellites. For that purpose, we compare the densities derived from orbital data with those computed using numerical atmospheric models.

In this study we have analysed the orbits of 56 1U CubeSats and the two *ANDE*-2 (Atmospheric Neutral Density Experiment) satellites. These satellites have been selected because of their rather simple geometry that will allow us to estimate their ballistic coefficient more easily. With these satellites we have analysed the thermospheric density during the last solar cycle (2009-2021).

Picone [6] showed that in order to derive the average density, SGP4 and TLEs can provide really good results in comparison with special perturbations orbital propagators, that demand a high computational cost. For this reason, both SGP4 and Picone's method were used in this study. Picone's method consists of integrating the following equation to compute the average density between two consecutive TLEs:

$$\rho_o\,(t_{ik}) = \frac{\frac{2}{3}\,\mu^{\frac{2}{3}}\,n_M(t_{ik})^{-\frac{1}{3}}\,\Delta_{ik} n_M}{BC_T\,\oint_i^k F\,v^3\,dt} \qquad (2)$$

where $\boldsymbol{\mu}$ is the terrestrial gravitational parameter, $\boldsymbol{n}_M$ is the mean orbital motion as a function of $\boldsymbol{t}_{ik}$, the time between consecutive TLEs, $\boldsymbol{\Delta}_{ik}\boldsymbol{n}_M$ the change of the mean orbital motion between the two considered TLEs, $\boldsymbol{BC}_T$ the true ballistic coefficient, $\boldsymbol{v}$ is the velocity of the satellite with respect to the atmosphere and $\boldsymbol{F}$ the wind factor, a correction factor to model thermospheric winds. In this case, only corotating winds have been modelled. For further information, the reader is referred to [6].

To integrate the equation, small time steps have to be considered. In our simulations, we have used a time step of 4 minutes, as suggested by [6]. An important aspect is to define what is considered as consecutive TLEs. Strictly consecutive TLEs show noisy variations in the results. For this reason, we have selected for each TLE the first available TLE after a time interval of three days and define the pair as consecutive.

To compute the thermospheric density deviation, the computed derived density has to be compared to the one computed using atmospheric models (NRLMSISE-00 and JB2008). To do so, the average is defined as:

$$\rho_M(t_{ik}) = \frac{\oint_{t_i}^{t_k} \rho_M v^3 F\,dt}{\oint_{t_i}^{t_k} v^3 F\,dt} \qquad (3)$$

However, before integrating both equations, it is necessary to obtain the ballistic coefficient. As already mentioned, giving an accurate value of the ballistic coefficient is one the most challenging tasks in this kind of studies. In this paper the ballistic coefficient was determined considering a $\boldsymbol{C_D}$ of 2.2 and a cross-sectional area equivalent to the average of the larger and the smaller possible cross-sectional areas of a 1U CubeSat. For the *ANDE*-2 satellites, as they were spherical, its cross-sectional area is a circle of radius equal to that of the satellites. On the other hand, for the case of the added satellites for the analysis with JB2008, the considered ballistic coefficients were the ones calculated in [7].

To verify our approach of the BC, the inverse calculation explained in equation 3 has been done using the density data yielded by JB2008 atmospheric model:

$$BC_T = \frac{\frac{2}{3}\,\mu^{\frac{2}{3}} n_M(t_{ik})^{-\frac{1}{3}} \Delta_{ik} n_M}{\oint_{t_i}^{t_k} \rho_M v^3 F\,dt} \qquad (4)$$

According to [4] a 10% of error is expected with this model. Thus, if our approach is valid, a deviation within this margin is expected if we derive the average BC coefficient of each satellite. The average deviation of the BC for all the satellites is about –4% with respect to our assumed values, which is within the expected value.

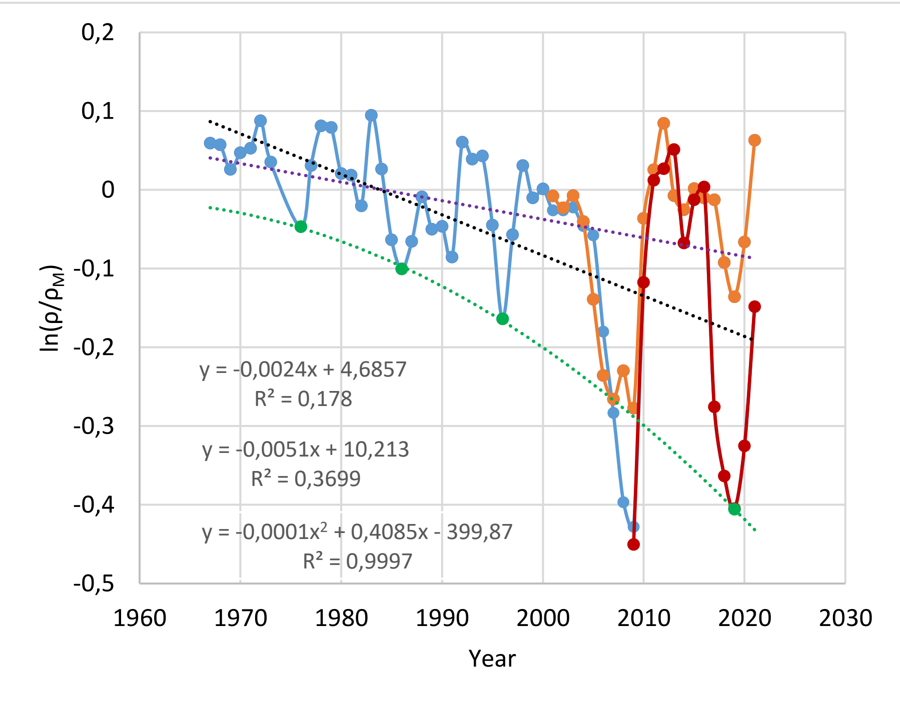

Figure 1: Thermospheric density deviation using NRLMSISE-00 (red for this study and blue for [8]) and JB2008 (orange). Green line represents the quadratic fit for minimums. Black line represents the linear regression for NRLMSISE-00 results (this study plus [8]). Violet line represents the linear regression for NRLMSISE-00 before 2009 and JB2008 from 2009 to 2021.

4. Density determination: results & discussion

In this section we examine the results of the simulations after computing the average density of each satellite following the methodology previously described (Figure 1). It is worth to mention that the present results are referred to an altitude of ~400 km. The results obtained have been combined with the ones obtained by [8] with the goal of having a longer time series. In this way, a better understanding of the long-term variations can be obtained.

Firstly, we analyse the results obtained with NRLMSISE-00. To evaluate the long-term deviation of the density, a linear regression has been done. This linear regression gives a decreasing tendency of a –5.1% per decade for the density. This result is in accordance with [9], whose study spanned from 1970 to 2010. As can be seen in the comparison made in [5], studies that do not take into account data after 2005 yield much less deviation than the ones that take more recent data. This shows that the difference between the studies is caused by the poor results yielded by the atmospheric models during the last two solar minima.

To evaluate the possible causes of this deviation, the solar activity and the geomagnetic activity were examined. We compare the median of both solar and geomagnetic activities during the minima and the density deviation obtained for these years. In that way, we can indirectly assess the possible effects of CO_2 too. The comparison with the solar activity does not show any correlation, however, it does with the geomagnetic activity (Figure 2).

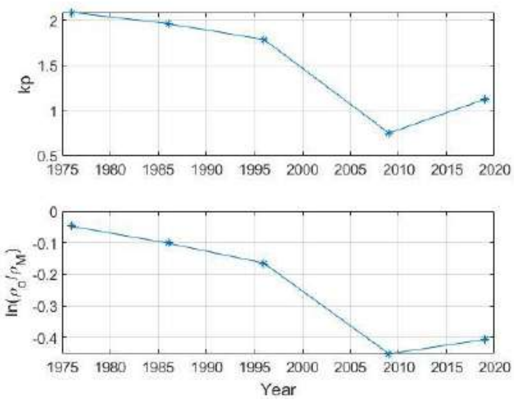

Figure 2: **Geomagnetic activity during solar minima (upper panel) and thermospheric deviation (lower panel).**

It can be seen in Figure 1 that, either using the data from JB2008 (which models more accurately the geomagnetic activity) with all the data, or disregarding the NLRMSISE data near the minima of 2009 and 2019, the errors are within the range obtained with NRLMSISE-00, from 1967 to 2005. Specifically, in the case of JB2008, the downtrend tendency is –2.4%. Thus, it appears that the downward tendency of the thermospheric density is mainly caused by an imperfect adjustment of the geomagnetic activity effects on the thermosphere. This was also proposed by [10].

Regarding CO_2, it does not seem to affect the thermospheric density as much as some studies such as Brown indicate, where deviations about 6% are considered to be caused by CO_2. As was analysed, the geomagnetic activity is the main cause for this deviation, not CO_2. To assess the effects of CO_2 in the middle-upper thermosphere a further study should be done since the performed in this study do not show a clear effect of CO_2. Uncertainties in solar and geomagnetic activities remain too high to really know the role that plays CO_2. On the other hand, what can be said from Figure 1 is that if CO_2 plays a role in the middle-upper thermosphere it should be low since if the minimums are removed, the tendency seems quite slow (if it exists).

5. Conclusions

As part of our research on the density of the thermosphere we have tapped the information stored in the orbital evolution of 1U CubeSats. This approach, already explored by [5,9], has yielded interesting results. Nevertheless, the lack of accurate knowledge of the drag coefficient and the attitude of these satellites introduce an uncertainty in the results.

To alleviate this problem, we have designed two femtosatellites to provide more direct measurements of the density: one of them, with high-accuracy accelerometers and a GNSS, would provide the values of local density; the second, based on the reconstruction of the satellite's orbit with the data provided by a GNSS, would infer average values for the density.

This paper has also presented an analysis of the trends obtained by deriving average density values from existing satellites using the method described by [6]. With this method, the average density deviation has been computed from 2009 to 2021 using two atmospheric models (NRLMSISE-00 and JB2008).

The results for NRLMSISE-00 show a decrease of –5.1% per decade and the ones yielded by JB2008 show a decrease of –2.4%. However, both show higher deviations during solar minima. Thus, an analysis was carried out to study possible correlations between solar and geomagnetic activities with density deviation. We have detected a strong correlation between geomagnetic activity and density deviation. Apart from that, it has been shown that JB2008 yielded lower density deviations during these minima due to its better input proxies and, furthermore, during the last solar cycle (2009-2021) yielded similar error to those yielded by NRLMSISE-00 during the previous solar cycles (prior to 2009).

Our work therefore hints that the long-term density deviations are probably caused by the bad adjustment of the effects caused by the geomagnetic activity. Regarding the possible effects of CO_2, we cannot conclude whether it has some effect on the thermosphere (medium and upper heights) or not since the uncertainties on the effects of geomagnetic and solar activities are larger than the possible effect that carbon dioxide could have. On the other hand, it has been proved that orbital information from small satellites can be efficiently used to assess the evolution of thermospheric density variations. Thus, the large number of CubeSats launched yearly represents a potential source of vast amounts of relevant data, which may help to better characterise the thermosphere.

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A Model-Based Systems Engineering Approach to Space Mission Education of a Geographically Disperse Student Workforce

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Abstract

The Alabama Burst Energetics eXplorer (ABEX) is a 12U CubeSat commissioned by the Alabama Space Grant Consortium; its astrophysics mission is to study the low energy, prompt emission of Gamma-ray Bursts in both gamma and X-ray spectra. The ABEX program is unique in that its workforce is comprised of individuals at seven colleges and universities around the state of Alabama. ABEX management releases Requests for Proposals (RFP) for Senior Design (SD) projects or university research groups to design and build spacecraft subsystems; university faculty with experience and facilities for the development of that subsystem respond to the RFPs to create a team. ABEX supports undergraduate SD students, graduate student mentors, and faculty technical advisors for all spacecraft subsystems in both ground and flight mission segments. Each team has between 5-15 undergraduate students, meaning ABEX teaches spacecraft design to ~85 undergraduate students at any given time; ABEX may be the largest collegiate CubeSat program in the world. The undergraduate labor force turns over, or cycles to new students, every 4-8 months, so ABEX can teach hands-on spacecraft design to over 100 students every year and has taught over 200 to date. Two features of ABEX create a difficult Systems Engineering (SE) environment: the undergraduate labor force turnover rate and the geographically disperse workforce. Most subsystem teams exist within two-semester SD courses, but some teams, like Flight Software, only exist for one semester before the undergraduate team turns over. This means the student onboarding process must be efficient and the material hand-off process effective if any substantive contribution to the spacecraft is to be made in their brief course period. A Model-Based Systems Engineering (MBSE) Integrated System Model (ISM) was created using SysML as a full-program organization of mission requirements, subsystem architectures, verification and validation procedures, and team interaction tracking methodologies for workforce turnover effect mitigation with ISM-exported artifacts as central objects of stage-gate reviews. An ABEX website was created with processes for first-time student onboarding, ISM artifact dissemination, and intercollegiate document transfer in addition to being a public relations arm for the program. With education at the forefront of ABEX, educational requirements and performance measures detailing onboarding efficiency, workforce preparedness, and alumni vocation results are defined within the ISM and used to evaluate program education proficiency. Program organization, ISM structure, and spacecraft design is presented with an emphasis on quantifying student education as a result of program involvement.

Keywords

Space Education, Model-Based Systems Engineering, Workforce Development

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Acronyms

AAMU	*Alabama Agriculture & Mechanical University*
ABEX	*Alabama Burst Energetics eXplorer*
AF	*Architecture Framework*
ASGC	*Alabama Space Grant Consortium*
DAC	*Design Analysis Cycle*
DBSE	*Document-Based SE*
DKM	*Domain Knowledge Map*
DSTC	*J. F. Drake State Community Technical College*
EPM	*Educational Performance Measure*
GRB	*Gamma-ray Bursts*
HBCU	*Historically Black Colleges & Universities*
ISM	*Integrated System Model*
KQ	*Key Question*
MBSE	*Model-Based SE*
NASA	*National Aeronautics and Space Administration*
PF	*Process Framework*
RDP	*Review Data Package*
SE	*Systems Engineering*
SME	*Subject Matter Expert*
SSO	*Sun-Synchronous Orbit*
TPM	*Technical Performance Measure*
UAH	*University of Alabama in Huntsville*
WBS	*Work Breakdown Structure*
WFF	*Wallops Flight Facility*

1. Introduction

The Alabama Burst Energetics eXplorer (ABEX) is a 12U CubeSat that will probe the energy dissipation in astrophysical jets by observing a currently unexplored energy domain in the universe's most energetic phenomena: Gamma-ray Bursts (GRBs). Understanding GRBs is a key element in both the National Aeronautics and Space Administration's (NASA) Astrophysics Roadmap [1] and the 2020 Astrophysics Decadal Survey [2] as a laboratory for high-energy physics, compact object formation, and gravitational waves. ABEX is a coalition effort between 7 universities and Goddard Space Flight Center, which will provide qualification testing and advise the project continually.

1.1. ABEX: A Space Education Program

ABEX is an educational mission uniting 1 NASA center, 7 colleges and universities, 12 faculty, and 19 graduate students with undergraduate teams to create the largest collegiate spacecraft project in the world (M. Swartwout, personal communication, March 7, 2022) and serve as a model for education-centric spacecraft development. Students working in a multidisciplinary and geographically dispersed environment co-lead all aspects of the project and are provided supporting classes with ABEX-specific coursework. ABEX also conducts outreach to underrepresented groups in aerospace through Historically Black Colleges and Universities (HBCUs).

1.2. NASA's Educational Goals

NASA's Strategic Plan and Astrophysics Roadmap both outline a need for engagement within a Science, Technology, Engineering, and Mathematics pipeline to increase diversity in the field [1,3]. ABEX strategically enables 7 academic institutions with faculty, graduate, and undergraduate students in all project domains; faculty members advise graduate students who lead undergraduates in senior-level projects. During major development phases, ABEX provides 19 graduate students with critical leadership roles, such as Project Manager and Chief Engineer, for early career opportunity experience. Academic courses are offered by ABEX faculty to educate students in specific topics relevant to each team. ABEX has a multidisciplinary and geographically disperse work environment, providing realistic working conditions compared to modern collaborative missions with students simultaneously gaining hands-on science and engineering skills and academic credits. Educational risk introduced by student involvement is mitigated by strong onboarding procedures, recorded seminars, process documentation, dedicated classes, faculty oversight, and Subject Matter Expert (SME) mentorship. ABEX provides a training environment to prepare future scientists and engineers to collaborate in managing, conceptualizing, designing, and implementing future NASA and aerospace missions. ABEX responds directly to the 2020 NASA Astrophysics Decadal Survey's recommendation that HBCUs be at the forefront of astrophysical research through its partnerships with J. F. Drake State Community and Technical College (DSTC) and Alabama Agriculture & Mechanical University (AAMU), both institutions proximate to the University of Alabama in Huntsville (UAH) [2]. DSTC will develop a cleanroom for ABEX and lead

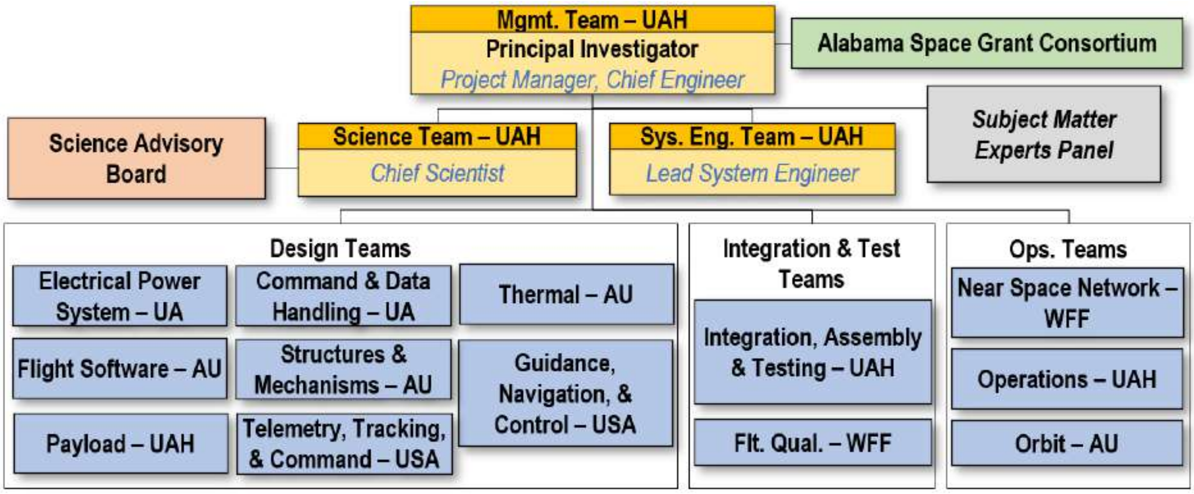

Figure 1. ABEX Management Hierarchy with Auburn University (AU), the University of Alabama (UA), and the University of South Alabama (USA). Blue text indicates management roles for graduate students

spacecraft assembly. Summer research opportunities will be provided to AAMU students to work with UAH science and engineering teams. Since the start of the ABEX collaboration in 2019, over 200 university students have been involved including 8 graduate students.

1.3. ABEX Program Structure

The student involvement in ABEX requires strong management structures and clear lines of authority. ABEX activities are coordinated around a Work Breakdown Structure adapted from NASA/SP-2016-3404 [4]. Undergraduates are managed by graduates overseen by faculty with project leadership from the Principal Investigator through the Project Manager and Chief Engineer. Supporting management roles are the Lead Systems Engineer and Chief Scientist. All teams are technically supported by the Science Advisory Board and SME panel. The Alabama Space Grant Consortium (ASGC) assists with outreach, student activities, and university negotiations to promote ABEX educational goals. The ABEX team hierarchy is shown in Figure 1. Graduate students outside of management roles are allocated to design, operations, and integration & test teams.

2. Astrophysics, Spacecraft, and Mission

GRBs are theorized to originate from powerful jets generated by compact object formation, but debate remains on Key Questions (KQ) concerning the composition of the jet and how energy dissipates forming the bright gamma-ray emission. To resolve KQs, observations must be pushed into a new domain, the low-energy prompt emission, which offers distinctive features able to resolve the tension between emission models. Figure 2 depicts the science mission goals.

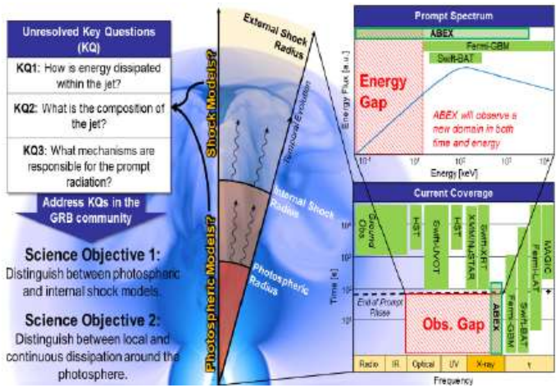

Figure 2. ABEX Science Objectives

To accomplish both education and science goals, the spacecraft bus was custom-designed including the on-board computer, electrical power system, software-defined radio, link antennas, structural chassis, thermal control system, and GRB detection payload. The solar arrays and attitude determination and control systems are vendor-supplied. Like the science mission and spacecraft bus, the mission architecture, shown in Figure 3, was designed and analyzed by students with data products publishing to a student-built website, abexmission.org.

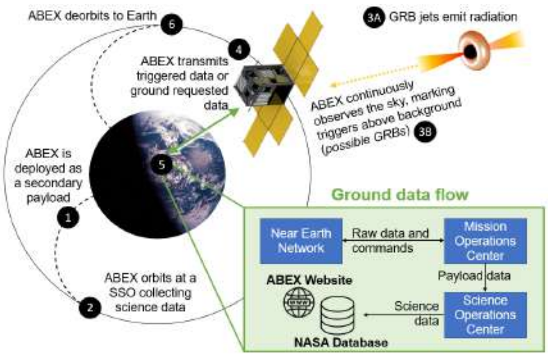

Figure 3. ABEX Mission Architecture

3. MBSE and Space Education

Model-Based Systems Engineering (MBSE) is defined by an Architecture Framework (AF) specifying a taxonomy of work products created throughout the mission, a Process Framework (PF) detailing the maturation of those products, an ontology expressing the properties of and relations between those products, and a modeling language used to create the Integrated Systems Model (ISM) which ties it all together [5]. The AF and PF organize which activities are accomplished in the mission and how they are accomplished, respectively; defining these explicitly affords rigid yet reinforceable structure to a project organization. The ontology aids in student conceptual understanding, product creation, and process execution by defining entity categories for concepts that exist in the program and strong, semantic relationships between those categories; ontologies represent an agreement on relationship usage rather than the usage itself. Graduate systems engineers interact directly with the ISM, not undergraduates. Methods for incorporating MBSE tenets into space education processes are discussed.

3.1. Integration of MBSE & Education

MBSE and space education are integrated in three primary sectors: Work Breakdown Structures (WBS), student onboarding, and review materials, each of which is given dedicated attention subsequently.

3.1.1. Work Breakdown Structures

Program management, in ABEX's case the Project Manager and Chief Engineer, organize engineering, operations, science, and enterprise work in terms of the AF and provide subsets of that work to students in the form of a Design Analysis Cycle (DAC) work package specific to an academic semester. Per the PF, descriptions are included for how the work package should be executed and in what form deliverables should be provided. The PF also dictates which deliverables are shown at which stage-gate reviews, informing the products that should be created for a given DAC. If the AF and PF are defined in mission concept development, all future DAC work is known, ordered, and communicable.

Work products in the AF will also be model-based if possible. ABEX utilizes SysML and UML as modeling languages that students can use to generate DAC work products, such as block definition diagrams for subsystem structure, activity diagrams for subsystem behavior, activity diagrams for integration test chain representation, parametric diagrams for analytical models, and sequence diagrams for software operations. Student-produced, model-based work can be imported directly into the ISM, reducing time required to translate student deliverables into the ISM.

3.1.2. Student Onboarding

Onboarding is the process of educating new members of a workforce in a relevant field and ensuring members can execute provided tasks using a set of provided tools; efficient onboarding provided by faculty and graduate students is paramount for student space programs because student turnover rates are high and knowledge retention is low. Three concepts have aided ABEX in student onboarding: traditional documentation, a centralized repository of onboarding materials, and Domain Knowledge Maps (DKM). Document-Based Systems Engineering (DBSE) is, unfortunately, how students are accustomed to learning. Documents such as analysis plans, development & integration plans, and verification activity plans can be provided as is common of any program, but DBSE material representation should be consistent with the AF, PF, and ontology with figures generated from the ISM. When students provide work products for import into the ISM, the products are polished, connected to other ISM entities such as requirements, structures, or behaviors, and exported back to the DBSE onboarding tools. When students learn subsystem onboarding material, they learn MBSE. Those documents, and any additional onboarding materials, must be available on-demand from a centralized repository for a geographically disperse program. ABEX utilizes a website, abexmission.org, as the first stop in a student's onboarding journey. Students receive onboarding packages specific to their team containing subsystem-specific plans, reports, tool usage guides, and more general spacecraft and SE education.

For analysis products, DKMs facilitate a direct connection between the ontology and the execution of analysis work outlined for a DAC. Ontologies can be created for a specific domain; ABEX subdivides a program-wide ontology into fragments such as the technical analysis domain for hardware and the software development domain for software. A DKM is an application of a domain ontology to a specific problem such as the calculation of a Technical Performance Measure (TPM) or the connection between user-defined software subsystems. If a domain ontology contains concept categories and relationships in that domain, a DKM

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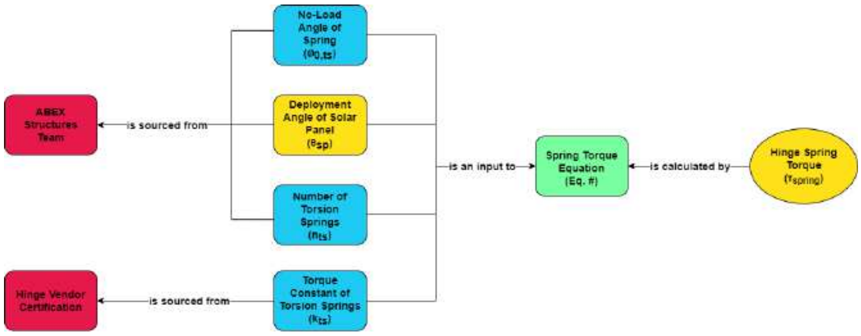

Figure 4. DKM Example. Instances of Source, Scalar Parameter, Array Parameter, and Equation categories are shown in red, blue, yellow, and green, respectively. TPMs are shown as ovals

represents instances of those categories and how they are used. A DKM example detailing instances of predefined categories is provided in Figure 4. The ontological triple, “Number of Torsion Springs is an input to Spring Torque Equation” is an instance of the ontological triple, “Scalar Parameter is an input to Equation.” Strong semantics inherent to DKMs remove ambiguity in concept representation.

3.1.3. Review Materials

Programs with rigorous Systems Engineering (SE) processes feature stage-gate reviews such as a System Requirements Review or Critical Design Review, and SMEs attending reviews need organized review material in the form of Review Data Packages (RDP) prior to reviews. Even at NASA, RDPs are usually created by sourcing materials from various documents, presentations, standards, and verification activity reports – a cumbersome, time-consuming process. A DAC may last only 14 weeks, and time to execute work products may be severely limited if 3 weeks are required for student onboarding and 3 weeks are required to organize RDP materials. Generating some, not all, RDP materials from the ISM is known as a model-based review and affords time-reduction methods when organizing review materials. Using the ISM, a subsystem can depict structural composition, behavior, integration flows, analysis plans via DKMs, test plans, and the satisfaction or verification of requirements as applied to any diagram. The generation of many RDP materials is then accomplished via perfunctory model exports rather than hunt-and-gather documentation.

3.2. Educational Performance Measures

As with TPMs, which are performance measures monitored by comparing current achievement of a parameter with that anticipated at the current time and on future dates [6], the performance of an educational program can be measured by Educational Performance Measures (EPM). Like TPMs, EPMs should be relevant, measurable, tailored for a project, and have a target value to compare performance against. Management should be able to trade cost or schedule to improve EPM performance, and performance should be expected to improve with time. For example, involvement percent of minority and female students is an EPM, and ABEX conducts post-DAC evaluations with anonymous student responses to gather EPM data. For DAC-2 in Fall 2021, 84% of ABEX students asserted that ABEX contributed their skills and knowledge, 68% asserted the learning objectives were clear at the beginning of the DAC, and 74% would recommend ABEX to another student. Target values for these EPMs are not yet justified, but EPM data tracking allows programs to analyze and identify educational improvement areas.

4. Lessons Learned

ABEX management and faculty collaborated on two CubeSat missions prior to ABEX, and various project structures, work vectors, and student activities were pursued before ABEX achieved persistent success.

4.1. To MBSE or not to MBSE

Students have a finite threshold for comprehension of new material and available time; other than the SE team, their efforts should be spent learning technical material specific to a subsystem and not the inner workings of MBSE. When management provides DAC work package material with products, product formats, and due dates, they are decoupling students from the AF and PF. Management knows which products should be presented at which stage-gate reviews; students should be focused on individual tasks in a DAC work package. MBSE is also not a panacea for all life cycle phases. Management should lean heavily into MBSE for student onboarding and RDP preparation, but the utility of MBSE decreases rapidly after test and integration activities are completed [7].

DOI: 10.5821/conference-9788419184405.042

4.2. Product Formatting is Critical

If a product is requested of 7 teams and a format is not specified, management will receive 7 products in 7 different formats. It is not sufficient to prevent product formats from being problematic; programs should make the formats work to their benefit. Students should deliver products in a format that is importable to the ISM and consistent with a predefined ontology.

4.3. Time is Limited for Every DAC

Two DAC fragments should be reduced as much as possible to maximize product execution time: onboarding and RDP creation. If a program with 20 planned DACs reduces onboarding time by 1 week and RDP creation by 2 weeks, that's 60 weeks of development and execution time gained per student. MBSE can reduce the time required for both.

4.4. Documentation is Unavoidable

Students are accustomed to learning by reading, and documentation passed down between student teams is usually the first step in new student onboarding. However, material representation within the documentation such as subsystem structure, behavior, and requirements can be represented using a modeling language. Doing so will prepare students to create MBSE-centric deliverables.

4.5. Roll the Teams Across DACs

Not every ABEX team is part of a senior design program, but many are. For those that are senior design teams, a strategy that has significantly improved knowledge retention is to start a new subsystem team every semester. First-semester teams do not produce many valuable deliverables, but they learn from second-semester teams and produce excellent deliverables their second semester in ABEX.

5. Conclusions

The organizational structure of the ABEX program can be emulated to create multi-institution space education programs with geographically disperse workforces. By aligning semesters with DACs and planning DAC operations using AF and PF structures, a program can coordinate mission development activities around SE life cycle phases without spending valuable onboarding time to educate undergraduate students on MBSE tenets. Reducing the time required for onboarding and RDP creation is vital to the long-term success of a program, and advanced MBSE techniques such as ontology definition and DKM utilization can facilitate and standardize spacecraft analysis techniques and report formats. MBSE should be employed heavily in early life cycle phases with DBSE being more useful after integration procedures. Rolling teams across semesters will increase program knowledge retention and onboarding document quality.

Acknowledgements

The authors would like to acknowledge the Alabama Space Grant Consortium for its continued support of ABEX through the Alabama CubeSat Initiative, the Complex Systems Integration Lab at the University of Alabama in Huntsville for supporting model-based research in spacecraft engineering, and all the ABEX faculty for their tireless efforts.

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BEXUS30 – ELFI: Measuring Schumann resonances in the atmosphere

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Abstract

The ELFI project was one of nine BEXUS experiments carried in two stratospheric balloons in 2021. The aim of the experiment was to develop a system for the non-stationary measurement of electromagnetic waves in the extremely low frequency range. The Schumann resonances that are part of this range are especially important for meteorological research. For the planned use of the system on a stratospheric balloon, various requirements and aspects regarding the measurement environment had to be considered during the development. The system is based on a magnetic loop antenna connected to a signal processing unit, the Analog Front-End. The antenna has special characteristics to enable the measurement of Schumann resonances. Due to the necessary high sensitivity of the antenna, a deployment mechanism was developed to lower the antenna for the measurement, thus reducing the influence of interference from the electronics or actuators of other experiments on the gondola. After the balloon is launched, the mechanism is extended, and the antenna is lowered below the gondola. The Analog Front-End has several stages that filter, amplify and digitalize the signal measured with the antenna. An on-board computer, built from reliable general-purpose hardware, performs the measurement, organizes and stores the measurement data, and provides communication with the ground station. Hence, monitoring and control of the experiment through the ground station was possible. In addition, an algorithm for automatic gain control was integrated to allow flexible measurement of different amplitudes.

In several testing periods the system was validated for functionality and reliability. Through numerous preliminary tests, frequencies from reference sources could be detected, e.g., 50 Hz of the power supply network or 16.67 Hz of the railroad power supply. Underground measurements confirmed that the system is suitable for detecting low frequencies. Furthermore, the system was tested and confirmed to be usable under extreme conditions like low temperatures and low air pressures. The developed deployment mechanism with scissor arms was proved to be robust and flexible. Both hardware and software worked as expected and are reliable and adaptable to different conditions. During final tests in an almost interference-free area our system was able to record optimal signals, in which the Schumann resonances could be detected. Based on these successful results, the system was ready to be deployed on the stratospheric balloon to perform measurements in the atmosphere.

Keywords

BEXUS, Extremely-Low-Frequency, Schumann-Resonances

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Acronyms/Abbreviations

AFE	*Analog Front-End*
AGC	*Automatic Gain Control*
BEXUS	*Balloon Experiments for University Students*
ELF	*Extremely-Low-Frequency*
OBC	*On-board computer*
OS	*Operating system*
SPS	*Sample(s) per second*
SR	*Schumann resonances*
TLE	*Transient luminous event*

1. Introduction

The experiment is designed to develop a system for capturing electromagnetic waves in the extremely low frequency (ELF) band in reference to varying ambient conditions. Of special interest in this band are the frequencies of the Schumann resonances (SR), e.g., 7.83, 14.1, 20.3 Hz as shown in Figure 1. The SR are the result of the earth's atmosphere acting as a resonant cavity. This resonator uses the ionosphere and earth's crust as waveguides and the atmosphere in between acts as the dielectric material. The waves are mostly excited by the global lightning activity or transient luminous events (TLE). TLEs are events which cause transients with the first mode of the SR as the dominant contributor (Q bursts first described by Boccippio et al. in 1995 [2]). Thus, SR are particularly of interest for meteorological research.

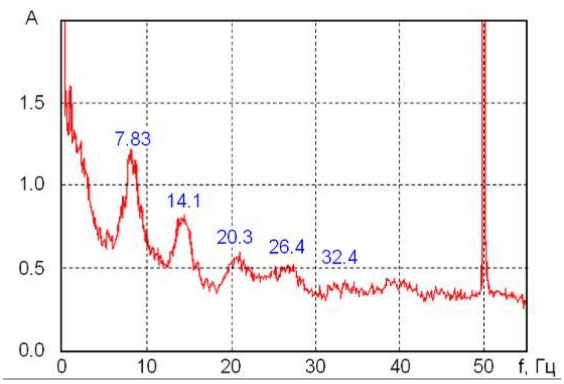

Figure 1. Typical ELF spectrum with SR [1]

The ELF spectrum is typically measured with fixed antennas on ground level. Those antennas are either built as ground dipoles, huge loop antennas or induction coil antennas. Out of these options only the loop antenna is a viable option for our requirements. Because measuring the ELF band needs those elaborate receivers there seems to be no data about the behaviour of the Schumann resonances on different altitudes. The aim of the ELFI experiment is to design a system that can perform non-stationary ELF measurements. Subsequently the system shall be deployed, and the measured data shall be analysed and compared with the ground level data.

2. Experiment setup

The experiment basically consists of an on-board computer (OBC), a signal conditioning unit, called AFE, and a loop antenna. The OBC as well as the signal conditioning unit will be placed in a box inside the gondola. The loop antenna will be mounted on a scissors lift, which will be attached on one side of the gondola. The scissors lift is designed to be extendable below the gondola during the flight. The experiment is designed with the requirements for the deployment on a BEXUS stratosphere balloon.

2.1. Mechanics

The mechanical parts of the experiment are the electronics box, called Braincase, the scissor mechanism with the antenna and the mounting plate, called Prime, to which the scissor mechanism with the antenna is mounted to. The Braincase is mounted inside the gondola whereas the Prime is attached to the outside of the gondola as shown in Figure 2.

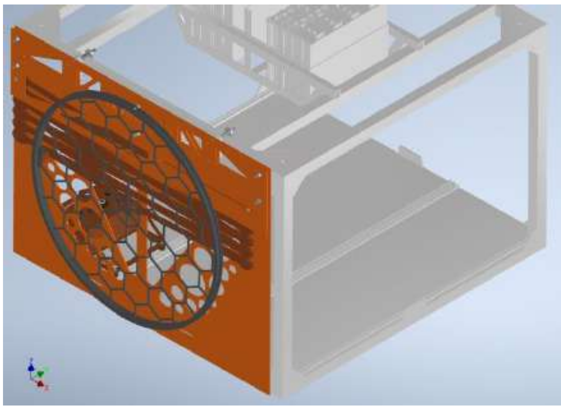

Figure 2. Prime, antenna, scissor mechanism and Braincase mounted on gondola

2.2. Electronics

Main part of the electronics is the developed AFE for signal conditioning shown in Figure 3. It includes two amplifier stages, a filter stage, and an analog-digital-converter (ADC). The stages have the following characteristics:

- 1st stage: non-inverting input amplifier with adjustable gain 19.667 – 57
- 2nd stage: 4th order low pass filter with 2 stage Sallen-Key architecture and Chebyshev characteristic, cut-off frequency 14 Hz, 0 dB attenuation
- 3rd stage: non-inverting output amplifier with adjustable gain 43.68 – 1001
- ADC: 24-bit Delta-Sigma ADC with SPI, TI ADS1220 with integrated programmable gain amplifier [3]

For the amplifier and filter stages the ADA4528 operational amplifier was used because of its high precision, ultralow noise, and zero-drift properties [4]. The operational amplifiers use a dual-ended power supply integrated into the AFE. The AFE is implemented on a single board with a 4-layer design (signal layer, ground layer, positive + negative layer) to ensure a good amount of capacitance between the single layers.

The antenna shown in Figure 2 is a magnetic loop antenna with a coil and a special frame. The coil has about 2649 turns of wire with a wire length of 6,660 m and a resistance of 3,623.7 Ohm. It is connected via a shielded 2-wire cable directly to the AFE. The frame has a diameter of 80 cm and to ensure robustness and flexibility it has a honeycomb structure and is made of Pertinax.

Another important part of the electronics is the power supply system. When mounted to the gondola of the BEXUS balloon, all experiments are connected to the battery power supply. Unfortunately, it does not provide a stable voltage during the whole flight and has only a few protections against e.g., short circuit caused by an experiment. Additionally, our experiments' power system needs to be isolated from the other experiments. To achieve this, we partially reused the IMUFUSION power board from the previous BEXUS IMUFUSION experiment of the University of Applied Sciences Nordhausen [5]. It provides the required voltages of 5 V and 12 V. Separate DC/DC converters are used to power the OBC and the Gear motor.

2.3. Software

The software system is divided into the OBC software and the ground station software. The OBC software performs all measurements during the experiment and in parallel takes care of data storage and transfer between the experiment and the ground station.

The *Raspberry Pi* runs the Linux distribution *Raspberry Pi OS* as the underlying operating system (OS). This was chosen because it is a reliable base system which can handle the parallelism and measurement timing according to our requirements. Thereupon the OBC software is implemented as a Python script. It performs multiple tasks in parallel by utilizing the threading capabilities of the SoC and the OS. A total of six threads and two timers are used to achieve asynchronous behavior and meet measurement timings. Two dedicated threads are responsible for performing the ELF and inertial measurements with two timers providing a sample rate of 2000 samples per second (SPS) for ELF and 1 SPS for inertial measurement. Two other threads take care of the data management, the storage of the measurement data on the internal memory and backup storage and the transmission of the data to the ground station. Another thread is used for automatic gain control (AGC). The AGC algorithm collects a subset of the ELF measurement data and evaluates it against predefined thresholds. This allows it to detect long-lasting saturation and then decrease gain or increase gain when the signal has small amplitudes. The main thread of the application initializes all other threads and is responsible for the communication with the ground station.

The ground station software is also implemented in Python and running on a usual

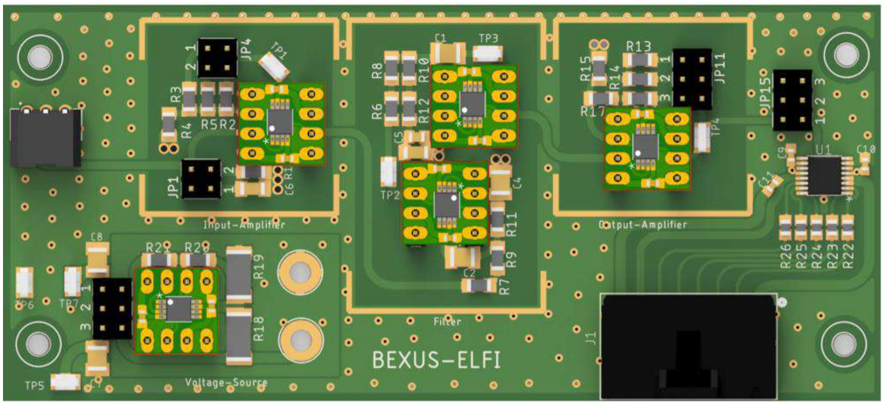

Figure 3. Developed Analog Front-End (AFE) for signal conditioning

PC. It provides network sockets for the communication. The received measurement data is decoded and stored in a local database for redundancy. The user interface of the ground station allows monitoring of the experiment with live plots of all measurements and FFT plots. The ground station is also used to trigger the release mechanism of the antenna.

3. Preliminary tests

The system had to be tested extensively in preparation for Campaign Week on ESRANGE. For this purpose, the hardware and software as well as the mechanics of our system were subjected to several tests.

3.1. Requirements

3.1.1. Mechanics

The mechanics of our experiment must be robust against shocks, vibrations and movements. The winch must ensure a smooth lowering of the antenna. Furthermore, the scissor arms must be able to withstand various movements of the gondola so that the antenna does not hang unsecured on the gondola.

3.1.2. Hardware

The hardware of our system should be prepared for the corresponding environmental conditions. Since we expect very low temperatures and air pressures during the flight, the hardware must be robust against temperature fluctuations, air pressure differences and alternating humidity. Furthermore, there must not be errors caused by vibrations, shocks, or even electromagnetic fields. Electromagnetic compatibility was particularly important here since the other experiments of the BEXUS30 balloon were close to our system.

3.1.3. Software

Since it is an essential part of our experiment, a test of the entire software was particularly important. Both the integration of the individual sensors and the programming had to be tested extensively so that no malfunctions occur during the flight. The system should correctly receive the data from the sensors as well as the antenna in real time, store it and send it to the ground station in appropriate intervals. Above all, the measures ELF data should be provided with appropriate timestamp so that the data can be correctly evaluated afterwards. Furthermore, the system should be able to receive commands from and transmit the measured data to the ground station. Another requirement is that the integrated monitoring systems successfully handle recoverable errors. The redundancy mechanisms shall ensure that no data loss occurs.

3.2. Test execution

3.2.1. Hardware and mechanics tests

The hardware requirements were tested during the Thermal Vacuum Week at ZARM in Bremen. The hardware and software were subjected to a vibration test during the trip to Bremen. The system was able to record and store all sensor reading during the trip. In a special thermal vacuum chamber at ZARM, both the electronics and the winch could be exposed to very low temperatures and air pressures. Both the hardware and the winch worked as expected even at temperatures of -60 °C and air pressures of almost 0 mbar.

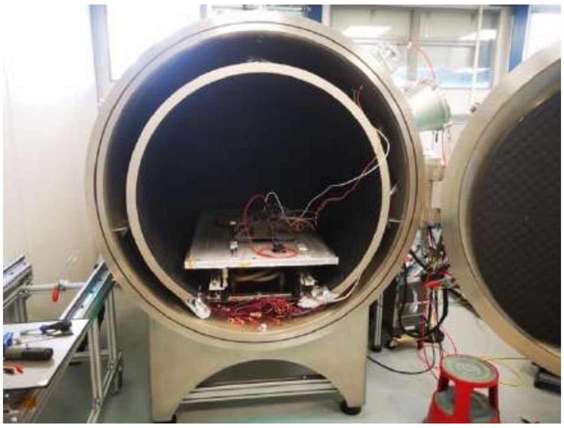

Figure 4. Thermal-Vacuum chamber at ZARM

Furthermore, a first deployment test of the antenna was carried out. For this purpose, the prime with part of the scissor arms and the antenna was lifted by crane to a height of about 3 m. The antenna was then lowered quietly and reliably by the mechanism. The deployment test was later repeated on ESRANGE, but with a total height of 5 m and using all the required scissor arms. Both tests in ZARM and ESRANGE were successful.

3.2.2. Software and interference tests

The hardware in combination with software could already be tested extensively during the design phase. The various components were first tested separately from each other. First, the reading of the corresponding sensors as well as the ELF data was checked. After this was successful, the measured values were stored and read again with an external device to ensure data integrity. Next, the communication to the ground station was checked. The data was sent from our OBC to the ground station and evaluated there. The sent and stored data were again checked for errors. Furthermore, the appropriate communication between the ground station and the system was checked, i.e., whether the system can react to the sent commands. A long-term test in which the system had to measure, store, and transmit data continuously over 24 hours was also carried out. Over this period, all data could be measured, stored, and sent correctly. There were no data errors and neither overheating nor other hardware failures occurred.

Furthermore, the system was tested external error sources. For example, during the launch campaign on ESRANGE, a check was made to figure out of the system was still functioning after a power loss, communication failures or similar. In addition, an interference test was performed. The aim of this test was to check the electromagnetic compatibility of our system. For this purpose, our system including the antenna was mounted on the gondola, and then the other experiments of BEXUS30 were added individually. Thus, we could check whether the other experiments would influence our ELF measurement. Fortunately, this was not the case; the experiments did not interfere with our system. We also tested our system for loss of connection to the sensors. The system was able to respond accordingly to the communication errors. There was no overall failure of the system.

3.2.3. Free-field test

The last thing to be tested was the antenna. For this purpose, several tests had already been carried out at the University of Applied Sciences in Nordhausen. The measured signals of the antenna were either viewed directly on the oscilloscope or stored with our system and analyzed later. The measured frequencies were particularly striking – both 50 Hz and 16.67 Hz were dominant.

Figure 5. Free-field test setup on ESRANGE launchpad

Since we were unfortunately unable to measure the Schumann frequencies there, an open-field test was carried out in Sweden. For this, our OBC and the antenna were moved to the launchpad of ESRANGE to find an environment as free of interference as possible. The test took place three days before the launch of the experiment. The primary goal of the test was to measure and prove the SR. Furthermore, the gain factor of our AFE had to be adjusted accordingly. Since the measurements during the tests in Nordhausen were disturbed by 50 Hz and 16.67 Hz, a suitable amplification factor could not be set prior to the launch campaign. The gain of the AFE should be set so that the internal gain of the ADC, which was set by the AGC, remains between 8 and 32. With this setting, we have enough margin for any in-flight fluctuations. Several test runs were necessary to determine a suitable gain factor. Each run included setting a gain on the AFE, recording the signal for a few minutes, and then evaluating the recorded data. Many different options were

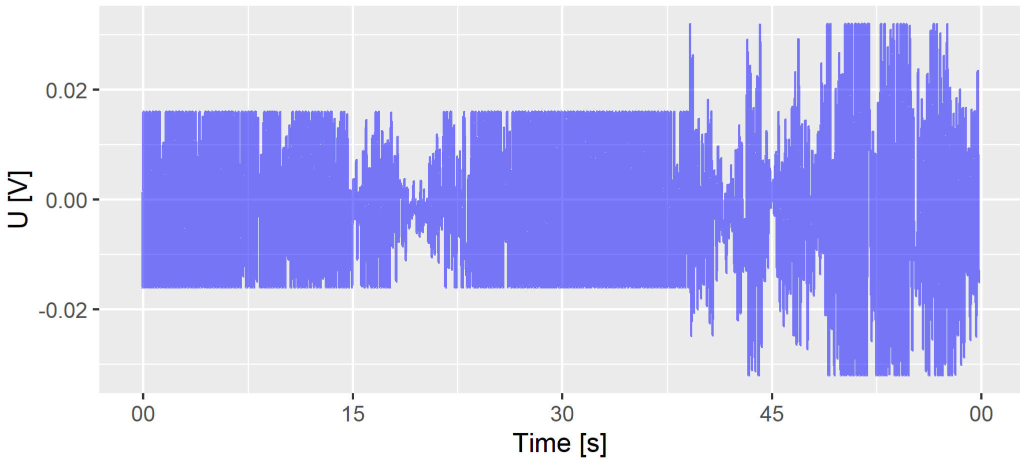

Figure 6. Signal measured during free-field test

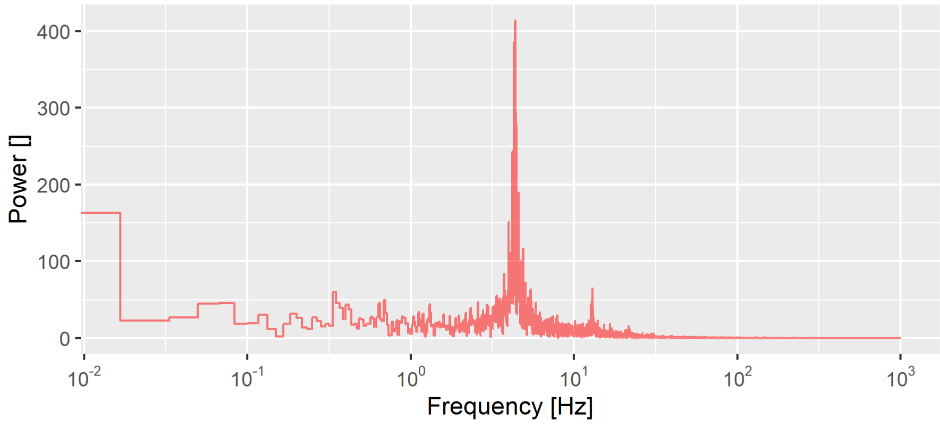

Figure 7. FFT analysis of signal in Figure 6

tried and compared to find the best possible setting for the system. The finally used gain was 1653 (input amplifier: 29, output amplifier: 57) with the AGC gain moving between 8 and 16.

4. Discussion

Both the mechanical and hardware tests ran without any major problems. The system proved to be very robust and reliable, so it met the requirements. The tests of the software also went very well. The individual components of the system functioned flawlessly, and errors were either avoided or handled appropriately, so the system should not have any problems during the flight.

The free-field test on the ESRANGE site delivered first satisfactory results. For example, the first Schumann frequency could be measured even before determining a suitable gain factor. Figure 6 shows a first measured voltage curve. It shows very well how our AGC works. The measured voltages were initially in the range of ±0.016 V. With a maximum voltage U_{max} of 2.048 V, this corresponds to an amplification of 128 of the integrated PGA. It can be seen that the measured voltages were very often in saturation for the first 40 seconds. The AGC then reduced the gain of the PGA to 64 to counteract the saturation of the signal. The voltage response is now in the range of ±0.032 V. Since this gain is still too large, the gain of the AFE was further reduced. Figure 7 shows the corresponding frequency spectrum calculated by an FFT. The frequency spectrum records a high peak at about 7.8 Hz. Furthermore, there is a smaller peak at about 12 Hz. Since the second Schumann frequency is at 14.1 Hz, it cannot be assumed that this is this frequency. It is noticeable that neither 16.67 Hz nor 50 Hz of power supply systems can be found. This indicates a very low interference environment. As a result, the voltage of the AFE was sufficiently reduced so that the measured voltages in the follow-up tests with an internal gain of the PGA were between 8 and 16.

5. Conclusions

Extensive testing of the individual components of our system ensured the functionality and safety of our experiment. Although the software as well as the mechanics presented us with greater challenges, the best conditions for a successful flight were created.

Acknowledgements

Thanks to Prof. Dr.-Ing Matthias Viehmann and Prof. Dr.-Ing. Klaus-Peter Neitzke for their support as senior scientists in this project.

Thanks to ZARM and all in the BEXUS programme involved organization for support in realization of this project.

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Hypergravity induces changes in physiology, gene expression and epigenetics in zebrafish

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Abstract

All living organisms that inhabit Earth have evolved under a common value of gravity, which amounts to an acceleration of 9.81 m/s^2 at mean sea level. Changes on it could cause important alterations that affect vital biological functions. The crescent interest in spatial exploration has opened the question of how exactly these changes in gravity would affect Earth life forms on space environments. This work is the result of a collaborative co-supervision of a master thesis between experts in the area of space sciences and biology, and it can serve as a case study for training experts in such interdisciplinary environments. In particular, we focus on the effect of gravity as a pressure factor in the development of zebrafish (*Danio rerio*) in the larval stage as a model organism using up-to-date (genomic and epigenetic) techniques. Given the high cost of any experiment in true low gravity (which would require a space launch), we performed an initial experiment in hypergravity to develop the methodologies and identify good (epi)genetic markers of the effect of gravity in our model organism. Previous studies in zebrafish have shown how alteration in gravity effects the development and the gene expression of important regulatory genes. For this study, we firstly customized a small laboratory scale centrifuge to study changes in fish physiology together with changes at molecular levels. We exposed zebrafish larvae from 0 to 6 days post fertilization to the simulated hypergravity (SHG) (100 rpm ~ 3g). After 6 days of hypergravity exposition the larvae showed changes in their swimming and flotation patterns, and presented corporal alterations. Then, we assessed gene expression of genes implicated in important biological processes, (e.g., epigenetics), and an upregulation were observed when compared to the control. Taken together, these preliminary findings show how gravity alterations could affect some basic biological responses, and illustrate the potential of developing new science cases to be developed by students at postgraduate level (MSc and beyond) in a multidisciplinary environment.

Keywords

Biology, Behavior, Gravity, Gene Expression, Multidisciplinary, Space Environment

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DOI: 10.5821/conference-9788419184405.044

Abbreviations

Dpf *Days post fertilization*

Hpf *Hours post fertilization*

SHG *Simulated Hypergravity*

1. Introduction

All the living organisms that inhabit the Earth have evolved under the same value of gravity, which amounts to an acceleration of 9.81 m/s2 at mean sea level [1]. Gravity has been responsible to shaping the life forms, its organs, bodies, and for consequence is involved in its behaviour [2], [3]. Currently we can find a few of studies that both simulate changes in gravity or study directly in the space, however, implementing these is not easy. Instead, a used tool to analyse the organisms changes under a different gravity is Simulated Hypergravity (SHG), where a centrifuge machine is used to simulate a gravity excess, that is, an acceleration greater than 9.81 m/s^2.

Studies under natural or simulated altered gravity have shown how the change on it is able to alter different systems on animal, cellular and human models. An investigation performed by Fritsch-Yelle and co-workers [4], shown how the arterial pressure and cardiac rhythm of 12 astronauts during a space missions were altered and decreased with respect to their normal values; and hypergravity also affected important systems such as, musculoskeletal system and bone formation in zebrafish [5], [6]. Zebrafish (*Danio rerio*) has been used on gravity altered studies, because it is an important animal model, that has been successfully used for a lot of scientific researches for more than 20 years thanks to its convenient features, such as: short generation time, high amount of eggs produced by each mating, and high number of orthologous genes with humans [7].

Epigenetics are defined as alterations in the gene function that do not involve changes in the nucleotide changes in the DNA. DNA methylation is a type of epigenetic event that implies modifications an addition of a -CH3 group at cytosines, primarily in CpG sites [8], [9]. DNA- methyltransferase 1 and 3 (*dnmt1, dnmt3*) and the tet methylcytosine dioxygenase 1 (*tet1)* are genes involved in epigenetic events, and thus considered as good epimarkers.

Given previous studies, we hypothesize that the alteration of gravity (hypergravity) will also have effects on the physiology, behaviour and gene expression of genes involved in DNA methylation mechanisms in zebrafish, and these effects can be measured on epigenetic markers. Developing the methodology to study these gravity sensitive markers for future studies in a space environment is the aim of this work

2. Materials and Methods

2.1. Centrifuge

To simulate the hypergravity we use a rotary mixer machine with a maximum speed of 100 rpm (model: ANR100DE, OVAN laboratory equipment), and added two perpendicular arms of 25 cm of long ended in two gondolas with the capacity to contain the plates with the zebrafish larvae (Figure 1).

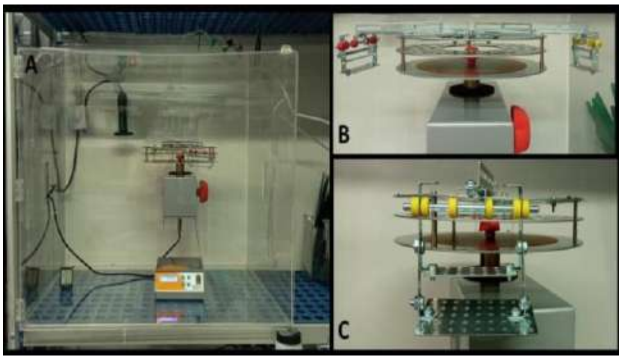

Figure 1. A: Incubator and centrifuge, B: Arms with gondolas, C: Gondola.

2.2. Zebrafish larvae

Zebrafish (TUE strain) were housed in the animal facilities of the experimental aquariums zone (ZAE) at the Institute of Marine Sciences (ICM-CSIC, Barcelona, Spain). Fish were held in 10L tanks on a recirculating system (Aquaneering, San Diego, CA) with a water pump of 3000 L/h and a UV light system to eliminate any possible bacteria in the water (Figure 5A) with a 12:12 h light: dark cycle. Water was maintained at (28 ± 0.2°C), pH 12 (7.2 ± 0.5), conductivity (750–900 μS) and dissolved oxygen (6.5–7.0 mg/l) [4], and monitored daily. Fish were fed twice daily, receiving dried food and live Artemia nauplii (AF48, INVE Aquaculture, Dendermonde, Belgium). The experiment was approved by CSIC ethical committee with the number 1166/2021.

2.3. Experimental conditions

A total of 4 independent breeding pairs were used. Once the eggs were fertilized they were collected and putted in the plates and tubes with 250 μL of embryo medium, and covered with adhesive sealer to avoid fluid loss, then they were placed into the gondolas to start the experimentation. At the same time controls were placed next to the centrifuge machine, and

DOI: 10.5821/conference-9788419184405.044

they were maintained at 27- 28°C, with 60-65% humidity and the temperature was measured and controlled daily.

The total number of analyzed individuals was 440 for the SHG condition, and 220 for Control, divided in four biological replicates. The centrifugation protocol was set to 100 rpm (revolutions per minute) spin delivering a centripetal acceleration (ac) of 25.8 m/s^2 that vectorially added to the existing Earth acceleration (g) of 9.8 m/s^2 , it results in an acceleration of 27.6 m/s2 ($a_T = \sqrt{g^2 + a_c^2}$), which corresponds to 2.82 g (or approximately 3 times the Earth gravity). This SHG condition was continuously maintained from 0 to 6 days post fertilization, only stopping the centrifuge during 10 minutes daily to asses survival and hatching rate. At the end of the 6 day we observed and assessed the physiologic changes and behavioral traits.

2.4. RNA Isolation & Gene expression

Total RNA from N=10 larvae treated and N=10 larvae control were isolated using TRIzol (T9424, Sigma310 Aldrich, St. Louis, Missouri), according to the manufacturer's instructions, and quantified with ND-1000 spectrophotometer (NanoDrop Technologies). RNA (100 ng) was DNase I-treated (Thermo Fisher Scientific 315 Inc., Wilmington, DE, USA) to remove genomic DNA contamination and reverse transcribed into cDNA with SuperScript III RNase 316 Transcriptase (Invitrogen, Spain) with Random hexamer (Invitrogen, Spain), all according to the manufacturer's protocol.

Quantitative PCR (qPCR) was performed using 5 uL 2X qPCRBIO SyGreen Mix Lo-ROX (PCR Biosystems), cDNA was diluted 1:10 with DNase free water and 10 µL of the dilution was used as a template for qPCR, each reaction additionally contained 0.5 µL of each primer (Forward, and Reverse), and 2 µL of DNase free water. qPCR was carried out in technical replicates (3) for each sample.

2.5. Statistical Analysis

We assessed 4 biological replicates to study survival and hatching rates (n= 220 Control, n= 440 SHG). Data from survival were expressed as medium rate ± S.E.M. while data from hatching are represented as the logarithmic transformation of rate, and normality was evaluated with a *Kolmogorov–Smirnov test*, and Levene's test was used to assess homoscedasticity of variances.

3. Results

3.1. Survival and hatching

Survival was not affected by SHG treatment (Figure 2), however so far we observed a delay in the hatching time in the SHG larvae treated (P=0.004326), it was evident between the 2- 3 dpf (Figure 3).

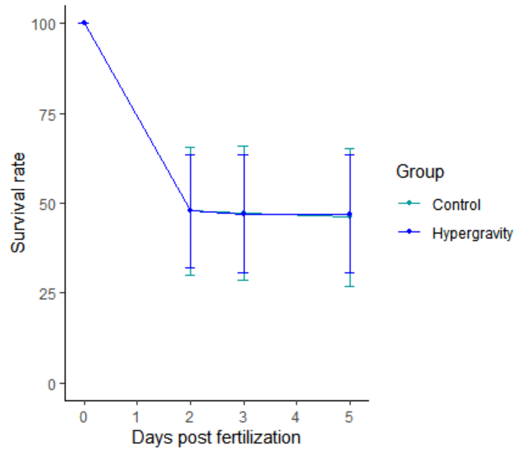

Figure 2. Survival rate of control and SHG larvae during 5 days of treatment. Data are shown as mean ± SE of 4 biological replicates. N=440 and N=220 individuals were used for both conditions, SHG, and control, respectively. No significant differences were found between the groups.

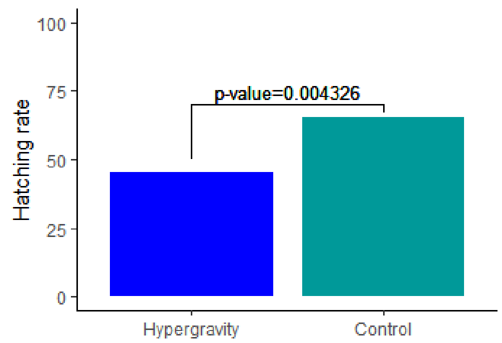

Figure 3. Hatching rate of larvae at 2 dpf treated with SHG compared with the control group. Four biological breeding pairs were used, with a total number of larvae of 208 and 273 in control and SHG, respectively. The bar graph represents the logarithmic transformation of hatching rate, finding significant difference (P=0.004) between control and SHG treated group. Normality was evaluated with a Kolmogorov–Smirnov test, and Levene's test was used to assess homoscedasticity of variances.

3.2. Physiology and Morphology

At the 6 day of exposition the larvae were observed and recorded to analyse the morphology and some behavioural features as

DOI: 10.5821/conference-9788419184405.044

swimming, position, and movement frequency. And we found that in the SHG treated larvae was frequent and statistic significant abnormal features, such as vertical ascendent position with a 47% of the larvae in this position s ($P<0.05$), jerky movements in the 32% ($P= 0.0003278$), and low movement frequency ($P< 0.05$).

Regarding to the morphology we could observe that SHG treated larvae after 6 days present abnormalities in traits such as, body shape, flat tail and abnormal eyes size are illustrated in (Figure 4)

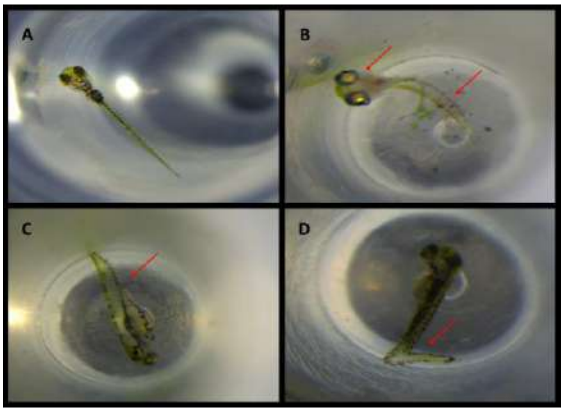

Figure 4. Morphology of the 5 dpf zebrafish larva. A: Dorsal view of a normal control zebrafish larva, B-D: Different views of SHG larvae exposed that presents alterations in its ocular, head, and tail morphology (arrows), also are in abnormal positions (B: Vertical ascendent position, C: Horizontal lateral position, D: Vertical descendent position).

3.3. Gene Expression Response

SHG exposure of zebrafish larvae caused the upregulation of two epigenetic markers, the *dnmt3 and tet1.* The expression on both of them showed significant differences regarding the control gene, the *dnmt3* in 4.4 fold change, and *tet1* in 3.2 folds with a p value< 0.01. On the other hand, the expression of *dnmt1* did not show a difference between treatments (Figure 5).

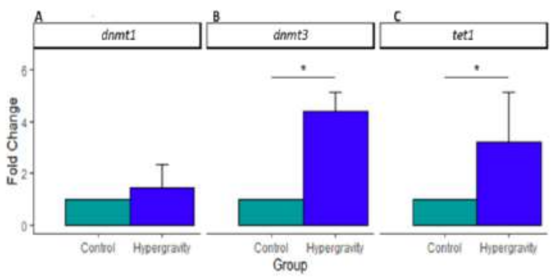

Figure 5. Gene expression of epigenetic markers. A: *dnmt1*, B: *dnmt3* and C: *tet1* expression profiles after 5 days of SHG exposure in N=10 larvae per group (control and SHG). Data are shown as mean ± SEM of fold change using control values set at 1. Significant differences (*P*<0.05) are symbolized by asterisks between treated and control groups. Gene specific primers for qPCR were mentioned in Table 3. The details of qPCR conditions were described in the materials and methods section.

4. Discussion

4.1. Survival and Hatching

According to our results survival is not affected by SHG, which is consistent with the findings by Wacker [10] whom neither found correlation between survival, and exposure to altered gravity. On the other hand, hatching rate showed a significant delay between 2 and 3 day post fertilization. Some studies have shown that changes in environmental conditions such as changes in temperature [11], oxygen level [12] could produce stress resulting in a hatching delay in zebrafish larvae. Our study is the first one to show the hatching effects of altered gravity is caused by mechanical stresses due to the container as a byproduct of the hypergravity.

4.2. Physiology and Morphology

Physiology and morphology was significantly affected by SHG. Those larvae exposed to 3 *g* had difficulties to acquire the normal position, and also showed changes in behavior as jerky movements and anormal swimming. In larval zebrafish, only the utricular otolith is responsible for gravity sensation [13], [14]. The vestibular system encodes information about head movement in space; both translational acceleration and tilt with respect to gravity are encoded by otoliths in the inner ear [15]. In unusual environments, such as in altered gravity, some of this information varies or is lost, then the perception of the correct direction can be affected [16].

A critical period in which the vestibular system is developed in zebrafish larvae begins before 30 hours post-fertilization (hpf) and ends after 66 hpf [13], then the exposition to altered gravity affects the normal growth and development of otoliths, which causes modification in the orientation patterns [17]. Modifications in normal position and orientation due to alterations in the vestibular system after gravity changes, also have been exhibited in murine [18], mollusks and amphibians [19], among others.

DOI: 10.5821/conference-9788419184405.044

Morphological traits also showed alterations: the body shape, the disposition and shape of tail, and head size exhibited abnormal sizes and shapes. Other studies in zebrafish revealed that after exposure to altered gravity morphometric alteration have been presented in cranial bones [69], and in the musculoskeletal system [20].

4.3. Gene expression

An important finding of this study is that simulated hypergravity exposure can affect the normal expression of genes that are implicated in the regulation of some epigenetic mechanisms. Hence it may induce changes in DNA methylation status in the genome. While several studies in altered gravity have reported changes in gene expression, there are only a few that report how changes in gravity produce epigenetic alterations.

The high expression that showed *dnmt3* in our study agrees with the results obtained in rats that were exposed to 2 *g* hypergravity during 7 days in which upregulation of these genes was observed [21]. Studies carried out in human lymphocytes subjected to simulated microgravity during 72 h also obtained an up-regulation in *dnmt3* gene [22].

Our qPCR results showed a high level expression in *tet1*) in the SHG exposed larvae compared with the control group, but no studies in altered gravity have evaluated *tet1* as an epigenetic marker, however the role of this gene is well known. *Tet1* facilitates DNA demethylation of regulatory regions linked to genes involved in developmental processes [23]. *Tet* dysregulations in zebrafish have resulted in abnormal phenotypes and embryonic lethality [24]. This is an indication that *tet* proteins are dispensable for the correct organ development and body plan formation [24], [25], and thus changes in gene expression occurred by gravity can trigger alterations in phenotypical traits during early development.

5. Conclusions

Our study shows that gravity alteration has an impact not only in physiology but also in behavioral aspects in zebrafish larva. This study provides the first evidence for hatching responses induced by altered gravity conditions in fish. Moreover, hypergravity impacts the gene expression in genes implicated in epigenetic mechanisms. In all, we can conclude that zebrafish is a good *in vivo* model to study gravity effects to better understand epigenetic alterations along early development. The finding of this study also provides the basis for further research on the role of hypergravity-induced epigenetic changes in the regulation of gene expression and associated adverse environmental effects on zebrafish development.

Acknowledgements

This research is supported by the Spanish Ministry of Science grant, PID2020-113781RB-I00 and 202030E004 grant from Spanish National Research Council (CSIC) to LR, and through the JAE-ICU fellowship programme at ICE-CSIC 2021

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Challenge of teaching complex, end-to-end space system design and development process: Earth Observation Satellite System Design training course

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Abstract

The Earth Observation Satellite System Design training course was first offered in 2018 at ESA Academy's Training and Learning Facility at ESA's ESEC Galaxia site in Belgium, and again in 2021 in an online format under the Covid-19 pandemic situation. The course covers the end-to-end design and development process of satellite Earth observation systems.

Two major challenges were faced by the teaching experts, consisting of the active and retired ESA staff, as well as ESA Academy's instructional designers for its development:

(1) Condensing such a vast subject domain, associated with a complex, multi-disciplinary engineering undertaking, into a compact format (e.g. 4.5 days in 2018) without sacrificing the quality of the essential technical knowledge, engineering practices and logic as taught;

(2) Presenting the course materials in a comprehensive form to a group of 30 M.S. and Ph.D. students with their backgrounds generally not covering all of the technical disciplines associated with the course subject domain.

The 2021 online edition of the training course, which drew on lessons learnt from 2018, consisted of 18 lectures, plus 5 group project sessions where the students put their acquired knowledge into practice and learned to work in a project team environment.

This paper concentrates on the approach and logic adopted by the instructional team to address the above 2 challenges. Difficulties encountered in some of the areas, e.g. remote sensing instrumentation designs, are discussed.

Keywords

Earth observation, end-to-end system engineering, ESA Academy, instructional design, satellite system design

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Acronyms/Abbreviations

EO	*Earth observation*
EOSSD	*Earth Observation Satellite System Design*
ESA	*European Space Agency*
GPX	*Group Project session number X*
GS	*Ground segment*
MW	*Microwave*
NG	*Next Generation*

1. Introduction

ESA Academy's Training and Learning Programme offers a portfolio of 4-5 days training sessions dedicated to university students from ESA Member States, Canada, Latvia, Lithuania and Slovenia [1]. It aims to complement the typical academic education in space-related disciplines in universities, offering direct transfer of knowledge and practices from the Agency, space research institute and aerospace industry professionals. The "Earth Observation Satellite System Design (EOSSD)" training course was developed by a team of retired and active ESA staff, under a cooperation agreement between ESA and the Association of Retired ESA Staff. The course covers the end-to-end design and development process of satellite Earth observation (EO) systems. It encompasses the system requirements definition, general system architecture, the design engineering process, remote sensing instrumentation designs, satellite design, ground segment design, operations concept elaboration, system assembly/integration and verification, launch campaign, in-orbit validation and applications overview of Earth observation data. It was first offered in 2018 at ESA Academy's Training and Learning Facility in Transinne (Belgium) [2], and again in 2021 in an online format under the Covid-19 pandemic situation [3]. The 2021 edition of the training course, which had been improved using lessons learnt from the 2018 edition, consisted of 18 lectures augmented by 5 group project sessions where the students put their acquired knowledge into practice and learned to work in a project team environment.

The unique features of the EOSSD course are two-fold: (i) it covers an end-to-end design and development process of large, complex satellite systems such as e.g. the Sentinel satellite systems serving the European Union's Copernicus services [4]; (ii) the course materials are prepared and delivered by a team of experts consisting mostly of retired ESA staff, complemented by a number of active senior staff, all having extensive hands-on experience in managing space system developments together with industrial partners. They bring together a synthesis of the vast technical know-hows existing in Europe.

2. EOSSD Training Course Content Outline

Table 1 summarises all lectures and Group Project sessions from the 2021 online edition. Following a post-delivery review of the 2018 edition, two lectures have been added, namely - "Introduction to Remote Sensing Methods" and "Climate Monitoring using EO Data". The lectures cover step-by-step the end-to-end system design and development process, whereas the Group Project sessions allow the students to apply the design theories and procedures in order to come up with an outline design of a next generation (NG) Sentinel-3 observation system (a follow-up of the current Sentinel-3 Copernicus system) [5]. Considerable efforts have gone into ensuring that the training materials are complete in terms of design theories and dimensioning of a satellite system as schematically depicted in Fig. 1, and cover all associated constituent elements. Ample design examples of existing systems and those in developments are presented to illustrate the design theories. In addition, a selected set of relevant video animations are shown at appropriate moments in order to complement the information content of the lectures with real-world examples.

3. Instructional Design Model for Adult Learning

The training course programme content is dense and the learning is intensive. This required particular attention during the design phase in order to ensure an optimal flow of information and tailoring of the Group Project tasks at an appropriate level of complexity.

For the students to truly benefit from the training course, the adult learning theories and methodologies were followed. Emphasis was given to the application of instructional design methodologies [6] during the update of the lectures and Group Project tasks for the 2022 edition. The instructional system design model takes account of learning psychology to design, develop and implement effective training content. It is similar to "system engineering" applied to learning and is

Table 1. EOSSD course content – Lectures & Group Project sessions

Subject type	Lecture	Group Project – Element Design	Group Project – System Design
Introductory lectures	Course Introduction		
	Introduction to EO & EO Satellite Systems		
	Introduction to Remote Sensing Methods		
System requirements & space system fundamentals	From Observation Requirements to System Requirements		
	Orbit Selection and Launcher Alternatives		
		Group Project Session 1 - Orbit Selection	
Microwave remote sensing payloads	Electromagnetic Wave Theory & Antennas		
	Radar Remote Sensing		
	Microwave Radiometry		
		Group Project Session 2 - Microwave Instruments Design	
Optical remote sensing payloads	Basics of Space Optics		
	Passive Optical Payloads		
	Space Lidars		
		Group Project Session 3 - Optical Instrument Design	
Satellite design & development engineering	Risk Management & Technology Development		
	Satellite System Design & Payload Accommodation		
			Group Project Session 4 - Space Segment Design
Overall system design, testing & in-orbit delivery	Ground Segment & Operations Concept		
	On-Ground AIV		
	Launch Campaign		
	In-Orbit Verification		
			Group Project Session 5 - System Design
Applications of EO data	Development of Applications Based on EO Data		
	Climate Monitoring using EO Data		
			Group Project Session 5 - System Design (continued)
Group Project Presentations by Students			

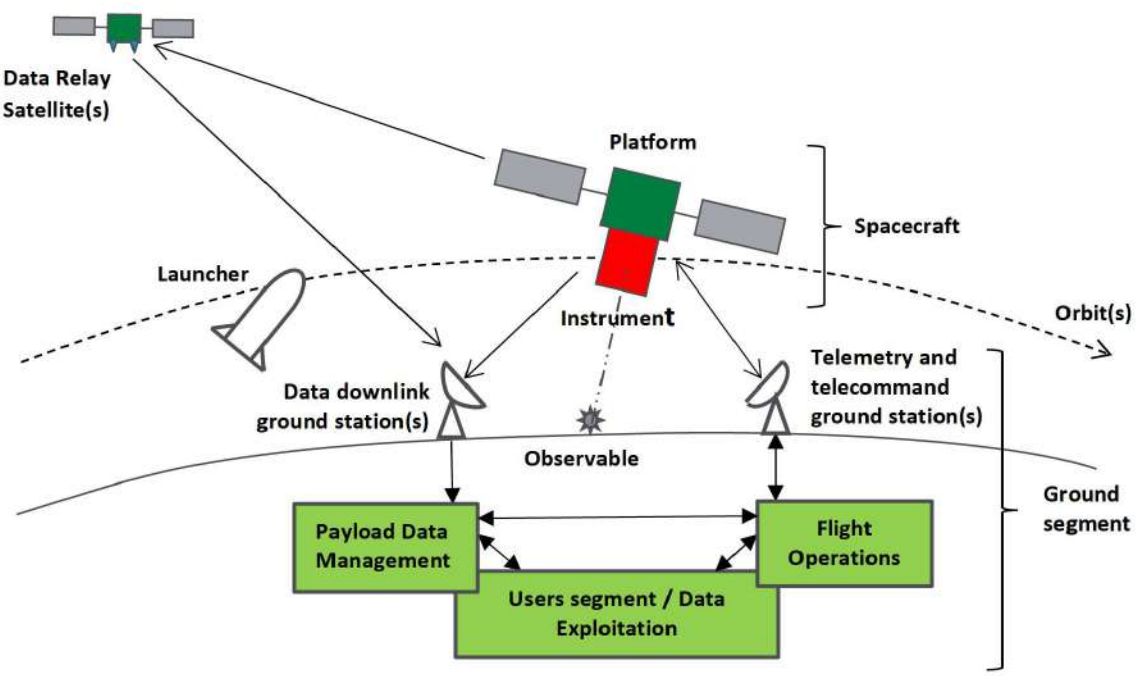

Fig. 1. Overall satellite observation system architecture model and constituting elements

DOI: 10.5821/conference-9788419184405.045

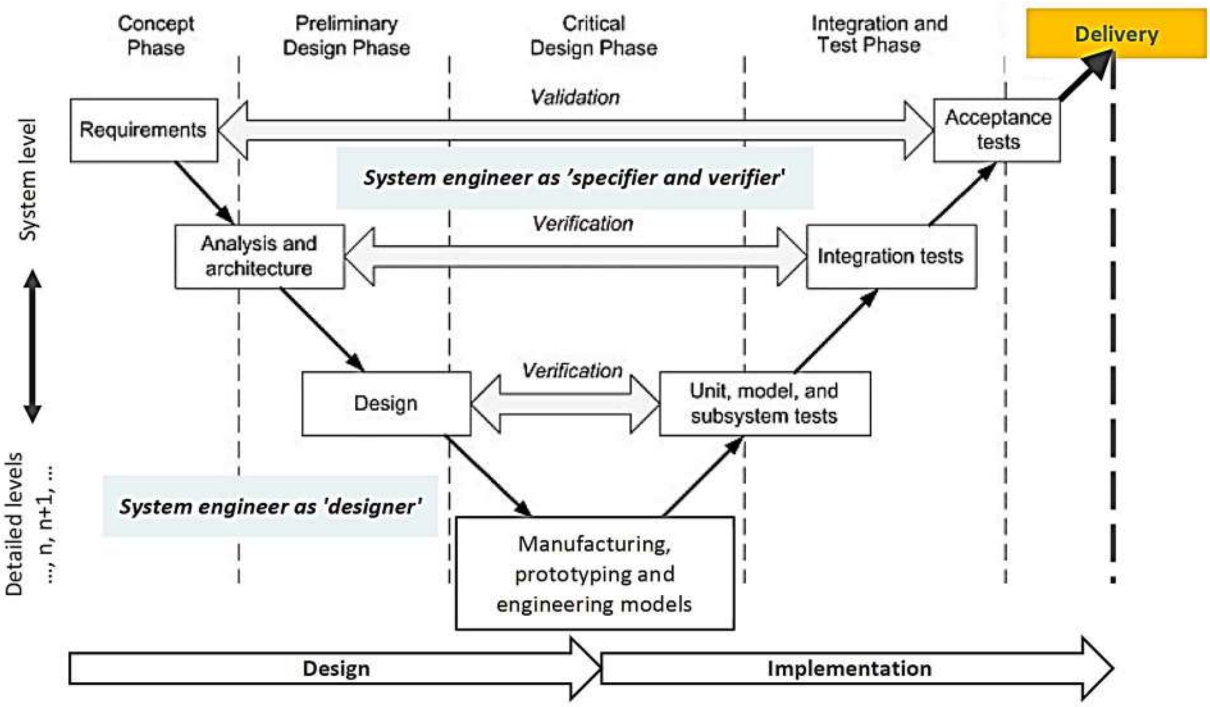

Fig. 2. The 'V' process of design and implementation

objective-oriented. Furthermore, the course elaboration guidelines established by ESA Academy for e-learning content development and delivery were followed.

4. Course Concept for Enhancing Training and Learning Experience

The EOSSD being a practice-oriented course, the payload and system design theories and procedures must be structured into the form of a complete development engineering process. The most common model for such development projects is the "V-process of design and implementation" as depicted in Fig. 2. The horizontal axis represents the elapsed time from the beginning of the project, also reflecting the maturity of the design. The vertical axis represents the level of detail of the system definition and design.

The EOSSD course starts at the upper-left corner with the definition of the requirements, followed by high-level trade-offs and analysis of the system such as the orbit selection and considerations of launcher alternatives. The lectures on the remote sensing payload designs (microwave and optical) constitute one of the core building blocks/elements for an observation system, ultimately driving its complexity and development risks. Payload designs are typically specialist subjects, touching a number of fundamental subjects such as the electromagnetic and optical theories, signal detection and noise. An ample variety of remote sensing instrumentation types commonly deployed for Earth observations, both active and passive, are covered (see the list of payload lectures in Table 1). Due to the vastness of the subject domains, it was necessary to restrict the lectures to the most fundamental aspects of each of the instrument types. State-of-the-art instrumentation design examples from the existing and planned ESA missions are used in order to illustrate how the design theories had been turned into reality. The Sentinel-3 Copernicus system design example is extensively used throughout the course for this purpose. As a preparation for participating in the course, the students are recommended to read the Sentinel-3 mission description document prior to its start [7].

The Group Project, carried out by the students, serves as yet another means to enhance the training and learning experience. Each step of the Group Project closely follows the relevant set of lectures, allowing the students to learn by doing (see Table 1 for the execution flow and order of the Group Project sessions with respect to the lectures). The conduct of the Group Project naturally follows the "V process of design and implementation", emphasizing again the systematic approach to a complex engineering development.

Table 2. Group Project team composition, respective responsibilities and tasks

Project team role	Responsibilities and Tasks
System lead engineer	System requirements compliances; system concept and architecture; project team task distribution and coordination; orbit selection; launcher selection; overall data flow
Altimetry/microwave (MW) payload engineer	Altimetry/MW payload design; observation performance; payload interface specification (accommodation)
Optical payload engineer	Optical payload design; observation performance; payload interface specification (accommodation)
Altimetry satellite engineer	Altimetry satellite design (microwave payload accommodation; communication subsystem; power subsystem; fuel budget); launcher accommodation; space segment interface specification
Optical satellite engineer	Optical satellite design (optical payload accommodation; communication subsystem; power subsystem; fuel budget); launcher accommodation; space segment interface specification
Ground segment/operations engineer	Ground segment design; data downlink performance; ground segment data flow; operations concepts elaboration

5. Group Project as a Teamwork Exercise and for Enhancing Interactions with Space System Experts

One of the important goals of the Group Project is to initiate the students into the necessary teamwork in a project environment, beside applying the acquired knowledge for designing a system. Thus, they are grouped into project teams, each team consisting of 6 members and each member with his/her specific assigned role within the Group Project as listed in Table 2. As the Sentinal-3 next generation system will consist of a series of satellite-pairs – namely the Altimetry and Optical satellites – there are 2 satellite engineers in each group designing one satellite each. The students are instructed to coordinate their work with other team members by means of extensive discussions and consensus building. And they are even encouraged to exchange information with the members of the other project teams. Those collective reflection and questioning process, plus exchanges and consultations with the space system experts, facilitate active learning and proactive design work.

The input to the Group Project is the set of system and observation requirements shown at the top of the Group Project flow chart in Fig. 3. The Sentinel-3 Next Generation (NG) system shall be an evolution of Sentinel-3, with the main difference that the altimetry and optical observation functions be separated onto 2 satellites, not necessarily flying in the same orbit. This brings positive benefits as

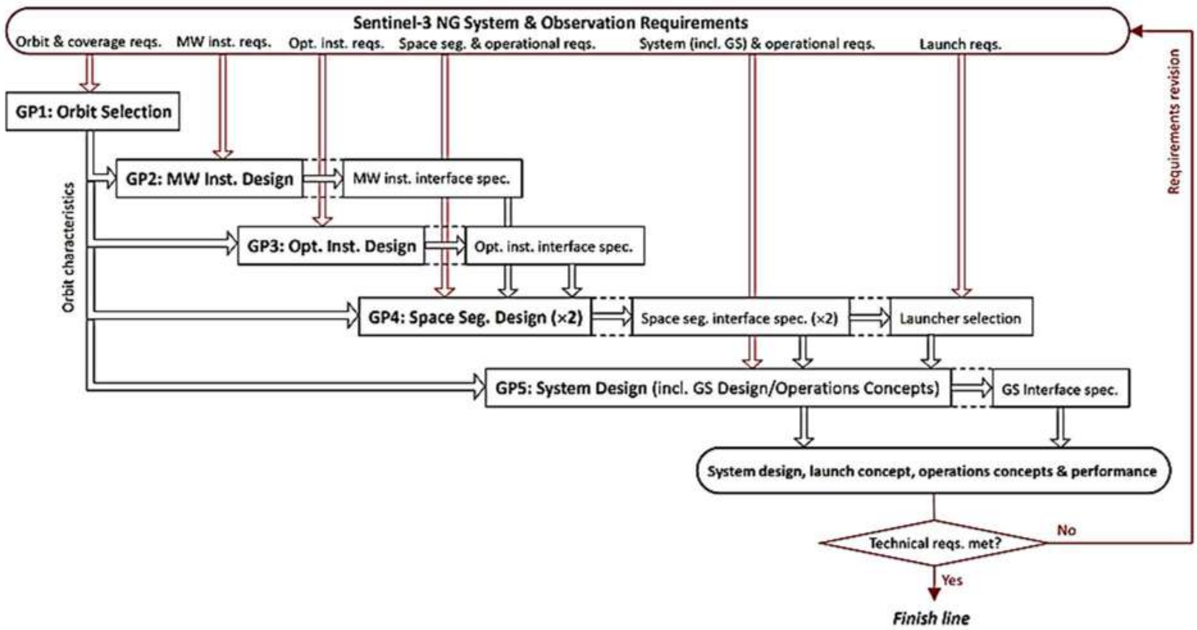

Fig. 3. Group Project flow chart

follows: (1) a simpler payload accommodation on both satellites as the available space around the respective platforms would be less crowded as compared to that of Sentinel-3; (2) a growth potential for the payload instrumentation in order to improve its observation data quality. Those benefits provide more freedom to the students for optimizing the performance versus power, mass and data-rate budgets of the individual satellites. Fig. 4 shows an example of students' design outcome as presented to the space system experts.

6. Conclusion

The EOSSD training course was delivered twice by ESA Academy, first in 2018 at its Training and Learning Facility and again in an online format in 2021. A total of 60 students from ESA's Member and Associated-States so far have taken the challenge with successful completion. The success of the course was measured based on the quality of their Group Project outcomes as well as from students' feedbacks on a detailed set of questionnaires concerning the course contents and deliveries. The next edition of the course is planned to be offered in 2023.

Acknowledgments

The authors would like to express their sincere thanks to Taitus Software Srl for the free use of the SaVoir application tool by the students for the orbit and coverage analysis, and to Thales Alenia Space France for having made the Sentinel-3 project documentation and associated video materials available for the course.

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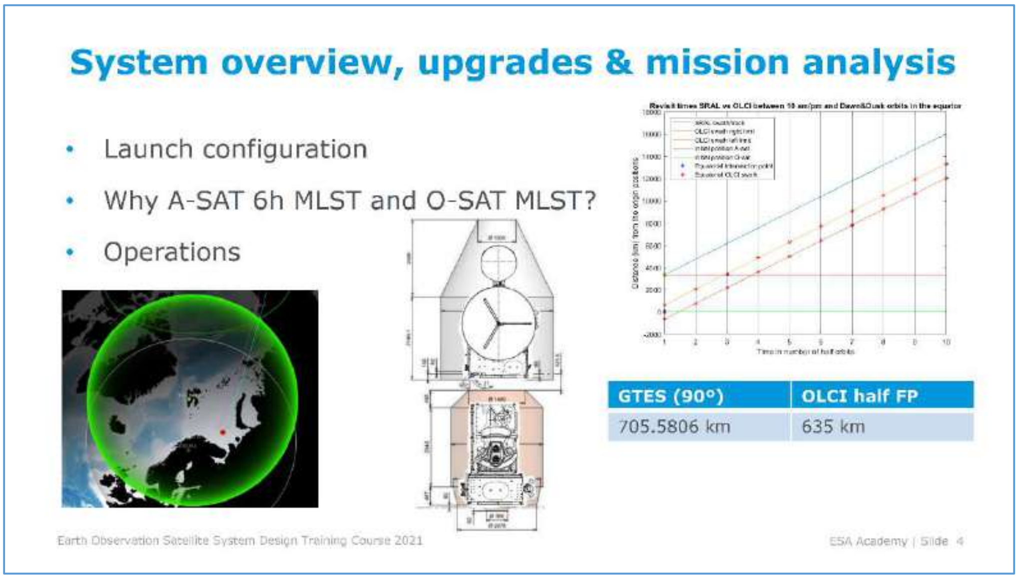

Fig. 4. An example of Group Project design outcome as presented by a student team

Blended-Learning Educational Concept for Earth Observation at University Level

Clémence Dubois[1], *Robert Eckardt*[1], *Christiane Schmullius*[1]

Abstract

The field of Earth observation has been undergoing a tremendous transformation for several years. From commercial data that used to be processed only by a circle of specialists, we are now in an era where numerous high-quality satellite data can be made available for free and used by diverse user groups in many applications. It is therefore of fundamental importance for new users to understand and use these data in an application-specific way, and teaching concepts need to be adapted accordingly. Specifically for the field of radar remote sensing, several activities already exist that intend to adjust educational offers with needs of the market place and to provide hands-on material for self-paced learning in many fields of application. At university level however, many courses still happen in a traditional classroom way, the lecturer being the principal source of information. We present here a blended-learning approach aiming the integration of high-quality eLearning material in traditional face-to-face courses to enhance the teaching and learning experience. The approach can be resumed in two main goals: 1) the specific integration of eLearning elements on a learning platform for a better preparation and follow-up of the course content by the students; 2) the creation of new eLearning content by the students in a peer-to-peer approach. For the first goal, existing content from Massive Open Online Courses (MOOC) are broken down into learning modules and supplemented with external digital learning content in order to best match the needs of the face-to-face course week by week. This prevents students from being overwhelmed by the enormous volume of online educational resources of the MOOCs and allows a better preparation of students for the current content of the lecture. For the second goal, a further deepening of what has been learned takes place through active co-creation of new digital content. This is based on the principle of the pyramid of learning that the best way to remember something is to explain it yourself. In this way, students who create new content from what they have learned should be able to remember it much longer as if they just listen to it. This blended learning educational model is conducted successfully since two years at university level with bachelor and master students and is being enriched regularly with new material, both from the open educational resources and students contributions.

Keywords

Blended-Learning, Earth observation, Peer-to-peer, university

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Acronyms/Abbreviations

MOOC *Massive Open Online Course*

LMS *Learning Management System*

1. Introduction

Like many other sectors, the field of Earth Observation is currently undergoing a BigData revolution: a continuously increasing number of missions and an exponentially increasing amount of data allow collecting information to learn more about our planet every day and tackle current political and climate challenges [1]. The Copernicus missions with their associated services are a good example thereof. Whereas satellite and Earth observation data were formerly reserved for a small circle of learned specialists, the current free and open policy of many of those data allows their handling and interpretation by diverse user groups and decision-makers in many different applications.

To cope with this paradigm shift and teach current and future users adequate skills that prepare them for the marketplace, educational concepts at all levels need to be adapted. Especially in the field of remote sensing, eLearning educational offers have developed significantly and allow apprehending this challenge [2]. Current activities aim at adjusting the educational offers to the needs of the marketplace by providing hands-on material for self-paced learning in various application fields [3,4] and learner-specific training relying on ontology-based educational curricula [5,6]. Those activities are mainly designed for a large audience and encompass basics and advanced knowledge in several online courses and tutorials.

In parallel, current educational offers at the university level include academic and practical courses evolving in a traditional classroom way, a lecturer mostly delivering information to the students. Even though the learner-instructor interaction is of high importance and has been reported to play an important role in the learning motivation of the students [7,8], the exponential development of tools and knowledge in the field of remote sensing requires these traditional educational models to evolve and consider new ways of imparting knowledge and skills to students.

In this approach, we present a blended-learning educational model that is applied at the university level in an introductory course to radar remote sensing, attended by both bachelor- and master students. The approach allows enhancing the educational experience by giving students the opportunity to learn from other scholars as well as to discover a multitude of tools that prepare them adequately for the marketplace.

This article is structured as follows: Section 2 presents the overall concept of our blended-learning approach from the didactical point of view, Section 3 addresses its technical implementation and Section 4 discusses remaining challenges.

2. Blended-Learning Concept

The proposed blended-learning approach revolves around two main didactical challenges: 1) even out heterogeneous foreknowledge of the students attending the course and 2) solidify what has been learned.

To achieve the first goal, an important role is given to self-study time. During that time, the students are encouraged to learn more about the specific topic of the course by themselves. To ensure that all students have similar and reliable sources of learning and possibly even out heterogeneous knowledge basis, existing material from different MOOCs are used, together with non-rated tests on a learning management system (LMS) for self-assessment. To help focusing the learning on the topics that are covered during face-to-face time, the MOOCs materials are selected and provided topic-by-topic on a weekly basis. This allows the students to prepare the material before the face-to-face course and therefore to address more advanced topic during course. Together with the MOOC contents, related links and additional material are provided to allow deepening the course topic afterwards. To keep up to date with latest advancements in the field of radar remote sensing and data processing, the eLearning content is updated regularly with new material.

To ensure that the students remember what they have learned for a longer time, the principle of the pyramid of learning is applied, which states that the retention rate about a topic is higher if you teach this topic yourself [5]. Indeed, explaining a topic requires to have deeply understood it yourself, and preparing how to teach it allows embedding it in your memory, establishing connections with related topics. To achieve this goal, students are therefore required to produce new teaching material during the course. This material is then intended to be incremented in the self-study material to be used as supplementary eLearning material by the next student generation. This allows therefore an update of the eLearning resources with material from peers. The created material

DOI: 10.5821/conference-9788419184405.046

by the students should respect specific formats and specifications as well as quality criteria to be used by later student generations. However, this form of learning motivates students in this sense that the produced material is not just for the sake of getting a grade but will be further used by other students to better understand the subject.

Figure 1 presents a schematic overview of our blended-learning concept. While the eLearning component in self-study only shows a relatively low level of understanding (x_E) as there is only a learner-content interaction, the use of this component to enhance face-to-face time with advanced subjects guarantees a better and deeper understanding of the content (x_B). The production of eLearning material by students increases even more the level of understanding of the students (x_S) and allow to update the eLearning material and subsequently to enhance the face-to-face time by allowing addressing further, more advanced topics.

3. Implementation

The technical implementation can be resumed in two principal actions: 1) the provision of the eLearning materials and self-assessment tests on an LMS on a weekly basis, and 2) the creation and integration of students works for future students generation.

3.1. MOOC Content on LMS

Many excellent eLearning resources exist in the field of remote sensing, especially in radar remote sensing. For our approach, we used the content of two specific MOOCs available on the EO-college platform (https://eo-college.org/): *Echoes in Space*, and *Basic Principles of Radar Backscatter*. While the first offers a complete tour in the history, principle and applications of radar remote sensing technology, the second is a mini-MOOC focusing principally on signal properties and its interaction with the Earth's surface. Both MOOCs are well adapted for an introduction in the topic of radar remote sensing, and provide enough supplementary material to address more advanced topics. However, both courses cover more topics than required for an introductory course at university level. To tailor the MOOC contents for the university course, a selection of relevant topics has been made and corresponding content (text, video material, interactive graphics, quizzes, etc.) has been extracted and made available for the students on the university LMS.

We used the LMS Moodle (https://moodle.de/) provided by our university. To ensure a breakdown of the MOOC content in weekly available topics, we created specific lesson pages on the LMS for each topic (see Figure 2a). The access to each lesson was permitted on a weekly basis, one week before the face-to-face course dealing with the corresponding topic. This allows for enough preparation time by the students. Between each lesson, self-assessments tests were created on the LMS, based on MOOC quizzes, for the students to check their achievements. The next eLearning lesson is only unlocked if at least 50% of the tests questions is answered correctly.

As the preparation of the course in self-study time requires in general more time, a reward system has been installed, for which students achieving all eLearning lessons and passing successfully all self-assessment tests would get

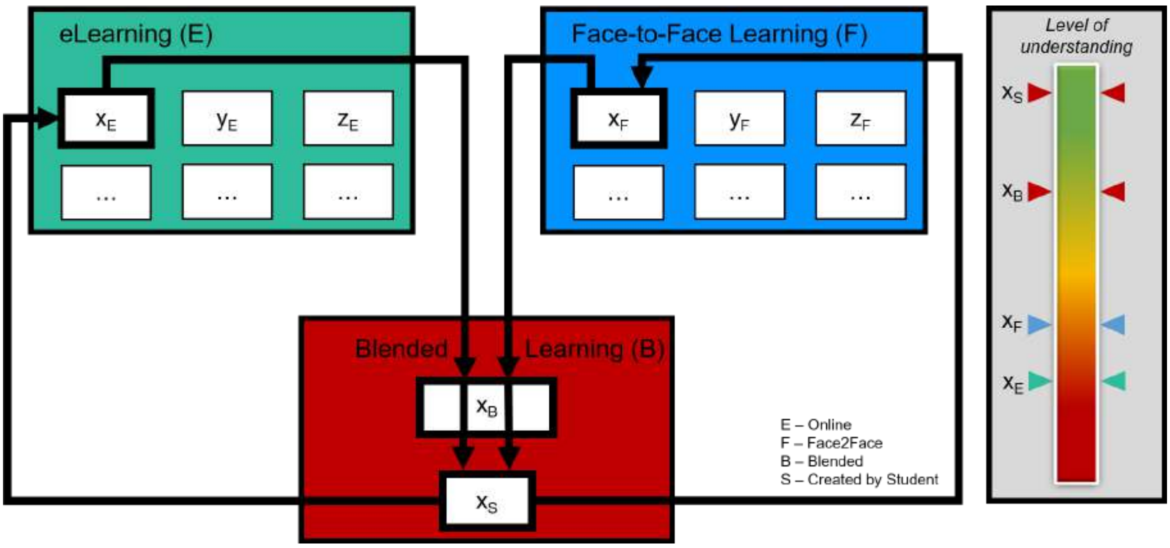

Figure 1. Schematic representation of the proposed blended-learning approach

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a certificate they would have gotten if performing the whole MOOCs on the EO-College platform directly. This certificate is recognized internationally and can be used in job application documents. This reward system is intended to encourage the students to learn independently and prepare the course, but has no influence on the course's final grade.

3.2. *Creation of eLearning material*

The creation of new qualitative eLearning material by the students necessitates the fulfilment of both, technical and didactical prerequisites. eLearning material can take a lot of forms: from simple textbook or slide-show to more complex animated graphics, video tutorials, or executable code. Very specific instructions need therefore to be communicated to the students to ensure that both content and form are satisfying and useful for future learners. To this goal, an extra introductory course for the creation of eLearning material was proposed at the beginning of the term, as well as additional contact times in between. Additionally, video tutorials on the creation of infographics and animations using specific design software solutions was produced in supplement of already existing online tutorials, to show their easy adaptation for the field of radar remote sensing. Finally, quality hardware was made available for the students for the creation of video tutorials. No specific limitation is given to the form of the created material, i.e. the students are free to create either a practical video tutorial or a more theoretical animation. Evaluation criteria of the produced material were only the correctness of the content, the easy-of-use, as well as the design and visual quality of the content. Those criteria are fundamental for ensuring the further use of the eLearning materials by a broader community of students.

If passing those criteria, the created eLearning material is then inserted into a dedicated blog-website (see Figure 2b). The choice of a dedicated website instead of the LMS and already existing lessons results from the fact that we want to foster inter-student interaction and build a student community, where they can receive peer-to-peer feedback and learn from each other, even after the course is finished. The blog is organized in the different topics addressed during course and practical exercises. A direct access link to the blog is given on the LMS to facilitate access and use of the blog content during self-study.

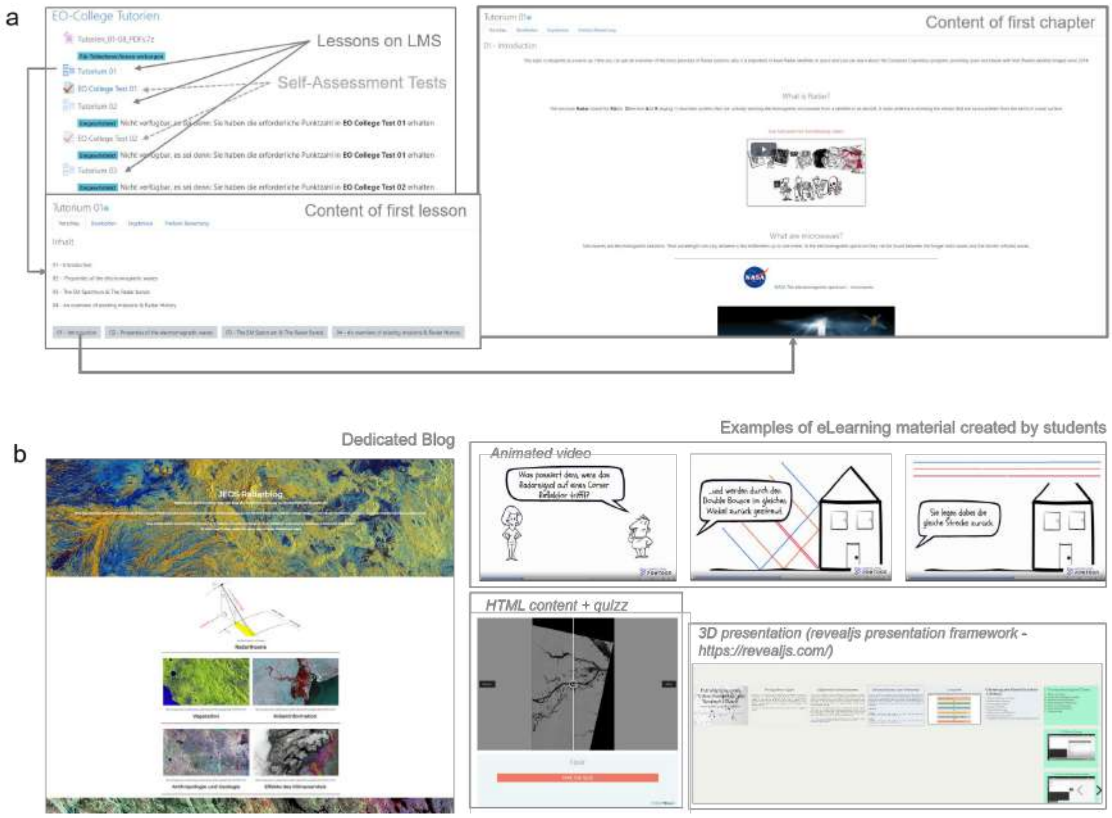

Figure 2. Implementation of the blended learning approach; a) selected MOOC content in the LMS in the form of lections and self-assessment tests; b) dedicated blog for the students and selected student material

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4. Discussion

The proposed blended-learning concept is applied for the second year at university level in an introductory course for radar remote sensing, which is attended by both, bachelor and master students. This chapter aims at showing the lesson learned and possible future improvement of the concept.

As both bachelor and master students attending the course have different background, the additional use of MOOC content in self-study was intended to level out heterogeneous knowledge of both student groups and allow each student to progress at his specific pace, while keeping a regular schedule. Whereas no particular difference has been noticed in the grades of the students, being normally distributed for both degrees, a difference has been observed in the degree of interaction and level of the questions arising during face-to-face class. Students having prepared the course in advance using the eLearning materials asked in general more questions going beyond the sole topic of the course. Subsequently, interaction during face-to-face time was enhanced and the treated subjects on a higher level, which finally encouraged all students to prepare the course properly in order to keep up. This is a particularly interesting fact, as most of this approach has been implemented during the Covid-19 pandemic situation, where interaction was not particularly facilitated through online teaching. The installed reward system with certificate about course achievement worked well and showed that most students used the eLearning material. However, this could be biased by the fact that students also used the eLearning material for exam preparation instead of preparing the course on a weekly basis.

Concerning the creation of new eLearning materials by the students, a thorough adjustment of the necessary achievements for passing the module has been mandatory. Whereas in the first year of implementation many students faced incomprehension towards the benefits of creating their own teaching material and considered it the job of the lecturer, no particular complaint was noticed in the second year of implementation. This could partly lies in the fact that the first year could not benefit from previous student works for learning or solving practical exercises, whereas the second year could use the created material from the previous year and considered it as useful. Besides, the ongoing pandemic situation showed students the necessity to acquire additional digital skills beyond traditional presentation methods. Finally, in the second year of implementation, we defined clearer instructions, created additional digital tutorials and offered more possibility of contact time for the production of the eLearning material so that students felt more encouraged and supported in their creation process.

All eLearning materials as well as a link to the dedicated students' blog were made available on the LMS of the module, with all other course materials (scripts, data, specific announcements). This was appreciated by the students, as they could find all course related information in one place. The integration of the students' material into the weekly eLearning material is not planned at the moment, as we want to foster peer-to-peer interaction between different student generation. The integration of students' material into the weekly eLearning content would not permit to distinguish clearly if a content has been made by students or was already a MOOC content. Furthermore, a comment function is given in the blog for students to discuss amongst peers and benefit from each other's experience. As the implementation of this approach is only in its second year, few material is available at the moment, but more material will come and even more students will have access to the blog and would be able to give feedback and use the material for their own learning.

The implementation of the blended-learning approach showed an additional benefit, which becomes now a new challenge: through the increased level of the course, practical exercises using simple software solutions come to their limits and more advanced exercises could be dealt with during course. Those necessitate however programming knowledge that most bachelor students acquire only at a later stage, starting their master study. To this goal, a rethinking of the structure of bachelor modules is mandatory, or simple programming solutions should be found to allow the advanced theoretical knowledge to be used in practice.

5. Conclusions

This paper presented a blended-learning approach in an introductory course for radar remote sensing, using existing material from different MOOCs and permitting students to create new content on their own to improve their understanding of the subject. Whilst the learner-instructor interaction is still present during regular classes, students prepare both theoretical and practical content using existing material provided by several Massive Open Online Courses (MOOC) and regularly updated content. Furthermore, to enhance students' interaction with the course content and improve their understanding, they produce new eLearning content by their own, which can then be used by the next student generations. The approach has been implemented successfully for the last two years at university level and shows an increased interest and a deeper understanding of the students for the principles and applications of radar remote sensing. Remaining challenges are the fostering of inter-students interaction amongst several student generations, and the adaptation of practicals to more advanced exercises necessitating programming knowledge.

Acknowledgements

This research was funded by the Thuringian Ministry for Economic Affairs, Science and Digital Society and the Stifterverband, in a Fellowship for innovation in digital education in Thuringia (Fellowships für Innovationen in der digitalen Hochschullehre Thüringen", Thüringer Ministerium für Wirtschaft, Wissenschaft und digitale Gesellschaft und Stifterverband).

The authors would like to thanks all Anastasiia Vynohradova and Jannik Jänichen for the support in the development of the blog website and all students whose contributions are partly shown in this manuscript.

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Development and Testing of the 3U+ CubeSat PCDU for SOURCE

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Abstract
SOURCE (Stuttgart Operated University CubeSat for Evaluation and Education) is a 3U+ research CubeSat that is being developed by students at the University of Stuttgart in cooperation with the Institute for Space Systems and the Small Satellite Student Society KSat e.V.. The objectives include technology demonstrations, atmospheric research and the investigation of satellite demise while also serving as an educational program. SOURCE was selected by ESA's "Fly your Satellite" program and is currently in Phase D.

The electrical power supply system combines commercial off-the-shelf parts with self-developed units to meet the requirements of the payloads. The solar array configuration and Power Conditioning and Distribution Unit (PCDU) are self-developed, while the battery is a commercial product.

A total of 56 solar cells provides up to 32W under ideal conditions, which can be stored in a 75Wh space-qualified lithium-ion battery. To maximise the power output of the solar cells, maximum power point tracking is performed by the PCDU. This is controlled by a radiation hardened microcontroller.

The PCDU provides regulated 3.3V, 5V and unregulated battery voltage to the subsystems with 32 switchable outputs, 27 of which are latch-up current protected. The microcontroller controls these individual output channels and the switching between the various CubeSat modes as commanded by the on-board computer. Additionally, every output channel power consumption is monitored for overcurrents. The PCDU functions as a watchdog by checking the health of the on-board computer, rebooting it in case of a failure. High priority commands can be sent directly to the PCDU from the ground via the communication system, bypassing the on-board computer. These can reset either the communication subsystem, the on-board computer or the entire satellite.

Four hybrid inhibits, using a combination of mechanical switches and FETs are integrated in the PCDU, replacing the usual fully mechanical design. Three are used to deactivate the satellite in the deployer configuration and the fourth is a remove-before-flight inhibit.

An engineering model was manufactured during phase C and is being tested functionally, environmentally and for performance. This paper presents the detailed design of the PCDU, the acquired test results and outlines issues encountered during the tests.

Keywords
CubeSat, EPS, PCDU, SOURCE

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Acronyms/Abbreviations

CSA	*Current Sense Amplifier*
DPS	*Deployment Switch*
EMC	*Electromagnetic Compatibility*
FET	*Field-Effect Transistor*
IRS	*Institute for Space Systems*
LCL	*Latch-up Current Limiter*
MPPT	*Maximum Power Point Tracking*
MRAM	*Magneto resistive Random-Access Memory*
OBC	*On Board Computer*
PCDU	*Power Conditioning and Distribution Unit*
PV	*Photovoltaic*
PWM	*Pulse Width Modulation*
RBF	*Remove Before Flight (pin)*
SOURCE	*Stuttgart Operated University Research CubeSat for Evaluation and Education*
UR	*unregulated (voltage rail)*

1. Introduction

Practical projects are an important part of university education. At the University of Stuttgart, the Small Satellite Student Society KSat e.V. and the Institute of Space Systems (IRS) are working together on a student CubeSat with the help of several industry partners to provide such a project. The Stuttgart Operated University Research CubeSat for Evaluation and Education (SOURCE) is a 3U+ CubeSat with many in-house developments designed and built by bachelor and master students under supervision of PhD students of the IRS [1]. The SOURCE project is currently in phase D preparing for the manufacturing readiness review as part of ESA's *Fly Your Satellite!* program.

The primary objective is to develop a reproducible CubeSat platform and verification of new technologies provided by industry partners. The secondary objective is the study of the re-entry of natural and man-made objects. The re-entry of SOURCE itself is also part of the mission [1]. For these purposes, the electrical power supply subsystem has to provide power over a wide range of mission phases and for a wide range of subsystems and payload components. There are several other student projects with custom Power Conditioning and Distribution Units (PCDU) like PW-Sat [2] or UpSat [3] and commercial products available by companies like GomSpace, ISISpace. Acquiring commercial components offers the benefit of already tested and validated hardware. However, none of the available products could satisfy the educational and technical requirements set by the objectives of SOURCE.

The PCDU was therefore self-developed to provide a comprehensive educational overview of a PCDU. Additionally, it could be tailored to the specific mission of SOURCE and at the same provide a base for future CubeSats projects. This paper will focus on the design of the PCDU, the findings made during testing and performances which were determined.

2. Functional Architecture

The general hardware architecture can be seen in Figure 1. The PCDU has two power inputs, and three voltage channels, 3.3 V, 5 V and an unregulated (UR) output. The UR output is directly connected to the 75 Wh lithium-ion battery, with the voltage depending on the charge level, varying from around 12 V to 16.8 V. The GomSpace BPX battery is a commercial component. The rad-hard microcontroller VA10820 from Vorago Technologies, controls the Maximum Power Point Tracking (MPPT) as well as collecting data and communicating with the On-Board-Computer (OBC), which includes a watchdog function, to restart the OBC.

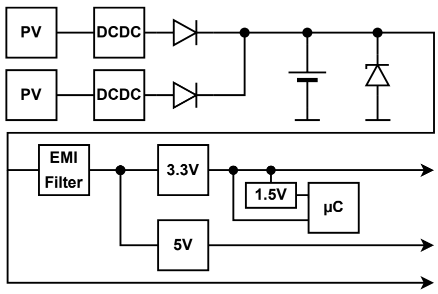

Figure 1. PCDU functional architecture.

The program code is stored on a hardware write-protected Magneto resistive Random-Access Memory (MRAM) chip. Measurement data and other non-volatile parameters are stored on a second MRAM chip. High priority commands to reset the PCDU, OBC or even the entire satellite are independent from the OBC. These commands are directly forwarded to the PCDU from the communication system by a simple high-low signal for maximum simplicity. In the following a brief overview of the key elements of the hardware design is given.

2.1. Power Input

2.1.1. Photovoltaic Arrays

A Photovoltaic (PV) string has seven solar cells (Azurspace 3G30C-Advanced) connected in series, with each individual cell having a bypass diode. The strings are arranged according to Figure 2, forming two large PV arrays made of carbon fibre reinforced polymer laminate.

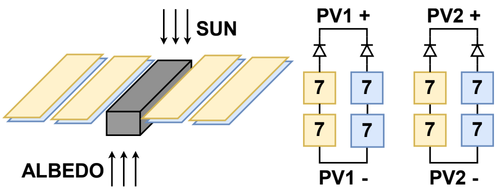

Figure 2. Solar-Cells Array configuration.

Two strings each are connected in series, with a string diode to prevent any reverse currents. The results in an open clamp voltage of 37.8 V and a maximum power point voltage of around 33.75 V. The DC-converters connected to the PV array were chosen to be buck-converters and therefore the input voltage must be higher than the output, which is determined by the battery (max. 16.8 V). In addition to this, the solar cells orientated to the albedo side, will be connected in parallel to the cells orientated towards the sun. This increases the total current and thus the efficiency of the DC-converters. The PV array provides up to 32 W under ideal conditions. The dual side PV array setup also improves power generation during tumbling.

2.1.2. Input Conditioning

A schematic of the input paths plus the interface with the microcontroller is shown in Figure 3.

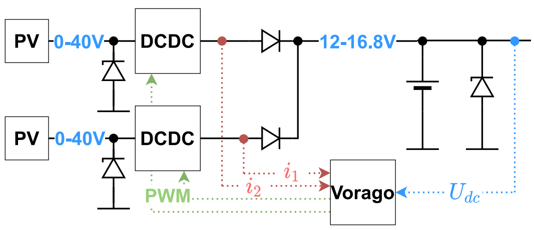

Figure 3. Schematic of input rails.

Each PV array is connected to redundant DC-converters which are controlled by an MPPT algorithm. Zener- or rather transient voltage suppressor diodes protect the input for voltage peaks, that will likely occur during the transition between the shadow and sun phases. In this situation, the solar cells are cold and the open clamp voltage is increased due to the lower temperature. The controlling of the DC-converter output is done by applying an external voltage at the feedback pin of the converter. The resistor and the capacitor form a low pass filter, which outputs the mean value (DC voltage) of the Pulse Width Modulated (PWM) input. By changing the duty cycle of the PWM signal, the control voltage changes, which then leads to a different output voltage. The PWM method was chosen for its simplicity and robustness since the rad-hard microcontroller is used to generate the PWM signal.

2.2. Power output

The power output is designed redundantly. The 3.3 V, as well as the 5 V rail, are supplied by three parallel non-synchronised Buck-Converters, each with a fixed voltage. Not synchronising the DC-converters usually decreases efficiency, due to unequal load sharing and by operating at lower loads on average. However, synchronised converters would not be fully redundant. Each voltage rail connects to the individual subsystem switches. A latch-up-current protection is also integrated for most switches. There are a total of 32 switchable channels, 27 of which integrate the latch-up current limiters (LCLs). Five protected and all five unprotected channels are on the UR voltage rail. The 5 V voltage rail supplies eight channels and the 3.3 V voltage rail is connected to 14 channels.

2.2.1. Output channel switches and Latch-Up Current protection

The switching circuit, with the LCL, can be seen in Figure 4. The microcontroller activates and deactivates the redundant high-side switches.

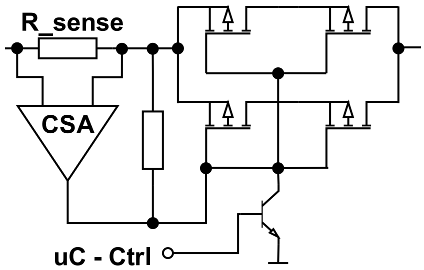

Figure 4. Switching circuit with current limiting.

The additional protection for latch-up events is handled in a hybrid configuration of hardware and software. The microcontroller monitors the current of the output and deactivates it in an overcurrent event. To avoid any damage due to the delay of the microcontroller processing, a hardware current limit is implemented. This is achieved by connecting the output of the Current Sense Amplifier (CSA) to the gate of the FETs. If the current reaches a certain value, the resistance of the FETs increases, thus leading to a limitation of the current. Then the microcontroller deactivates the output.

2.3. Inhibits

The configuration in Figure 5 of the deployment switches represents the standard configuration to fulfil the requirements from ESA and launcher companies like Nanoracks [4].

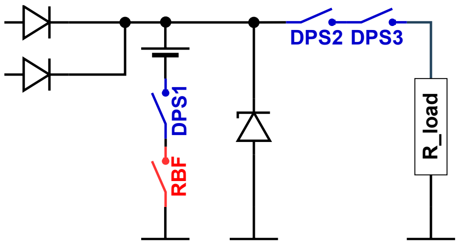

Figure 5. General inhibit configuration.

Usually, these inhibits are large mechanical switches, in the structure of the CubeSat, that are being actuated while they are in the deployer. Due to lack of space in the structure of SOURCE, small switches had to be used instead. These cannot handle the high currents of the main bus, which is why an electro-mechanical approach was developed. This consists of replacing the large mechanical switches with FETs which are activated by the smaller mechanical switches. This also improves overall magnetic cleanliness since it reduces major current loops through the satellite. Figure 6 shows the functional architecture.

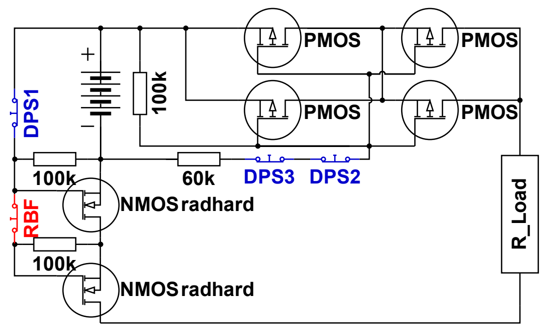

Figure 6. Inhibit configuration for the electro-mechanical solution.

3. Test Results

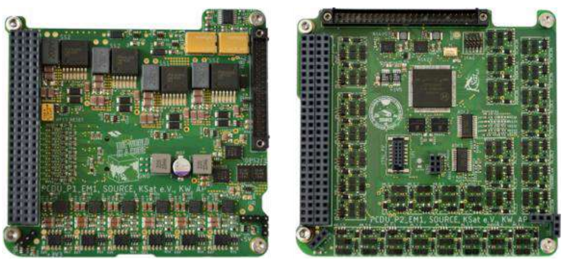

Figure 7. PCDU engineering model.

Part of the development process is the functional testing campaign. For this purpose, an engineering model (see Figure 7) was manufactured in phase C.

Testing began in March 2021 and is still ongoing. Since SOURCE is a student project, testing campaigns were intermittent and had to be paused during exam periods. Overall, all functions of the PCDU could be verified, however not without some troubleshooting and iteration. At the time of writing, the thermal-vacuum tests and full system efficiencies measurements are still to be conducted.

3.1. Anomalous component tests

3.1.1. Inhibits

During the development of the inhibits it was discovered that the battery could still be charged while all Deployment Switches (DPS) were actuated. This could lead to overcharging of the battery, since the control logic is disabled by the inhibits. Therefore, the enable pins of the input DC-converters were integrated in the design, actively enabling and disabling the converters together with the DPS FETs. This however requires the battery voltage at the enable pins of the converter to enable charging with the solar panels. This prevents solar-only operation, without the battery.

3.1.2. Latch-up Current Limiters

For testing the maximum current before current-limiting, a DC load in constant resistance mode was used to emulate a high current draw on the LCLs. During testing highly anomalous behaviour occurred with LCLs on all output voltages. Figure 8 shows the oscilloscope measurement of the 5 V output during current limiting operation. Similar behaviour could be observed with the 3.3 V and unregulated (UR) LCLs.

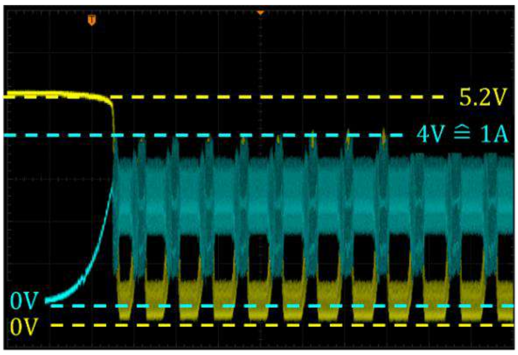

Figure 8. Anomalous behaviour of a 5V LCL during current limiting operation over 6ms. Yellow is the output voltage; Blue is the voltage of the CSA and corresponds to the current.

Extreme oscillations can be seen and no stable current limiting could be established.

The first assumption was an instability in the feedback circuit, mainly due to high resistor values, insufficient smoothing capacitance and due to the large amplification of 500x by the CSA. New simulations in LTSpice did not provide any new findings, neither did additional tests with new configurations with different resistors and CSAs. The test setup was re-evaluated and an additional test was conducted using fixed load resistors instead of the DC-load (using the same resistance values).

The result can be seen in Figure 9. Apart from some ripple, stable current limiting could be achieved and the DC-load was determined as the cause for the initial anomalous behaviour.

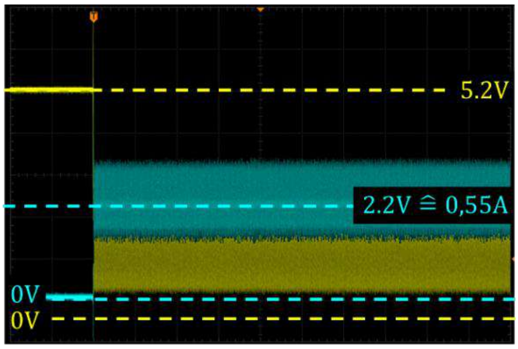

Figure 9. Stable current limiting of a 5V LCL during current limiting operation over 6ms.

The original design of the LCL circuit was concluded to be functional as intended as the anomalous behaviour was solely caused by the initial test setup.

3.1.3. MRAM chips

It was discovered that the initially selected Everspin 128 kB MRAM chip could not be flashed properly. This was because the smaller chips of Everspin's MRAM chip range have a smaller address width and therefore cannot be used with the VA10820. The 1 Mb version on the other hand could be flashed without issues.

3.1.4. Electromagnetic compatibility tests

In addition to the functional testing, a radiating emission test has been performed to verify conformal emission of the PCDU, especially in the S-band range. This range is relevant because most of SOURCE's communication is done via S-band [1]. A horn antenna was positioned at 1 m distance from the PCDU. Both polarizations were measured. The results showed some peaks in the S-band (up to 50 dBµV/m). Future measurements will involve sniffing tests to localize the emitting element. However, the result is not necessarily critical since it has to be compared with the sensitivity of the S-band module.

3.2. Performance

3.2.1. Inhibits

The hybrid design of the inhibits has the disadvantage that a small leakage current is always present. The results for different combination of active inhibits switches are seen in Table 1. The leakage is minimal and acceptable for a required state of charge of 80 % at deployment.

Table 1. Leakage of hybrid inhibits. Time t until battery is discharged to 80% state of charge.

	U / V	I / mA	P / mW	t / d
RBF	14.28	0.250	3.57	175
DPS1/2/3	14.28	0.020	0.29	2156
DPS1/2/3 + RBF	14.28	0.001	0.02	36473

Additionally, during operation losses also occur due to the on-resistance of the FETs. These losses are listed in Table 2 and are not negligible for higher currents.

Table 2. Losses of hybrid inhibits. Current and voltage on the main bus.

I / A	U / V	P_IN / W	P_loss / W
0.50	13.95	6.97	0.04
1.00	13.90	13.90	0.11
2.00	13.80	27.59	0.41
2.50	13.73	34.33	0.67

3.2.2. Input DCDC converter

Lower performance due to unequal load sharing was reproduced in the tests. One converter delivered the main load up until 1 A output current. After that both converters delivered the same amount of power, raising efficiency to that of a single converter. The input converter can be operated in a large range of operation. This includes an input voltage range of 20 – 38 V, an output voltage range of 12 – 18 V (set by PWM duty cycle between 0 – 100 %) and a load current range of 0 - 2.5 A. Over the whole range an average input efficiency of 88% was achieved.

3.2.3. Output DCDC converter

The output converters also are not synchronised and do not share the load equally. A 12 – 18 V main bus voltage and 0 – 2.5 A output current was used for both 3.3 V and 5 V. Full load

DOI: 10.5821/conference-9788419184405.047

sharing between all three converters was only reached at 2 A output current for both voltage rails. In this case this proved to be beneficial, as the higher efficiency of a single converter was achieved during lower load operation. An average efficiency of 89 % was achieved on the 5 V rail and an average 87 % on the 3.3 V rail. The most efficient operating range was between 0.5 A and 1 A output current for both voltage rails.

3.2.4. Latch-up Current Limiters

Hardware current limiting could be achieved in 2 µs for the 3.3 V LCLs, 10 µs for the 5 V LCLs and 20 µs for the UR LCLs.

4. Discussion

Many Student projects face the decision whether to purchase a commercial product or to build their own PCDU. The experience made in SOURCE, shows that the added complexity and manpower necessary for the entire development and testing must be considered carefully. However, the benefits in education and for future developments have proven to be valuable.

One of the lessons learned during the testing was recognising the role of measurement and testing equipment and their ability to interfere with the measurements. Another lesson was, that power converters are often portrayed in their optimal operating conditions in their datasheets, with real-world applications performing differently, especially when converters are used in parallel. Additionally, testing the PCDU with wide-ranging operating conditions, leads to numerous tests and drastically increases testing time. For example, the input converters were first to be tested, following the logical paths of the PCDU from the PV cells to the switches. In hindsight, these initial tests, which covered the entire range of operating conditions and were conducted manually, only provided limited benefit and the testing could have been reduced to simple functional testing for a selection of operating conditions. A better way of conducting full operational tests would have been to use automated data acquisition combined with the internal logging capabilities of the PCDU at a later date.

The hybrid inhibit design provides great benefits for the size and mass constraints of CubeSats, however the higher losses need to be considered in the power budget and the added complexity must be taken into account as well.

5. Conclusion

For SOURCE, a custom PCDU was developed. The functionalities were all successfully tested and their performances were determined to be as expected. Further tests yet to be conducted are the thermal vacuum chamber test and radiation sniffing tests to find and assess the source of the radiated emission in the S-band spectrum, and tests of the MPPT algorithm using the PCDU and solar cells.

The testing of the PCDU will continue and likely provide further educational value. The next milestone of SOURCE is the mission readiness review mid-2022, at which point functional testing of the PCDU must be completed. Afterwards, the flight hardware will be manufactured and FlatSat system testing will begin. There are still several test campaigns to be conducted until the PCDU is fully flight worthy and can be considered for future projects. However, the design, development, and lessons learned are already being applied.

Acknowledgements

A special thank you to all the students who have been and are working tirelessly to create a flight ready in-house PCDU for SOURCE. Additional thanks go to the students of KSat and academic personnel at the IRS who supported us with their time and expertise. Finally, the SOURCE project would not be possible without the industry partners and ESA's *Fly Your Satellite!* team.

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Development of a CubeSat CLIMBing to the Van-Allen belt

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Abstract

Based on its successful CubeSat mission PEGASUS, the University of Applied Sciences Wiener Neustadt (FHWN) is preparing its new CubeSat mission called CLIMB. CLIMB is a 3U CubeSat that will be launched to a low, circular orbit of about 500 km. Using a Field Emission Electric Propulsion (FEEP) system commercialized by the company ENPULSION, the satellite will be lifted to an elliptical orbit with its apogee around 1000 km – well inside the inner Van Allen belt. During its 1.5 yearlong ascent and its operation in the Van Allen belt, the satellite will continuously monitor the space radiation with a RadFET dosimeter payload and the impact on CLIMB's subsystems. Comparisons with radiation testing on ground will allow the assessment of the capability of ground tests to predict effects of space radiation on CubeSat subsystems.

The operation of the propulsion system will raise the satellite's apogee on average 16 times a day. A comprehensive analysis has been conducted to assess its collision probability throughout its mission time. Using various tools, provided by ESA (CROC, MASTER and the DRAMA ARES python package), the collision probability for the entire mission duration (~3 years) was calculated to be 3.38×10^{-5}, i.e. a magnitude smaller than the requested probability of 10^{-4}.

The second payload of CLIMB is an anisotropic magnetoresistance (AMR) magnetometer with a, for CubeSats high, sensitivity of about 10 nT RMS. The first results of measurements with this COTS based magnetometer are presented as well as experimental assessments of the satellite's magnetic cleanliness.

The benign thermal conditions on CubeSats operating close to Earth are complicated by the relatively high-power propulsion system onboard CLIMB. Detailed numerical analysis (ANSYS, ESATAN) and experimental verifications resulted in the identification of possible methods to deal with up to 18 W of dissipated electric power. The main heat sources are the thruster and the battery unit, during thruster operation.

Keywords

Field Emission Electric Propulsion System, FEEP, Van-Allen Belt, Magnetometer, Magnetic cleanliness, DRAMA, Thermal analysis, ENPULSION, magnetic cleanliness, CLIMB

1. Introduction

After the successful PEGASUS mission, the University of Applied Sciences Wiener Neustadt (FHWN) is preparing its new CubeSat called CLIMB. By using a Field Emission Electric Propulsion (FEEP) system by the company ENPULSION, the satellite will be transferred to an elliptical orbit with its apogee in the inner Van Allen belt. During its about 1.5 yearlong ascent and its operation in the Van Allen belt, the satellite will continuously monitor the space radiation and its impact on CLIMB's subsystems.

2. Orbital planning and assessment

CLIMB will be launched into a circular orbit of 500 km altitude and is planned to raise its apogee up to 1000 km using the IFM thruster from the company ENPULSION. Due to the power budget of CLIMB and the properties of the IFM, a quasi-spiral orbit is not possible, and the thruster will be operated at almost every perigee. The apogee raising orbit also ensures a lower perigee for the final orbit, which results in an orbit lifetime below 25 years and ensures a proper deorbiting at EOL.

2.1. Orbit raising

CLIMB's orbit will be raised by several minutes of thruster operation almost every time CLIMB crosses the perigee. Comprehensive numerical simulations of the orbit manoeuvres have been conducted with the firing time, drag area variations, thrust variations, thrust misalignments and many other parameters as input variables. The values obtained for the total raising time varies from 350 days for 10 minutes firing duration up to 504 days for 8 minutes firing duration (Figure 1). The requirement of continuous realignment provides a real-life scenario; however, the NEPTUNE propagator does not provide the possibility to align the satellite in the direction of the Sun. For the assessment the extreme cases are considered, i.e. maximum and minimum possible cross-section as drag area. This results in a change of 9 days from minimum drag to the maximum drag area, which is small, compared to overall orbit raising time. Similarly, during the de-saturation of the reaction wheels with magneto-torquers the satellite needs to be aligned in a specific orientation depending on the magnetic field, which also will have an insignificant impact on satellite raising time. Assuming that one day in a week is required for desaturation, 52 days will be added in the overall raising time. The raising time rather depends on perturbations than on the satellite attitude. For example, a solar maximum will change the atmospheric density around the satellite and the drag value even though the drag area remains unchanged.

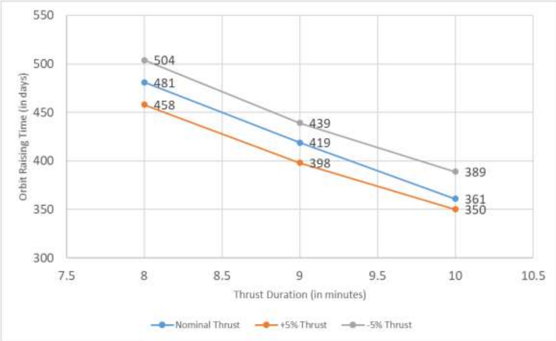

Figure 1: Orbit raising time for different thruster firing durations.

2.2. Annual collision probability levels

ESA's MASTER tool was used for the population estimation. It considers a condensed population of all man-made objects and the meteoroids with predicted orbits until 2027. The results show that the population density increases with increasing inclination with a maximum between the altitudes of 700 km and 900 km. This is also verified from the UCS satellite database. The population data served as input for an initial assessment of conjunctions and collisions with ESA's DRAMA ARES Python package. The orbits are raised in segments of 10 days and for each segment the collision probabilities are calculated. The values are then averaged over the whole mission duration to obtain the collision probability and the number of required avoidance manoeuvres. The overall collision probability results in 3.38 x 10^{-5}. This involves a requirement of 0.2 avoidance manoeuvres to achieve the probability of 10^{-4} and two manoeuvres to achieve the probability level of 10^{-6} (Figure 2). According to industrial standards, 10^{-4} is considered as safe. Hence, these initial values demonstrate that the CLIMB mission will not require any collision avoidance manoeuvre during its complete mission lifetime. However, these values do not consider the screening volume as suggested by 18SPCS, which is considered below.

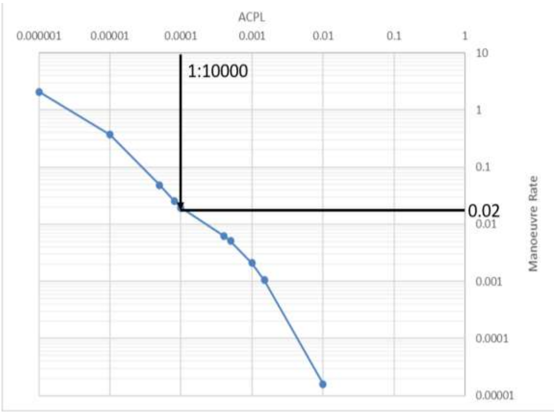

Figure 2: Number of manoeuvres required based on annual collision probability level.

2.3. Conjunction assessment

The conjunction assessment considers a firing duration of 8 minutes and an inclination of 70 degrees. The initial data are evaluated for a screening volume of 50 km × 50 km × 50 km, which is subsequently filtered down to the screening volumes suggested by the 18 SPCS. For filtering the data, two screening volumes are considered, first 'Basic', which is generally used for a non-manoeuvrable satellite with a size of 1 km × 1 km × 1 km, and an 'Advanced' screening volume for manoeuvrable satellites, with a size of 2 km × 44 km × 51 km. The identification of the worst-case conjunction events is based on the overall miss-distance and subsequently on each orthogonal component to determine the validity of the conjunction event. The data confirms that there are no single event conjunctions, which need to be avoided, as predicted in the initial results by DRAMA. However, there are many conjunctions events depending on the chosen screening volume, which requires a careful planning of thrust operation in order to avoid the occurrence of conjunction events.

3. Thermal experiments and simulations

The thermal validation of CLIMB is essential to ensure a proper operation of all subcomponents of the satellite throughout the mission and up to the EOL. As CLIMB will undergo large temperature changes as well as temperature cycling, the thermal design of the CubeSat must balance the distribution and radiation of excess heat, while keeping the satellite in a proper temperature range.

3.1. Critical components

The most thermally critical components of CLIMB are the thruster, the batteries, and, to a lesser extent, the electronic circuit boards. The estimated (conservative) heat dissipation of the thruster implemented in CLIMB is around 4 W in cruise mode and 13.5 W in propulsion mode. The set of eight batteries is estimated to dissipate 2.36 W of heat in cruise mode and 6.32 W in propulsion mode, due to discharging.

Figure 3: Thermal vacuum testing of CLIMB's thermal model with ENPULSION's NANO thruster.

3.2. Validation of thermal model

CLIMB's experimental thermal model was constructed to simulate the heat generation characteristics of the real components of the CubeSat. To validate the accuracy of the thruster's thermal model, TVC tests were done with the model as well as on the thruster (Figure 3), and the temperatures measured on various positions were compared.

3.3. Experimental results

Table 1 summarises the temperatures measured on exemplary components in both the IFM thruster test and the thermal model test. Though the temperature deviation between both models is acceptable at 20℃, it increases significantly as the environment temperature decreases. The largest difference between temperatures of corresponding components was 13℃, measured at the interface located at the base of the thruster and with an environment temperature of -20℃.

Subsystem	Temperature (°C)					
	Cruise mode @20°C			Cruise mode @-20°C		
	IFM Test	Thermal Test	Temperature Difference	IFM Test	Thermal Test	Temperature Difference
Environment	22.4	22.15	0.25	-17.3	-18.14	0.84
Y- Side Panel	44	39.74	4.26	19.1	10.05	9.05
X- Side Panel	43.6	37.89	5.71	18.9	8.23	10.67
Y+ Thruster Interface	47	41.84	5.16	22.5	12.87	9.63
X- Thruster Interface	43.9	45.49	-1.59	30.6	16.68	13.92
Copper Plate	46.6	46.67	-0.07	21.1	17.68	3.42
Converter PCB	60.6	58.69	1.91	37.5	33.16	4.34

Table 1: Comparison of CLIMB thermal test and IFM test component temperatures in cruise mode.

DOI: 10.5821/conference-9788419184405.048

Alongside the validation of the thermal model, TVC tests were used to assess the thermal performance of the CLIMB model. This shows that at an environment temperature of -20℃, component temperatures remain within an acceptable operable range of 8℃ at the X- side panel up to 33℃ at the converter PCB. However, higher environment temperatures require attention – the batteries and battery converter models experienced significantly elevated temperatures at an environment temperature of 20℃, reaching up to 60℃ under cruise conditions and up to 100℃ in thrust mode (Figure 4). These temperatures well exceed the operable limit of the batteries, highlighting the need for further optimization of CLIMB's thermal design or of the thermal model validation.

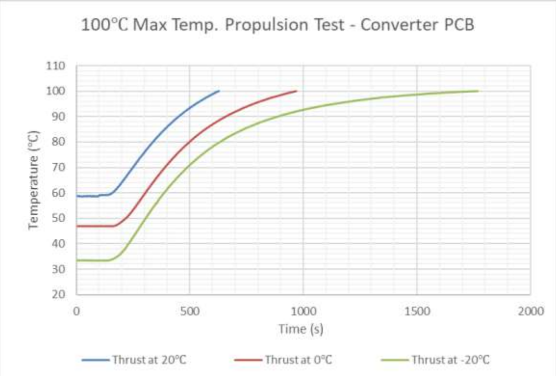

Figure 4: Power converter PCB temperature in thrust mode, up to 100℃.

3.4. Numerical simulation

To support the experimental efforts, a numerical model of the experimental thermal model was established in ANSYS. The simulation results were validated with the experimental results and showed a deviation of only < ±5 °C. The ANSYS model was exploited to simulate a larger variety of temperature ranges, as well as to assess the impact of different material properties with the objective of identifying potential design improvements. Based on the ANSYS thermal model, a further model was established in ESATAN. ESATAN offers the opportunity to implement orbital parameters and therefore perform dynamic tests with unknown temperature cycles which is a more detailed simulation of inflight conditions - something which is not possible with ANSYS. The input parameters were correlated to those of the ANSYS model and the results similar to the ANSYS model and therefore also to the experimental result. Overall, this further validates the thermal results.

4. Magnetic cleanliness

As CubeSats continue to become more versatile, the number of use cases and (professional) missions increase steadily. Measurements of magnetic fields in space are one example, as the NASA ARCS mission impressively demonstrates [1]. For such applications not only the magnetometers need to be improved, but also the satellite platform and its magnetic cleanliness. Therefore, a numerical assessment as well as experiments were conducted to better understand the magnetic properties of the satellite and its impact on the measurements.

4.1. Simulation of the magnetic flux

The theory behind the simulation is based on current loops, which are conducting rings with a certain area and an electrical current. The Biot-Savart law serves to calculate the magnetic induction (Eq. 1). It results in the magnetic induction corresponding to the elemental ring segment $d\vec{L}$ and current I and the magnetic moment $\vec{\mu}$ measured in Am², using Eq. 2. In that equation, A is the area of the current ring, and $\hat{n}$ is a unitary vector normal to the ring. [2]

$$d\vec{B} = \frac{\mu_0 I}{4\pi} \frac{d\vec{L} \times \vec{r}}{r^3} \qquad (1)$$

$$\vec{\mu} = IA\hat{n} \qquad (2)$$

The simulations are based on the MATLAB function from Levron [3], which itself is based on the numerical technique from Haus [4]. The provided function computes the magnetic field B by a given geometry, represented as point coordinates. Each space between two consecutive points is treated as a straight conductor, also called current stick [3].

4.2. Modelling the satellite

The use of current loops to model the whole satellite turned out to be the wrong way. If the loops of the PSU are considered, all loops are closed at the battery unit and therefore several current loops overlap at the same location. This would result in an overestimated magnetic field strength. Secondly, the batteries are connected in parallel, which excludes one closed loop as the current path splits. For those reasons, another approach was chosen, which assumes current sticks only and the loops are not mandatory to be closed. The modelling process uses any PCB design tool, compatible with "DXF"-files. Those are opened in CATIA to manipulate them and end up with a point cloud representing all current sticks. This is exported to MATLAB for the magnetic field calculations using VBA scripts.

DOI: 10.5821/conference-9788419184405.048

4.3. Simulation results

The simulation in MATLAB has been done with a resolution of 5 mm and an additional surrounding field extending 0.5 m in each direction, to especially evaluate the magnetometer position on the boom. Figure 5 shows the magnetic field of current paths on the PCBs on an x-y-plane in the centre of the satellite, at about 15 cm height. The red rectangle marks the satellite's shape. The solar panels generate an increased magnetic field in their vicinity.

Further refinements of the model and the computation will be done by considering soft and hard magnet materials and will be followed by a comparison with measurements.

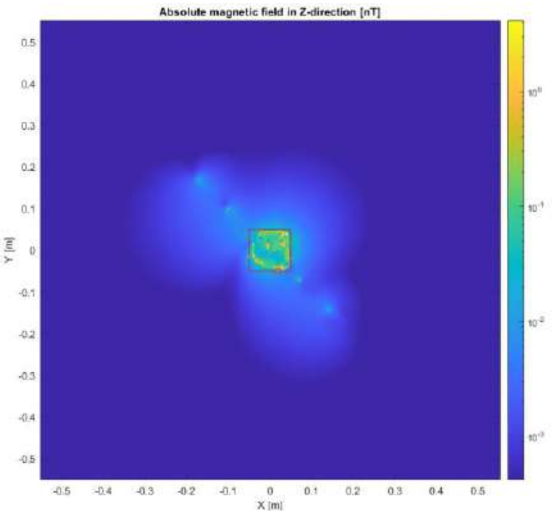

Figure 5: MATLAB plot of the CLIMB simulation showing the absolute magnetic field values in the satellite's centred x-y-plane.

5. Magnetometer Instrument

The Magnetometer Instrument of CLIMB will be used for scientific measurements of the magnetic field in the Van Allen Belt. The subsystem will be divided into an internal instrument control unit and a boom. The height of the boom and deploying mechanism is required to be lower than 5 mm as it will be mounted on the outer surface of the side panels. The boom shall not introduce low eigenfrequencies during launch and therefore the length has to be fine-tuned with regard to its width and thickness and material properties during the last stage of development.

5.1. Engineering model of the Magnetoboom

An Atmega128 is used for reading out the data of the sensors and forwarding it to the On-Board- Computer (OBC). The main magnetic field sensors used on the boom are Honeywell HMC1022 and HMC1021Z to provide measurements with an accuracy of ±10 nT (RMS) and a dynamic range of ±500 μT. The secondary sensors are Memsic MMC5983MA with a lower resolution. They are equally distributed on the boom for a differential field measurement that will serve as housekeeping data corrective values for the HMC measurement. The Serial Peripheral Interface (SPI) of the instrument controller is used to communicate with all connected sensors. Honeywell sensors give a differential output that is translated by the LTC 2440 ΔΣ 24-BitAnalog to Digital Converter (ADC). After acquiring the magnetic field data, it will be transferred to the OBC via Two Wire Interface (TWI). The PCB tracks on the boom are designed to twist themselves through the copper layers as Dong Gun Kam, et. al. [5][6] recommend to reduce cross talking between sensor tracks and magnetic interference by power supply tracks.

5.2. Testing procedures

The simulation of the expected magnetic field of Earth with the Systems Tool Kit (STK) from AGI results in an estimated field strength of about. ±50 μT. These fields are applied via a custom made Helmholtz cage. Additionally, in cooperation with IABG, external fields were applied in the company's magnetic field simulation facility. The components survivability and thermal drifts of the magnetic field sensors will be evaluated in a thermal vacuum chamber.

5.3. Testing results

The axial applied fields during tests at IABG were at ±30, ±50 and ±60 μT. The results of the secondary sensors show that apart from a zero-point calibration, all fields were sensed correctly (figure 6). The subsystem software needs to be adapted to convert the output into CLIMB's coordinate system.

The preliminary results of the main sensors showed a higher noise level than expected and thus need to be optimised via additional passive components on the engineering model. It was shown that the subsystem circuit itself is functional and can be forwarded to thermal vacuum tests.

DOI: 10.5821/conference-9788419184405.048

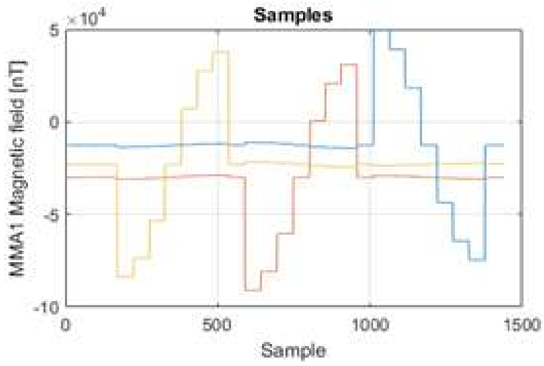

Figure 6: Test result of secondary sensors at magnetic field simulation facility.

6. Summary and Conclusion

The results of this paper show that CLIMB is able to withstand the extreme thermal environmental conditions during its trip to the Van-Allen belt. All simulated and measured temperatures are within the acceptable range. Simulations of the orbit raising time have shown that CLIMB is able to lift the apogee to the desired altitude within 1 to 1.5 years, with the necessary time mainly depending on the thrusting duration during each orbit. Most importantly, it was shown that the threat of collisions is negligible and, although possible, no collision avoidance manoeuvre is required throughout the mission time. A new magnetic boom is designed for the CLIMB mission, allowing very accurate magnetic field measurements. Simulations of the magnetic field generated by the satellite itself, have shown a negligible impact on the magnetic field measurements. Those simulation results were recently compared to measurements taken in the large magnetic field facility of IABG.

Acknowledgement

This project is funded by the University of Applied Sciences Wiener Neustadt and Lower Austria. The CLIMB team also expresses its gratitude to IABG for providing the magnetic facility for testing and ECOPLUS GmbH for sponsoring the trip to the symposium.

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Improved Sensor Fusion for Flying Laptop Based on a Multiplicative EKF

Maximilian von Arnim[1], *Steffen Gaisser*[2], *Sabine Klinkner*[2]

Abstract

Flying Laptop is a small satellite carrying an optical communications payload. It was launched in 2017. To improve the satellite's attitude determination, which is used to point the payload, a new sensor fusion algorithm based on a low pass filter and a multiplicative extended Kalman filter (MEKF) was developed. As an operational satellite, improvements are only possible via software updates.

The algorithm estimates the satellite's attitude from star tracker and fibre-optical gyroscope (FOG) measurements. It also estimates the gyroscope bias. The global attitude estimate uses a quaternion representation, while the Kalman filter uses Gibbs Parameters to calculate small attitude errors. Past Kalman filter predictions are saved for several time steps so that a delayed star tracker measurement can be used to update the prediction at the time of measurement. The estimate at the current time is then calculated by predicting the system attitude based on the updated past estimate. The prediction step relies on the low-pass-filtered gyroscope measurements corrected by the bias estimate.

The new algorithm was developed as part of a master's thesis at the University of Stuttgart, where Flying Laptop was developed and built. It was simulated in a MATLAB/Simulink environment using the European Space Agency's GAFE framework. In addition, the new filter was applied to measurement data from the satellite. The results were used to compare the performance with the current filter implementation.

The new Kalman filter can deal with delayed, missing, or irregular star tracker measurements. It features a lower computational complexity than the previous standard extended Kalman filter used on Flying Laptop. The mean error of the attitude estimate was reduced by up to 90%. The low pass filter improves the rotation rate estimate between star tracker measurements, especially for biased and noisy gyroscopes. However, this comes at the cost of potentially less accurate attitude estimates. Educational satellites benefit from the new algorithm given their typically limited processing power and cheap commercial-off-the-shelf (COTS) sensors. This paper presents the approach in detail and shows its benefits.

Keywords

Attitude Determination Systems; Fibre-Optical Gyroscope; Kalman Filter; Sensor Fusion; Star Tracker

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Nomenclature

β	*Gyroscope bias*
ϑ	*Error angle*
ω	*Angular velocity*
A	*Assembly matrix*
F	*State matrix / jacobian*
H	*Observation matrix*
I	*Identity matrix*
P	*Filter covariance estimate*
q	*Quaternion*
Q	*Process noise covariance*
R	*Observation noise covariance*
t	*Time*
T	*Filter step time*
x	*System state*
$\otimes$	*(Shuster) quaternion multiplication*
$\hat{a}$	*Estimate of* a
$[a\times]$	*Cross product matrix of* a

Acronyms/Abbreviations

COI	*Center of Integration*
COTS	*Commercial-Off-The-Shelf*
EKF	*Extended Kalman Filter*
ESA	*European Space Agency*
FIR	*Finite Impulse Response*
FLOP	*Floating Point Operation*
FLP	*Flying Laptop*
FOG	*Fibre-Optical Gyroscope*
IIR	*Infinite Impulse Response*
LSQ	*Least Squares*
MEKF	*Multiplicative EKF*
MUKF	*Multiplicative UKF*
OLS	*Ordinary Least Squares*
PF	*Particle Filter*
STR	*Star Tracker*
UKF	*Unscented Kalman Filter*

1. Introduction

Flying Laptop (FLP) is a small satellite, developed and built at the University of Stuttgart. It measures $\mathbf{60}\times\mathbf{70}\times\mathbf{80}$ cm and has a mass of $\mathbf{110}$ kg [1]. A fixed optical communication system, OSIRISv1, is one of FLP's payloads. OSIRISv1 nominally requires an attitude determination accuracy of $\mathbf{0.034}$ mrad [2]. FLP carries two star trackers (STR A & B) and four fibre-optical gyroscopes (FOG) as high-precision attitude and rate sensors.

A standard extended Kalman filter (EKF) was previously developed for FLP. This filter was computationally expensive but did not achieve the required attitude determination performance [3], even after optimization [4].

Therefore, a new filter was sought. It was desired to reduce the risk of filter divergence, handle delayed, asynchronous and missing STR measurements, estimate the FOG bias and utilize oversampled FOG measurements.

FLP uses quaternions as attitude representation. This means that any algorithm must preserve the unit quaternion property [5]. The basic MEKF guarantees this by using a multiplicative error quaternion given in eq. (1) [5].

$$\boldsymbol{q}^{true} = \boldsymbol{\delta q} \otimes \hat{\boldsymbol{q}} \tag{1}$$

Other popular filters such as unscented Kalman filters (UKF) [3, 6–11] or particle filters (PF) [12] exist but were dismissed as being too costly for the limited computational capacity of FLP [13]. They have their greatest strengths with highly nonlinear systems, whereas the rotation dynamics and kinematics can be linearized well for short time steps [5]. Recent UKF developments such as the Multiplicative UKF (MUKF) [14] are unproven and require adaptation to the sensors [13]. Conversely, combining low pass filtering with Kalman filters promises cheap noise reduction.

This paper presents a new filtering concept that combines low cost and high precision sensor fusion utilizing variable measurement rates.

2. Methodology

2.1. Definitions

This paper uses the same quaternion definition as [5] and the internal FLP algorithm, eq (2),

$$q = \begin{bmatrix} q_{1:3} \\ q_4 \end{bmatrix} = \begin{bmatrix} q_{x:z} \\ q_0 \end{bmatrix} \tag{2}$$

for the quaternion product of $\boldsymbol{q}$ and $\boldsymbol{r}$ as eq. (3).

$$q \otimes r = \begin{bmatrix} q_4 I_3 - [q_{1:3}\times] & q_{1:3} \\ -q_{1:3}^T & q_4 \end{bmatrix} r \tag{3}$$

It can be applied to vectors $\boldsymbol{\omega}_{3\times1}$ as shown in eq. (4) with the functions $\boldsymbol{\Omega}, \Xi$ given in [5].

$$\omega \otimes q = \begin{bmatrix} \omega \\ 0 \end{bmatrix} \otimes \mathrm{q} = \Omega(\omega) q = \Xi(q)\omega \tag{4}$$

All reference frames are right-handed cartesian coordinate systems.

2.2. Filter Development

The new algorithm consists of three elements: A digital low pass filter to pre-process the raw gyroscope measurements, an ordinary least-squares (OLS) algorithm to fuse the gyroscope measurements in the satellite body frame, and finally a Kalman filter with a propagation and update step.

2.2.1. Low Pass Filtering Gyroscope Measurements

Five different 5th-order Cauer-type IIR filters were designed, one for each normalized cutoff frequency $\omega_c \in \{\frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \frac{1}{6}, \frac{1}{10}\}$, as they offer the lowest signal delay [8] [15]. The passband ripple was limited to $\delta_c = 0.002$ dB and the stopband attenuation was set to $\delta_s = -40$ dB to achieve minimal signal distortion and significant high-frequency noise suppression.

Least Squares for Gyroscope Fusion

A simple OLS algorithm was chosen to fuse the four partially redundant gyroscope measurements into a single three-dimensional measurement vector, utilizing the sensor assembly matrix A_{FOG} in eq. (5).

$$\omega_k^* = (A_{FOG}^T A_{FOG})^{-1} A_{FOG}^T \widetilde{\omega}_k = A_{FOG}^* \widetilde{\omega}_k \tag{5}$$

Modifying A_{FOG} allows an easy adaption to the case of missing gyroscope measurements.

2.2.2. Multiplicative Extended Kalman Filter

The new MEKF uses a propagation algorithm similar to [5]. It estimates a delta-state $\delta x_k = [\delta\vartheta_k, \beta_k]^T$ to determine the global state estimate q_k, ω_k. The rate measurement is adjusted with the bias estimate by eq. (6).

$$\widehat{\omega}_k = \omega_k^* - \widehat{\beta}_k \tag{6}$$

to propagate the attitude and covariance estimate. The discretization of the system Jacobian F_c (eq. (7)) is done via linearization in eq. (8) to minimize the computational effort [5].

$$F_c(t_{k-1}) = \begin{bmatrix} -[\widehat{\omega}_{k-1}^+ \times] & I_3 \\ 0_{3\times3} & 0_{3\times3} \end{bmatrix} \tag{7}$$

$$F_{k-1} = I_6 + T_k F_c(t_{k-1}) \tag{8}$$

so that eqs. (9)- (11) propagate the state.

$$\hat{q}_k^- = exp\left(\frac{1}{2}\Omega(\widehat{\omega}_{k-1}^+)T_k\right)\hat{q}_{k-1}^+ \tag{9}$$

$$\widehat{\beta}_k^- = \widehat{\beta}_k^+ \tag{10}$$

$$P_k^- = F_{k-1} P_{k-1}^+ F_{k-1}^T + Q \tag{11}$$

The à-priori estimate of the error angle is always set to zero (eq. (12)) as it is the best estimate given the data available for this step.

$$\delta\hat{\vartheta}_k^- = 0 \tag{12}$$

If no STR measurement was received, the filter execution ends here. The propagated value gets passed on to the controller and is added to the buffer for an eventual later update. If a STR measurement was received, the filter can proceed with the update step.

As the STR measurements can be taken asynchronously, their measurement must be compared with the estimated attitude $\hat{q}_{COI}^-$ at the time of measurement t_{COI}. This à-priori estimate is calculated by propagating from a previously buffered state using eq. (7) with an adjusted timestep $T_{COI} = t_{COI} - t_{k\ prior\ to\ COI}$. The error angle between a single STR measurement and estimate is given by eq (13).

$$\delta\vartheta_{STR} = 2\frac{(\mathrm{q_r^{-1}} \otimes \mathrm{q_{STR}} \otimes (\hat{\mathrm{q}}_{\mathrm{COI}}^-)^{-1})_{1:3}}{(\mathrm{q_r^{-1}} \otimes \mathrm{q_{STR}} \otimes (\hat{\mathrm{q}}_{\mathrm{COI}}^-)^{-1})_4} \tag{13}$$

If two STR measurements arrive in the same filter execution cycle, eq (13) is calculated for each measurement. The two error angles are then assembled by eq. (14).

$$\delta\vartheta_{STR\ AB} = \begin{bmatrix} \delta\vartheta_{STR\ A} \\ \delta\vartheta_{STR\ B} \end{bmatrix} \tag{14}$$

This gives the measurement Jacobian for a single measurement as eq. (15) and for two measurements as eq. (16).

$$H_A = H_B = [I_3 \quad 0_{3\times3}] \tag{15}$$

$$H_{AB} = \begin{bmatrix} H_A \\ H_B \end{bmatrix} \tag{16}$$

The matrices H and R for the Kalman gain must be chosen according to the number of STR measurements [13]. This leads to eq. (17) for the update of the error state.

$$\begin{bmatrix} \delta\hat{\vartheta}_k^+ \\ \hat{\beta}_k^+ \end{bmatrix} = \begin{bmatrix} \delta\hat{\vartheta}_k^- \\ \hat{\beta}_k^- \end{bmatrix} + K\delta\vartheta_{STR} \tag{17}$$

The global estimate prior to the COI is then updated with the error state per eqs. (1) and (6). The error quaternion is constructed from the error angle with eq. (18) using the definition of the Gibbs parameter [5].

$$\delta\hat{q}_k = \frac{1}{\sqrt{4 + \left(\delta\hat{\vartheta}_k^+\right)^T \delta\hat{\vartheta}_k^+}} \begin{bmatrix} \delta\hat{\vartheta}_k^+ \\ 2 \end{bmatrix} \tag{18}$$

With the oldest global state updated, the buffered FOG measurements can be used to propagate the updated state iteratively from the COI to the current time with eqs. (9)- (11). The propagated values replace the estimates in the buffer. If another STR measurement arrives in the next filter cycle, this updated buffer ensures that each update builds upon the best estimate at the time. An illustration of the algorithm is shown in Figure 8.

2.3. Simulations

The algorithm was simulated in MATLAB using ESA's GAFE framework [16] and the known parameters of FLP [13]. It is compared against the previous implementation. The true FOG bias and FOG noise are varied between simulation runs to determine the effect on the filter estimate. The initial values were chosen as

$$\hat{q}_0^+ = [0.5 \quad 0.5 \quad 0.5 \quad 0.5]^T \tag{19}$$

$$\widehat{\omega}_0^+ = 0_{3\times1} \tag{20}$$

$$\delta\hat{x}_0^+ = \begin{bmatrix} \delta\hat{\vartheta}_0^+ \\ \hat{\beta}_0^+ \end{bmatrix} = 0_{6\times1} \tag{21}$$

$$P_0^+ = 1 \times 10^{-2}\, I_6 \qquad (22)$$

2.3.1. Covariance Matrices

The measurement covariance matrix of each STR assumes uncorrelated noise, although a lower accuracy is expected for the around-boresight angle in eq. (23). Prior work with adaptive covariances was unsatisfactory [4].

$$R_A = R_B = diag([\sigma_{STR}^2 \quad \sigma_{STR}^2 \quad 10\sigma_{STR}^2]) \qquad (23)$$

with $\sigma_{\mathrm{STR}}^2 = 10^{-11}$ [4]. The bias covariance is incorporated in the process noise covariance matrix. OLS is used to transform the four FOG variances into the bias estimate covariance [5].

$$Q = \begin{bmatrix} Q_\vartheta & 0 \\ 0 & A_{FOG}^* R_\beta (A_{FOG}^*)^T \end{bmatrix} \qquad (24)$$

with eqs. (25) and (26) [4].

$$Q_\vartheta = diag([10^{-14} \quad 10^{-14} \quad 10^{-14}]) \qquad (25)$$

$$R_\beta = diag([10^{-15} \quad 10^{-15} \quad 10^{-15}]) \qquad (26)$$

3. Results and Discussion

3.1. Filter Estimation Performance

The new MEKF converges within 400s as shown in Figure 1 and Figure 2. Its attitude estimate error is unaffected by the FOG bias. Although the old EKF shows lower errors in the unbiased case in Figure 3, this advantage quickly vanishes when a bias is introduced in Figure 4. The new MEKF is more robust in this respect. While the desired accuracy is not reached yet, performance is improved.

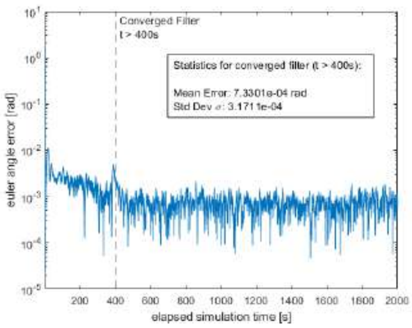

Figure 1: MEKF with unbiased FOG, Kalman filter at 5Hz, low pass filter $\omega_c = 0.25$

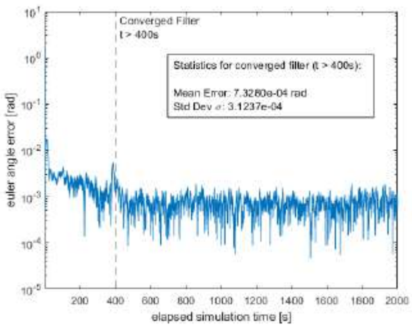

Figure 2: MEKF with FOG 0 bias $\beta = 10^{-2}\frac{rad}{s}$, Kalman filter at 5Hz, low pass filter $\omega_c = 0.25$

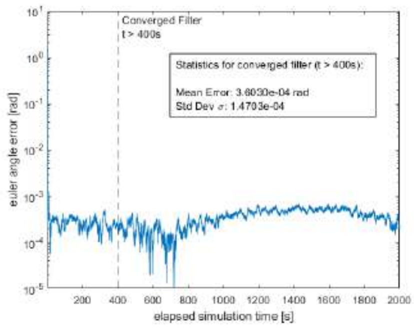

Figure 3: Old EKF with unbiased FOG, Kalman filter at 5Hz

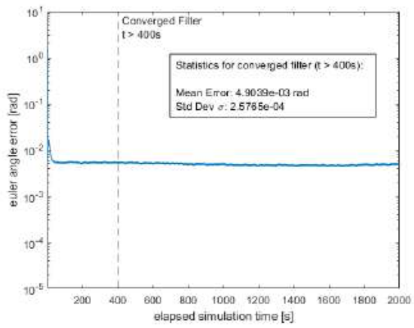

Figure 4: Old EKF with FOG 0 bias $\beta = 10^{-2}\frac{rad}{s}$, Kalman filter at 5Hz

The low pass filter is beneficial only if the Kalman filter cannot run fast enough to directly process all FOG measurements. The case where both the new MEKF and the FOGs run at 10Hz is shown in Figure 5 while the case with the MEKF running at 5Hz is given in Figure 6. Both the mean error, and the standard deviation of the mean, are improved in the latter case. Care must be taken to choose the correct cutoff frequency of the filter. A small cutoff frequency leads to signal delays that are too large for this relatively dynamic system. The optimum is found to lie around $0.2 < \omega_c < 0.5$.

3.2. Application to in-orbit data

The MEKF was applied FLP's in orbit measurements. This data included several periods without STR measurements, or only one STR providing data. This was due to blinding or high sensor noise preventing the STR's internal algorithm from finding a solution. The STRs are considered nearly exact for the purpose of analyzing the filter performance.

The result is shown in Figure 7 with two long periods without STR measurements, as well as brief gaps where a few samples are missing. The MEKF performs well.

DOI: 10.5821/conference-9788419184405.049

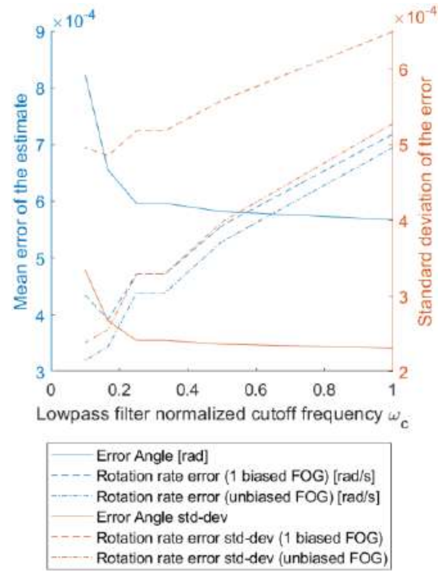

Figure 5: Error of the MEKF running at 10Hz depending on the cutoff frequency

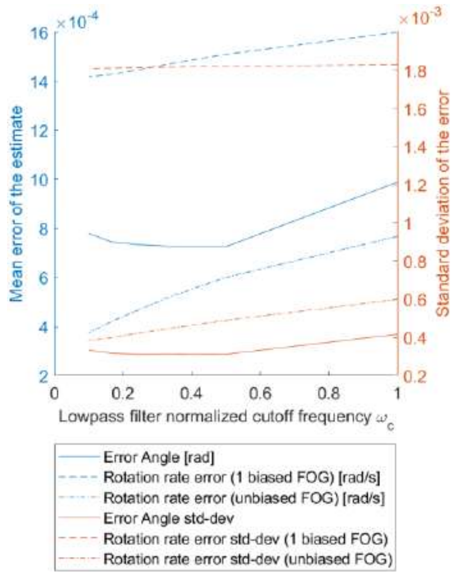

Figure 6: Error of the MEKF running at 5Hz depending on the cutoff frequency

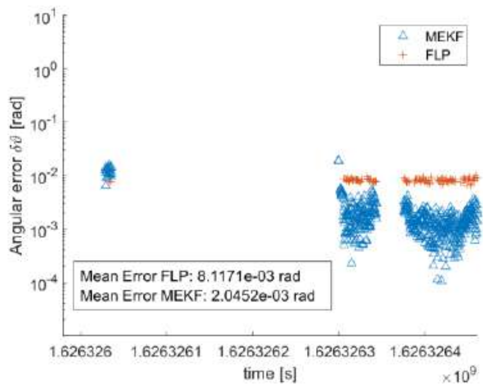

Figure 7: Error of the EKF running at 5Hz compared to the embedded FLP estimate using in-orbit STR and FOG data

3.3. Computational complexity

The required number of FLOPs was calculated theoretically [13]. The most expensive operations of the MEKF are the Kalman gain and the matrix exponential to propagate to the current. It is still more efficient than the old EKF, partially because the MEKF uses fewer measurement states. More iterations become necessary the longer the STR measurement is delayed. Both methods are equal for a STR delay of 2s, or 10 propagation steps [13].

4. Conclusions

A new sensor fusion algorithm was developed for FLP to try and improved its ACS based on a MEKF with a low pass filter to improve the filter robustness. Neither of the filters is quite able to reach the originally formulated required accuracy motivated by FLP's OSIRISv1 optical communications payload. However, the improved robustness should make communications more reliable. The new filter was shown to handle delayed and biased measurements in simulations, as well as missing measurements in real-world data from FLP. The low pass filter cutoff frequency needs to be optimized for the system and sensor parameters. Low pass filtering should only be combined with a Kalman filter if this enables the processing of additional measurements between two Kalman filter executions. The new MEKF it is advantageous in terms of FLOPs up to a STR measurement delay of 2s.

Acknowledgements

The first author would like to thank his co-authors for their support during the master thesis that laid the foundation for this paper.

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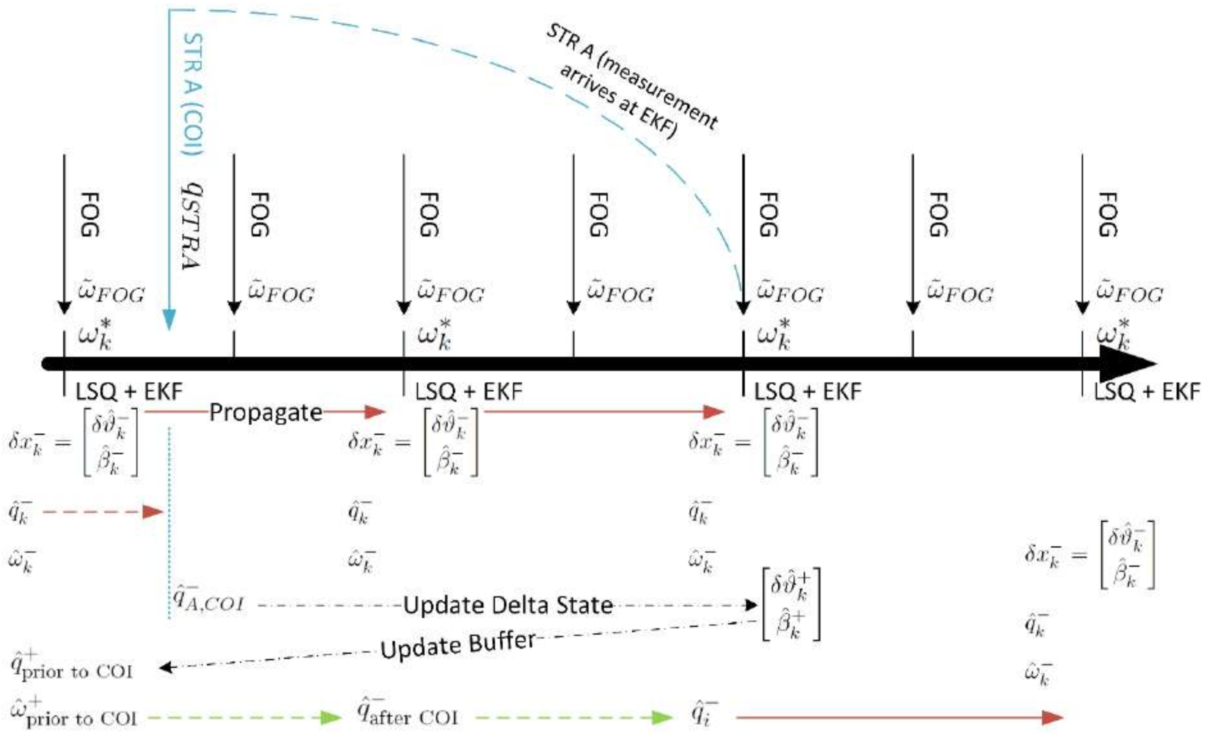

Figure 8: Schematic of the new algorithm with a single STR measurement

Space Communication System for Education

Anton Atanasov[1], *Viktor Danchev*[2]

Abstract

This article describes EnduroSat's Space Educational modules which are used to physically simulate radio wave communication in space applications for small satellite missions. The educational modules generate physical ultra high frequency radio waves and recreate the conditions of the environment. They can also simulate the effects of S-band and X-band frequencies by changing the losses accordingly while the physical simulation remains at ultra high frequencies. They are intended for practical hands-on exercises of students in the space communications sector. The modules utilize the same equipment currently used in space and are used to experimentally analyze the link budget, noises and error rate of signal. Simulating a given configuration of a satellite and ground station's parameters with them exposes the system's vulnerabilities and its reliability when transmitting signals. The system consists of two identical transceiver modules that can emit and receive information in the form of radio waves, and a free space propagation simulator module. Each of the modules connects via Universal Serial Bus to a host computer with the simulation software. In this paper we present the modules and some of their uses for education.

Keywords
Budget, Communication, Link, Satellite, Simulation

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Nomenclature

P_r	Power received
P_t	Power transmitted
G_t	Gain of the transmitter
G_r	Gain of the receiver
λ	Wavelength
r	Distance
π	Mathematical constant
E_b/N_0	Energy per bit per unit spectral noise density
L_s	Free space propagation loss
L_a	Additional signal losses
k_B	Boltzman's constant
T_s	Effective system temperature
R	Data transmission rate

Acronyms/Abbreviations

UHF	Ultra High Frequencies
PER	Packet Error Rate
BER	Bit Error Rate
GFSK	Gaussian Frequency-shift Keying
FSPS	Free Space Propagation Simulation
USB	Universal Serial Bus
CRC	Cyclic Redundancy Check

1. Introduction

The subject of this paper is EnduroSat's Space Communication System for Education modules, which are a part of the European InnoSpaceComm project. EnduroSat's Education modules work physically with ultra-high frequencies (UHF), S-band and X-band frequencies and simulate the conditions of space environment. They can be used to analyze the reliability of a space communication system with given parameters. The Education modules are developed with the intent to expand the space communications industry and academic fields. Simulating communication with a satellite can serve as a testing method to check the functionality of developing ground station and amateur satellite equipment. 50 of the modules were donated to universities to facilitate hands-on educational activities as part of the InnoSpaceComm project.

We have provided an example of how the modules can be used for education and how through a practical experiment students can acquire intuitive understanding of link budget, interference, Doppler shift. They will also be able to compare the empirical results with theoretically based expectations.

2. Equipment Description

As shown in Figure 1. the system consists of three modules. Two are identical transceiver modules that can emit and receive information in the form of radio waves. The third is a free space propagation simulator module that imitates the signal strength losses. Losses are caused due to the electromagnetic waves traveling in free space and the atmosphere, polarization mismatch and interference with external noises. The transceivers represent modern communication modules, used in CubeSat missions. They are additionally modified to be used for simulations on ground with standard interface connectors and adjusted for the purposes of education.

Figure 1. EnduroSat's Educational Communication System [1]

2.1. Capabilities

The transceiver modules can be set to different Gaussian Frequency-shift Keying (GFSK) modulation schemes ranging from 1200 to 19200 bits per second. The simulation parameters can be adjusted for transmission power between 27dBm, 28dBm and 31dBm. The actual power used is between -3dBm and 1dBm with the intent of minimizing radiation emission outside the modules for safety reasons. Except for the rate and power, the transmitter and receiver gain, carrier wave frequency, feeder loss and Doppler effect compensation can be configured. The modules' capabilities are in the UHF range between 430MHz and 450MHz with a tuning step of 10kHz. The modules generate radio waves via analog hardware – they are equipped with a micro controller unit that communicates the data send by the host computer to a radio frequency modulator chip and modulates it onto the carrier frequency, generated by the local oscillator. S-band and X-band frequencies are also hardware-simulated but are outside of the frequency range of the internal oscillator. The workaround method is the original signal being reprocessed with help from the software. This

DOI: 10.5821/conference-9788419184405.050

enables simulation in the 2GHz and 8GHz range link budget parameters while the actual RF signals remain in the UHF range.

Both transceiver modules are equipped with hardware for automatic frequency shift compensation. Frequency shifts in the simulations are caused by the simulated velocity between the transmitter and the receiver.

The free space propagation simulation (FSPS) module simulates the decay in radio signal strength throughout its propagation from a satellite transmitter to a ground station receiver. It substitutes the signal strength attenuation caused by free space path loss and the influence of the atmosphere, dependent on the signal wavelength. Those effects are achieved using hardware attenuators. Apart from electromagnetic propagation, losses caused by polarization mismatch and pointing inaccuracy on the receiver, Doppler shift, monochromatic wave interference, or a 20dB increase of background noise floor that can be simulated. This module is equipped with an additional coaxial port for connecting to external noise/interference generators for more realistic noise profiles in cases of jamming.

3. Working with the equipment

Each of the modules connects via Universal Serial Bus (USB) at a symbol rate of 115200 bits per second to a host computer with the simulation software, developed for the modules, installed. The modules are connected to eachother by coaxial cable. The modules simulate information transmission using radio waves from a satellite to a ground station on different frequencies and different parameters for power of transmission and receiver antenna gain. One of the transceiver modules is used with typical parameters to mimic a CubeSat in orbit, sending its data to a ground station. The second transceiver module is used as the receiver antenna and demodulator on the ground station. The third, FSPS module, is used to substitute the losses in signal strength that occur when the carrier wave travels the distance between a satellite in orbit and the station on ground. It represents the attenuation caused by atmospheric conditions but also the effects of Doppler shift, difference in polarization of the transmitter and receiver as well as noises and interference from external sources. Using the software, the user can adjust the system parameters separately for each module. A spectrogram can be used to visually display the shape of the signal in any stage of message transmission. It enables students to monitor the free space propagation losses, the effect of noise and external signal interference, which is especially useful in telecommunications and communication technologies studies.

4. Use for education

4.1. Link budget [2]

As the name suggests, this is simply a ”budget” which lets you know how much power is available versus how much power is needed with respect to a given noise - it is one of the most important quantities to consider. Link budget is performed iteratively in order to determine what antennas should be used and gives restrictions on frequencies, power, modulation scheme and signal readability. The procedure we are going to introduce will also allow us to evaluate the BER (Bit Error Rate) for the system under consideration and determine how to improve it if necessary.

Link Budget is calculated during the design phase of a communication system to determine the received signal to noise ratio from a given transmitted “budget”, after accounting all gains and losses. A high enough budget ensures the probability of errors in the received information is within some margin. The primary quantity in the link budget is the amount of power that is received with respect to the system noise (usually per unit bandwidth). Determining the link budget of a system will indicate what limitations it has, regarding the type of the antenna, frequency used, transmission power, modulation scheme and error checking method.

4.2. Antenna gain

To understand antennas, one needs to understand directivity [3]. It is determined by the radiation pattern of an antenna’s type and design parameters. Directivity is a property that describes the distribution of power radiated by an antenna in space. It represents the ratio of the amount of power radiated by an antenna in its direction of strongest emission to the power radiated by an isotropic antenna (which has an ideal spherical radiation pattern) with the same transmission power. The directivity is straightly proportional to an antenna’s gain, which is a key value in Link Budget. The gain describes how well antennas turn radio waves into electrical power or electrical signals to radio waves in a specific direction. Gain increases the amount of received or transmitted power. It is one of the most important parameters to consider in a communication system both on the receiver and transmitter antennas.

4.3. Why decibels

Knowing the output power and the gains of the antennas and taking into account all losses, we can estimate the amount of power that would be received on the other end of the system. This is done using Friis' equation of propagation [4].

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi r)^2} \tag{1}$$

Because the terms Friis' equation vary a lot in orders of magnitude, usually in telecommunication systems, the budget is expressed in decibels. This allows to substitute multiplication with very large and small values with addition and subtraction of smaller numbers in logarithmic scale. For this reason, equation (1) is frequently used in its decibel notation:

$$P_r(dBWs) = P_t + G_t + G_r - 10log_{10}\left(\frac{4\pi r}{\lambda}\right)^2 \tag{2}$$

The last term in equation (2) is referred to as the free space propagation loss. This is the reduction in power carried by the electromagnetic wave due to the distance it has traveled from its origin and depending on its wavelength. The received power returned by Friis' equation is the absolute power that is turned into electricity by the receiver antenna. Since a physical system is never perfect, it always has noise. Because of this, the reliability of the communication system is determined by the ratio of the received power to the noise power.

4.4. Powers and noises

To compare the signal strength to the strength of noises, the noise is mathematically substituted with an equivalent amount of thermal noise, also known as Nyquist-Johnson noise [5][6]. The thermal spectral density of that noise is constant per unit bandwidth and is equal to the product of Boltzmann's constant and some effective temperature in Kelvin. Knowing the absolute received power and the spectral noise density, we can compare them to estimate the error rate of the communication channel. This is the carrier-to-noise ratio of the system [7]. The carrier-to-noise ratio is expressed by the total power received, given by the Friis' equation (2), divided by the noise spectral density and the bandwidth of that channel, where high ratios correspond to low error rates. The error rate of each one bit in a message is directly connected the energy per bit per unit spectral density (E_b/N_0), as represented by the following equation:

$$\frac{E_b}{N_0} = \frac{P_t G_t G_r \lambda^2}{(4\pi r)^2 L_a k_B T_s R} \tag{3}$$

As described in section 4.3, equation (3) is converted into decibel notation:

$$\frac{E_b}{N_0} = G_t + P_t + \frac{G_r}{T_s} - L_s - L_a + 10log_{10}k_B - 10log_{10}R, \tag{4}$$

where the less energy a bit carries, the higher its probability of error. The type of modulation and error checking method determines the impact the signal to noise ratio that any one bit has on the error rate of a whole transmitted message.

4.5. Margins

Typically, a telecommunication system has some requirement on the bit error rate, depending on its application, which defines a required E_b/N_0 ratio. In terms of decibels, positive values indicate the bit error rate is lower than the required amount and negative values denote that the system needs improvement in order to fit the required link margin. In this case, the parameters of the antennas, transmitter, receiver, modulation, etc. must be adjusted to guarantee the required link reliability.

5. Results

5.1. Experiment results compared to expectations from theory

Link budget is an important concept that is dependent on various parameters. Because of that, it can pose a difficulty in the introduction to communication technologies. Simulations done using the Space Educational Modules can ease this process by revealing the impact of different parameters on link budget in real time. They also contribute the opportunity for comparing theoretical expectations with empirical observations of real ground station to satellite communication systems.

5.2. Effects of Doppler shift

The Doppler shift depends on the relative speed between the satellite and the ground station, which changes over time and also with the type of orbit. At higher frequencies such as UHF, the effect of Doppler shift can alter the carrier frequency and offset it outside of the receiver's range and this has to be compensated. Simulations done using the modules demonstrate how the shift of frequency affects the PER both with and without automatic frequency compensation. Figure 2. displays how frequency compensation automatically adjusts the receiver's frequency and reliably locks on to signals with a maximum deviation of 11.7kHz at 4800Hz frequency deviation, which is comparable to the signal bandwidth. Signals immediately outside of that range are lost. Such high frequency shifts occur at low elevation angles during satellite passes from low Earth orbit, since small altitudes correlate to higher amounts of Doppler shift.

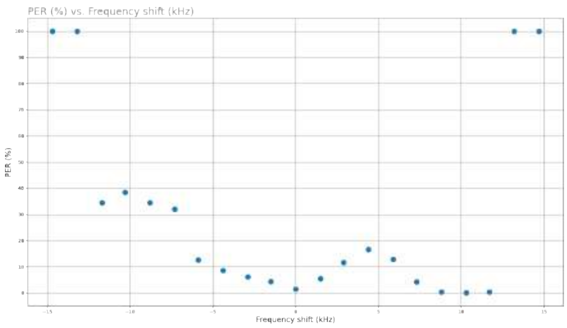

Figure 2. Doppler shift with frequency compensation

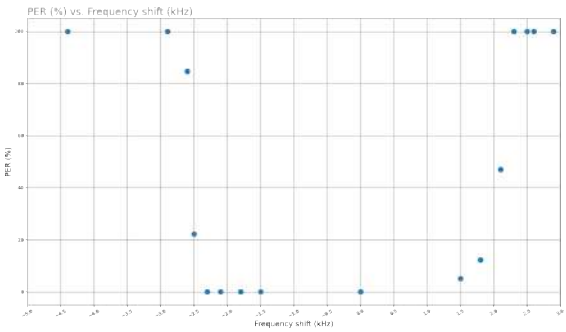

Figure 3. Doppler shift without frequency compensation

Figure 3. shows a setup without automatic frequency compensation, where the receiver is only at the base frequency. In the second setup, the receiver starts reading signals with a deviation of up to 2.9kHz with high PER. The reliability increases when the received frequency approaches the base frequency. When the shift is lower than half the frequency deviation of the modulation scheme (in this case ½*4800Hz), the losses due to Doppler effect are negligible.

5.3. Effects of external noise and sensitivity to interference

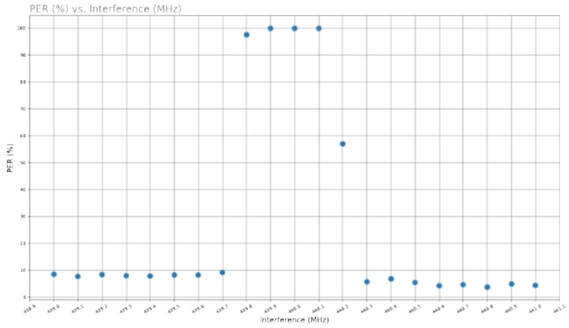

Figure 4. Packet loss to interference

External noise can directly increase the BER of a signal since it means a higher noise spectral density. Interference with the same intensity can cause from increase of error rate to complete signal loss, depending on the frequency. The closer the interference frequency is to the carrier frequency, the more of the channel's bandwidth is overlapped by the interference wave and its information is lost. The graph demonstrates that when the difference between the interference frequency and the carrier frequency is close to the frequency deviation of the modulation scheme (between 439.8MHz and 440.2MHz), almost all of the information is lost.

5.4. Receiver and transmitter gain

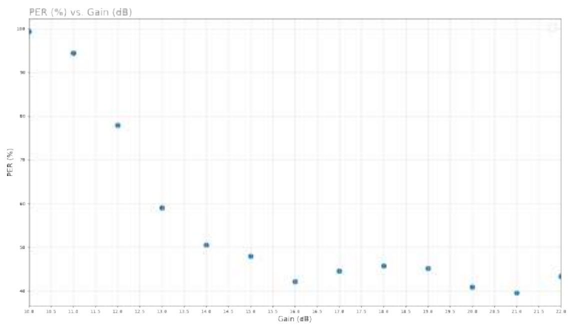

Figure 5. Packet loss and gain

Higher gain is directly proportional to the amount of power that is radiated in the proper direction by the transmitter or the amount of power that the receiver turns an electromagnetic wave into. Therefore, the received power is proportional to the gain. Higher power correlates to a higher signal-to-noise ratio. Consequently, a link with higher gains will transfer information with lower error rate, and this is exactly what is observed in measurements done using the modules.

DOI: 10.5821/conference-9788419184405.050

5.5. *Results*

The software performs a simulation with the specified parameters. The transmitter module streams a sequence of a given number of packets with information (random bits), after which the simulation is over. The software keeps track of the number of received packets and the count of bit errors, caused by the signal being altered in the FSPS module. The bit error rate (BER) is tracked by the program and is directly reflected on the PER displayed value where corrupted bits cannot be corrected by the packet's cyclic redundancy check (CRC).

6. Discussion

With the introduction of space practice to the education programs, the access to space will increase significantly. This will speed up development in the space industry, allowing mankind to progress towards its goal of space exploration. Producing communication systems for space often involves problems without pure analytical solutions, where simulations solve this issue. Simulating the system's performance in the target environment is a utile tool for determining the system's vulnerabilities and its reliability by monitoring the PER in given scenarios. The Space Communication System for Education modules closely represent the equipment already used in standard CubeSat missions and precisely imitate their use conditions. They serve as a suitable method to study communication systems in the classroom and in the lab.

7. Conclusions

The education modules serve as a tool for simulating a satellite and ground station system. Their use is a method for strengthening student's knowledge of link budget through actual measurement and comparison between theory and reality. This is an exceptionally useful tool for enthusiasts who are looking to build their own ground station in order to analyze their system requirements as well as for universities aiming to launch CubeSats for education purposes.

Acknowledgements

The authors would like to thank EnduroSat's InnoSpaceComm project which has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 768049. The educational modules used in the experiments have been donated as part of the project's outreach activities. V. D. would like to thank Radostina Avramova and Vanya Buchova for their significant contribution in the development of the InnoSpaceComm educational content. Thanks should also go to project MASRI - Infrastructure for sustainable development of marine research and participation in the European research and participation in the European infrastructure EURO-ARGO-MASRI for developing the methodology for working with the Space Communication System for Education modules, considering that the proposed communication modules take part in the MASRI project in the domain of education, their function establishing and operating virtual and physical training systems.

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ESA Academy's Orbit Your Thesis! programme

Joost Vanreusel[1], *Nigel Savage*[2], *Jeffrey Gorissen*[3]

Abstract

ESA Academy is the European Space Agency's overarching educational programme for university students. It takes them through a learning path that complements their academic education by offering a tailored transfer of space knowledge and interaction with space professionals. As a result, students can enhance their skills, boost their motivation and ambitions, and become acquainted with the standard professional practices in the space sector. This happens through the two pillars of ESA Academy, the Training and Learning Programme and the Hands-on Programmes. The latter enables university students to gain first-hand, end-to-end experience of space-related projects.

One of the latest additions to the portfolio of opportunities for university students is "Orbit Your Thesis!". It offers bachelor, master, and PhD students the opportunity to design, build, test, and operate their experiment onboard the International Space Station. The experiment operates within the ICE Cubes Facility in ESA's Columbus module, where it can operate for up to four months in microgravity. Throughout the programme students develop essential scientific, academic, and professional skills that will help them build their future careers. These skills include project management, risk identification and mitigation, problem-solving, and working within a diverse workplace. Participating teams will experience first-hand the project management process for space missions and participate in multiple reviews of their experiment and design throughout the programme.

Participating students are supported and guided through the process by engineers and scientists from ESA, Space Applications Services, and members of the European Low Gravity Research Association. The programme schedule follows a similar path to many space-faring projects. The design, development, testing, launch preparation and operations are structured in a series of project phases and technical reviews. Participating teams are guided towards the subsequent milestones to pass the necessary safety reviews and achieve launch readiness.

The first team that successfully sent up their ICE Cube is OSCAR-QUBE, a multidisciplinary team from the University of Hasselt in Belgium. Their experiment is the first diamond-based quantum magnetometer that ever operated in space. Thanks to the unique characteristics of their sensor, they have been mapping the Earth's magnetic field from inside the Columbus module aboard the ISS without the need to be housed on the exterior. This paper will describe the various phases and technical aspects of the programme in more detail.

Keywords

Academy, ESA, Hands-on, ISS, Microgravity

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Acronyms/Abbreviations

AIM	*Artery In Microgravity*
ATV	*Automated Transfer Vehicle*
CDP	*Critical Design Phase*
CR	*Cargo Review*
ECSS	*European Cooperation for Space Standardization*
EFSDP	*Experiment Flight Safety Data Package*
ELGRA	*European Low Gravity Research Association*
ERA	*European Robotic Arm*
ESA	*European Space Agency*
ESTEC	*European Space Research and Technology Centre*
FAR	*Flight Acceptance Review*
FSR	*Flight Safety Review*
ICF	*ICE Cubes Facility*
ICMCC	*ICE Cubes Mission Control Centre*
ISS	*International Space Station*
OYT	*Orbit Your Thesis!*
OSCAR-QUBE	*Optical Sensors based on CARbon materials: QUantum BElgium*
PDP	*Preliminary Design Phase*
RID	*Review Item Discrepancy*
UHB	*User Home Base*

1. Introduction

The International Space Station (ISS), with a weight of 420 tonnes and a pressurised volume of 916 m^3, is the world's most expensive international project. The construction of the ISS started in 1998 and grew over the years to its current size [1]. It gained a plethora of modules, robotic arms, and laboratory equipment. Most notable European contributions are the European Robotic Arm (ERA) [2], Cupola [3], the Automated Transfer Vehicles (ATV) [4], and the Columbus module [5].

The Columbus module is home to many experiments aboard the ISS, as it acts as Europe's permanent research facility in space. Europe's most significant contribution to the ISS features state-of-the-art equipment and allows external platforms to support various experiments. Within its 75 m^3 of space, the Columbus laboratory houses ten standardised racks capable of providing power, data, and cooling systems [5]. Aside from ESA payloads such as Biolab [6], the Fluid Science Laboratory [7], and the European Physiology Modules Facility [8], it also offers room for commercial partners and payloads such as the ICE Cubes Facility (ICF).

The ICE Cubes Facility is a commercial European research facility operated by Space Applications Services aboard the ISS [9]. The facility offers a total capacity of up to 20 units, based on the ten-centimetre cube standard, one unit, and provides communication, power, and cooling. This offers unprecedented timescales when compared to standalone CubeSats, "From idea to reality in a year, anybody's experiment can be launched to the Space Station" [10].

Within ESA Education, the ESA Academy's hands-on programmes offer gravity-related research platforms for university students. The addition of Orbit Your Thesis! (OYT) meant that a gap in the portfolio got filled [11]. The need for this programme manifested most notably for experiment proposals where the duration of microgravity was of paramount importance. Parabolic flights offer up to 22 seconds of microgravity [12], while access to the ISS enables weeks to months of microgravity exposure with a substantial increase in its quality.

For the students to maximise their educational experience in a professional setting, the programme's philosophy is to adopt the same approach as any space-faring project. This is done by using the European Cooperation for Space Standardization standards. However, these standards are geared towards the students and are thus less strictly applied, leading to a light, adapted version mimicking industry-accepted ECSS standards.

The students are encouraged to form multidisciplinary teams with skills spanning disciplines such as software, electronics, science and mechanical engineering.

2. ISS and Ice Cubes Facility environment

The ISS provides an environment of microgravity averaging at 10^{-6}g during nominal operations for a potentially unlimited amount of time in a pressurised (1bar) environment. The

ICF hosts experiment cubes within the ISS and maintains the temperature between 20 and 25 degrees Celsius [13].

The available electrical interfaces provide GND, +5 V, and +12 V. The +5 V line can deliver up to 1 A of current (5 W max), and the +12 V line can deliver up to 3.1 A of current (37.2 W max). However, the maximum power an experiment can use for preliminary design purposes is 10 W per unit [13].

The communication with IP-enabled cubes happens through an Ethernet connection. The maximum data rates for the entire ICF are 4Mbps for downlink and 0.5Mbps for uplink [13].

3. Benefits of ESA Academy

ESA Academy provides expert training in crucial topics including but not limited to requirement definition, risk and project management, systems engineering, space structures and software architecture, verification and validation, environmental testing and outreach/communication workshops. With this knowledge, student teams begin their project with all the necessary tools to complete the programme successfully.

ESA Academy conducts regular meetings with the teams to monitor progress and guide the students throughout the various phases of their project. In line with ECSS practice, ESA Academy also conducts reviews during Phases C, D and E. Each Phase begins with an introduction of expectations and success criteria thus anticipating potential misunderstandings and project derailment.

Additional assistance is also given by payload engineers from Space Applications Services particularly with respect to interfaces with the Ice Cubes Facility and ISS safety aspects. For scientific insight, ELGRA provides services for review of applications but also dedicated mentorship once teams are selected.

Some costs of student travel and accommodation during test campaigns are also absorbed by ESA Academy, and in general test campaigns performed at ESA premises such as ESEC-Galaxia for the vibration test campaign are also covered by ESA Academy. Thus, the team may focus all their efforts on raising funds for hardware through external sponsorship and university sources.

4. Schedule

Being a student driven project with the aim of being initiated and completed by the same team of students, the project must fit in an academic schedule and therefore not exceed 2 years. Within this relatively short time frame, ESA Academy must deliver an authentic industry-level space project. To this effect the ECSS-driven schedule can be split up into five main parts with defined time frames despite the fact that at the start of the OYT programme, some dates, such as the launch date, may be tentative. These parts are selection, design and development, launch, operations and disposal/retrieval and data analysis.

4.1 Selection (~14 weeks)

It is expected that before selection, teams perform Phase A analyses, as per the ECSS, at their institute and join the programme only at Phase B. This ensures that the feasibility assessments and preliminary requirements definitions are in line with the platform and programme requirements.

Upon submission of an experiment proposal using provided templates, teams elaborate on their team composition and the academic supervisor who will endorse their project. ESA Academy advocates multidisciplinary teams with complementary skills and backgrounds to increase chances of success. The experiment proposal also provides detailed scientific and technical details, programmatic milestones, and basic management information which gives the selection panel sufficient information to judge the proposal on several aspects. ESA Academy also encourages projects that are in line with ESA exploration or technical roadmaps. In addition to the experiment proposal, the team is also expected to deliver an Experiment Flight Safety Data Package (EFSDP), indicating to the board if the experiment can be safely executed on the ISS.

Shortlisting of student proposals is done by a selection board hosted by ESA Academy and a selection of industry experts. All eligible teams that show knowledge of the subject and prove their compatibility with the ICF are shortlisted during this process.

After the shortlisting, the teams are invited to participate in a selection meeting organised at ESA's European Space Research and Technology Centre (ESTEC) in Noordwijk, the Netherlands. This meeting allows the students

DOI: 10.5821/conference-9788419184405.051

to present their projects to the selection board. This allows the students to perfect their presentations skills in an international and interdisciplinary setting. The board is composed of three large main groups.

- The engineers and scientists from Space Applications Services; will review the experiment based on safety aspects and feasibility.
- ESA specialists from Human Spaceflight and Robotic Exploration and ESA Education Office; investigate the scientific or technological relevance and educational return of the project.
- Members of the European Low Gravity Research Association (ELGRA); focus on the scientific and technology achievements for the respective field of research.

4.2 Design and Development (~20 weeks)

Soon after selection, the team(s) are given expert training on topics mentioned above, after which the students may begin to develop and refine the design of their experiment. Within this stage, three ECSS Phases can be observed. The Preliminary Design Phase (Phase B), Critical Design Phase (Phase C), and the Qualification and Production phase (Phase D). Phase D encompasses all the environmental tests and functional tests which give confidence that the hardware is ready to survive the launch environment, and to operate on the ISS (see Figure 1 & 2).

Figure 1. OSCAR-QUBE in the Ice Cubes Facility ground model

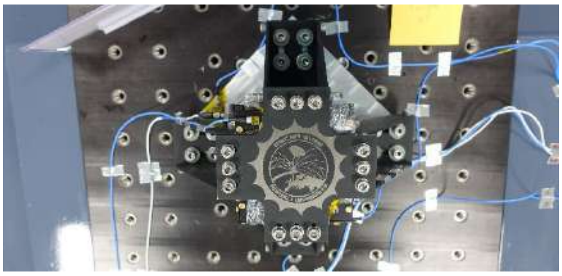

Figure 2. OSCAR-QUBE vibration testing

Each phase concludes with the associated data package submission by the team. For a successful transition to the next phase of the schedule, the teams must pass a Preliminary Design Review (PDR- Phase B), a Critical Design Review (CDR – Phase C) and finally a Flight Acceptance Review (FAR- Phase D). The reviews are conducted by the experts from the selection board and any experts pertinent to the payload. In parallel a series of Flight Safety Reviews (FSR) occurs to ensure that the development of the payload remains safe for operational use on the ISS.

4.3 Launch Campaign (~6 weeks)

When the team pass the Flight Acceptance Review, the hardware is shipped to ALTEC in Turin, Italy. Here a final cargo review (CR) is performed to check proper packaging, labelling and outwardly appearance before the experiment Cube is sent to the launch site and integrated into the launch vehicle.

4.4 Operations, retrieval/disposal (~16 weeks)

After launch and berthing, the experiment is removed from the vehicle and is installed in the ICF (Figure 3 & 4). The ICE Cubes Mission Control Centre (ICMCC) based at Space Applications Services, in Belgium, subsequently activates the experiment. The control is then passed to the students who can operate their experiment from their User Home Base (UHB) according to their predefined operations plan.

After, typically, four months in orbit, the experiment cube is removed from the ICF and disposed of through destructive re-entry of a cargo vehicle or returned intact for further analysis. Data can also be stored on removable media and be sent back to the team using the next available return vehicle.

Figure 3. OSCAR-QUBE in the Columbus module


Figure 4. OSCAR-QUBE in the Ice Cubes Facility

4.5 Data Analysis (~16 weeks)

Using the OYT programme, the team is expected to draft a scientific paper for publication in a peer-reviewed journal and present its findings at an international congress. For archival purposes in line with ESA mandate, the students will enter all their OYT information into a database repository. This will include all the raw data, analysed results and conclusions from the project.

5. Requirements

Students willing to participate in the OYT programme must fulfil some eligibility criteria. They need to be citizens of either an ESA member state or be a citizen of Canada, Latvia, Lithuania or Slovenia. It is also required that the field of study is focussed on a scientific or engineering subject.

At least one of the students within the team is required to have the experiment as an integral part of their thesis. This can be a master's thesis, PhD thesis, research programme, or a project course supported by the applying students at their university.

Application is only possible if the students can prove their university's support through a letter of endorsement, from the academic supervisor(s).

To participate, at least six team members should fulfil the eligibility criteria. The upper limit of participants is limited by the experiment requirements.

It is highly recommended for purposes of knowledge management to have one or more PhD students in the team as the timeline of this project spans over more than one academic year.

To participate, a team must finally be supported by an endorsing professor, a team leader and/or a system engineer.

6. Discussion and Conclusions

So far, two teams have participated in the programme; OYT-1 Artery In Microgravity (AIM) from ISAE-SUPAERO (FR) and Politecnico di Torino (IT) and OYT-2 Optical Sensors based on CARbon materials: QUantum BElgium (OSCAR-QUBE) from University of Hasselt (BE). Team AIM will launch to the ISS June 2022, and team OSCAR-QUBE have been on board since August 2021. Currently, the OSCAR-QUBE experiment is still gathering data in orbit.

Both teams provided positive feedback in their participation in Orbit Your Thesis, from the educational nature of the programme but also in the form factor as the platform proves to be suitable for student experimentation. In addition, the schedule of the programme is particularly favourable for academic research and projects whilst also remaining very flexible. The opportunity to work on a project that is operated on the International Space Station during university studies provides several competitive advantages to participants as they become young professionals and enter the job market.

The third cycle will soon pick up pace once a team has been selected and it is envisaged that ESA Academy will continue to offer the educational programme.

Acknowledgements

ESA Academy would like to acknowledge Space Applications Services, ELGRA and ESA HRE directorate colleagues for assisting in the programme operations.

For the images, credit goes to Jeffrey Gorissen for Figure 1, to ESA for Figure 2, and to ESA/NASA for Figures 3 & 4.

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Update on the status of the Educational Irish Research Satellite (EIRSAT-1)

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Abstract

The Educational Irish Research Satellite, EIRSAT-1, is a 2U CubeSat being implemented by a student-led team at University College Dublin, as part of the 2nd round of the European Space Agency's Fly Your Satellite! programme. In development since 2017, the mission has several scientific, technological and outreach goals. It will fly an in-house developed antenna deployment module, along with three custom payloads, which are integrated with commercial off-the-shelf subsystems.

In preparation for the flight model, a full-system engineering qualification model of the spacecraft has undergone an extensive period of test campaigns, including full functional tests, a mission test, and environmental testing at the European Space Agency's CubeSat Support Facility in Redu, Belgium.

Beyond the technical, educational, and capacity-building goals of the mission, EIRSAT-1 aims to inspire wider study of STEM subjects, while highlighting the importance of multidisciplinary teams and creating greater awareness of space in everyday life. A wide range of outreach activities are being undertaken to realise these aims.

This paper provides a status update on key aspects of the EIRSAT-1 project and the next steps towards launch.

Keywords

EIRSAT-1, CubeSat, Fly Your Satellite!

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1. Introduction to EIRSAT-1

EIRSAT-1 is a 2U CubeSat under development by a student-led team at University College Dublin (UCD) [1]. The mission, which is Ireland's first satellite, is supported by the 2nd edition of the European Space Agency (ESA) Fly Your Satellite! (FYS!) programme.

EIRSAT-1's fundamental objectives are educational [1]. However, additional scientific and technology demonstration goals are also being achieved with three novel payloads, known as GMOD [2, 3], EMOD [4] and WBC [5]. In addition to custom-built payloads, EIRSAT-1 (Figure 1), will fly an in-house developed antenna deployment module (ADM) [6] and commercial-off-the-shelf (COTS) components. To reduce risk and build expertise on spacecraft development within the team, two separate models of EIRSAT-1 are being built – an engineering qualification model (EQM) and a near-identical flight model (FM).

In this paper we provide an update on the status of the EIRSAT-1 project with particular emphasis on the EQM. Given the project's educational objectives, the team's outreach activities are also discussed. Finally, the remaining steps towards a 'ticket to launch' will be discussed. In addition to providing a project update, this work also gives insight into the lifecycle of a CubeSat project participating in ESA's FYS! programme, the 4th edition of which was announced in October 2021. While not explicitly discussed in this work, we note that the project timeline has been impacted by the COVID-19 pandemic as on-site working, travel and access to test facilities were highly restricted throughout 2020/21.

2. Building the EQM

Following selection to the FYS! programme in May 2017, the EIRSAT-1 mission design was subject to a critical design review (CDR). As part of this review, detailed documentation (spanning hundreds of pages across several documents) was produced and then reviewed by the FYS! team as well as ESA experts. After several review cycles, the successful close-out of this CDR was announced in September 2018, allowing the EIRSAT-1 team to proceed with more hands-on development of the EQM.

2.1. EIRFLAT-1

The EQM parts of EIRSAT-1 were initially assembled on a FlatSat [7], in which the satellite is assembled on a large motherboard or series of motherboards laid out horizontally.
Over the course of several months, the FlatSat was fully populated, as COTS components were received and acceptance tested, and as custom-built payloads were developed, tested and space qualified [8, 9, 10]. This FlatSat was then subject to a functional test campaign, for which formal test documentation was specifically developed. Although FlatSat-level testing to this extent is not a requirement of FYS! 2, this testing was carried out to reduce risk by ensuring key functions of the spacecraft's subsystems work reliably as a complete system prior to final integration. This testing was found to be an invaluable learning experience for the team, with largely successful results [11].

2.2. EIRSAT-1

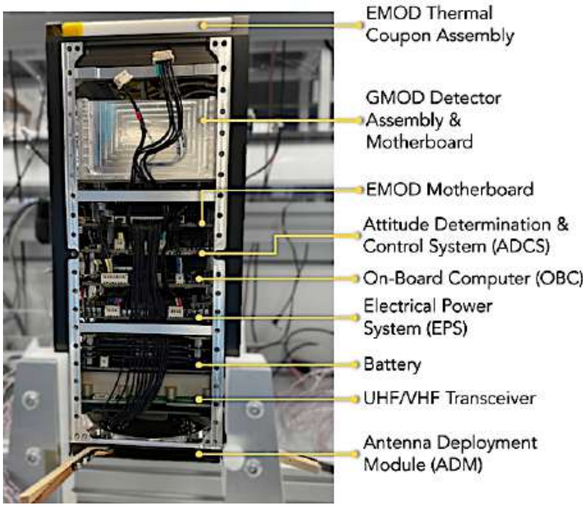

Figure 1. Stacked configuration of the EQM, showing EIRSAT-1's sub-systems and payloads.

In November 2020, the EQM components were integrated in a stacked configuration. A time-lapse demonstrating this integration process can be found here:

https://www.esa.int/ESA_Multimedia/Videos/2019/04/EIRSAT-1_team_integrating_their_CubeSat

3. Testing the EQM

Once built, the EQM underwent a series of rigorous tests to verify that the spacecraft can satisfy the mission requirements, which were defined during CDR, and survive the extremes of spaceflight while doing so.

3.1. Ambient Testing

3.1.1. Functional Testing

Extensive, functional tests were carried out on the EQM, starting in December 2020 [11]. Unlike the FlatSat tests, full system-level functional testing is required by all teams within the FYS! 2 programme.

DOI: 10.5821/conference-9788419184405.052

This testing continued until July 2021, longer than planned, due to four test anomalies (i.e., unexpected events that can lead to a test failure). Two of the anomalies, related to the ADM, were classified as major due to the associated risk to antenna deployment on-orbit. A redesign of the ADM was ultimately required. Following this redesign and its installation into the EQM stack, the relevant functional tests were repeated and passed [11].
While these test anomalies impacted the project schedule, the comprehensive functional testing performed was successful in identifying and mitigating critical risks to mission success that were not previously known and justified the model philosophy adopted, despite the additional time and resources required.

3.1.2. Mission Testing

A mission test is a long duration, flight-representative test in which realistic aspects of on-orbit operations are simulated in the expected in-flight sequence, starting from launch. This testing is also required within FYS! 2, and provides further confidence in the ability of the system to perform its intended mission on-orbit.
The EQM mission test began in early August 2021 (Figure 2) and ran for 27 days continuously [12].

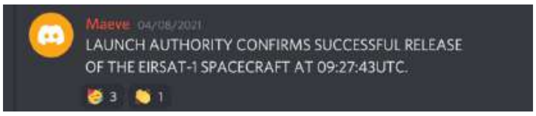

Figure 2. 'Launch' notification during EIRSAT-1's EQM mission testing.

Team members took on the role of 'spacecraft operator', acting within the constraints of real on-orbit operations (e.g., limited 2-way communication passes) to control the mission. In contrast to other tests, where activities are often suspended due to an anomaly, in this test, the operators were required to work through anomalies as part of the mission test simulation. This approach tests the mission's ability to manage faults and recover nominal operations. The EQM mission test was largely a success in terms of achieving the predefined test objectives. The team also gained valuable operations experience through the simulation [12].

3.2. Environmental Testing

While all ambient testing was performed in ISO class 8 cleanrooms at UCD, adequate facilities for environmental testing, required as part of FYS! 2, were not available locally. Therefore, in September 2021 the team travelled with the EQM to ESA's CubeSat Support Facility (CSF) in Belgium for vibration and thermal-vacuum (TVAC) testing [13].

3.2.1. Vibration Testing

Prior to testing, the EQM was integrated into a flight representative model of a 3U CubeSat deployer (Figure 3), along with a mass model of a 1U CubeSat.

Figure 3. Integration of the EQM into a representative model of a CubeSat deployer.

The deployer was then mounted on an electrodynamic shaker table (Figure 4).

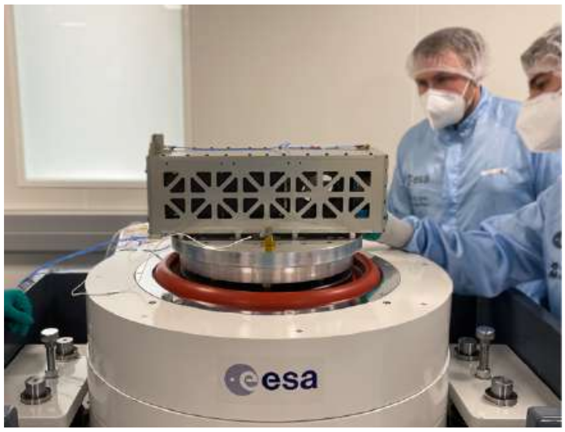

Figure 4. CubeSat deployer, containing the EQM, mounted on the shaker table.

Starting on 16th September, vibration tests were carried out, where each axis of the spacecraft was tested separately. Each axis experienced a random vibration level of 14g (RMS), exceeding those expected during launch of EIRSAT-1, for a period of ~2 minutes. This testing, which involved some data analysis as well as changes to the test set-up between axes, continued until 20th September, after which the EQM was removed from the test set-up and a health check performed.
The health check (essentially a reduced functional test that had also been completed

DOI: 10.5821/conference-9788419184405.052

pre-test) proved that all critical subsystems (i.e. EPS, battery, OBC and radio) had survived the launch-like vibrations. The reduced functional test also revealed anomalous behaviour from the GMOD payload. On-site investigations suggested that some hardware damage to the payload was the likely cause of the observed behaviour (Section 4).

3.2.2. TVAC Testing

Although hardware damage to GMOD was suspected following vibration, the payload was still operational (e.g., it was capable of I2C communications with the OBC) so the decision was made to continue environmental testing. Therefore, on 27th September, the EQM was integrated into the CSF's TVAC chamber (Figure 5). The EQM was suspended in the chamber to ensure thermal isolation. Umbilical cables and thermocouples allowed communication with and monitoring of the EQM while in this test set-up.

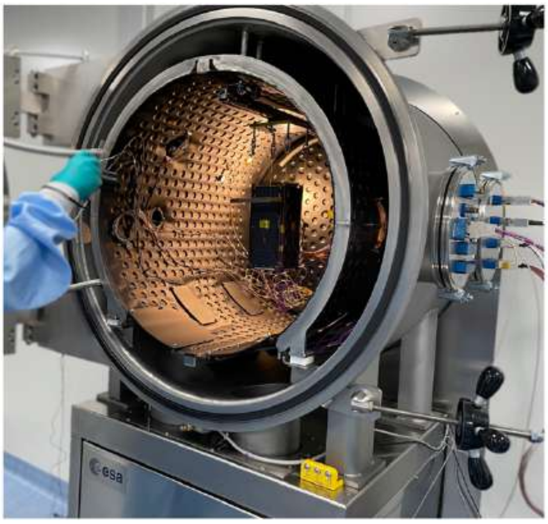

Figure 5. EQM integrated in the TVAC chamber.

During TVAC testing, the spacecraft was subjected to a vacuum of ~10^{-6} mbar, and temperatures ranging from −26°C to +56°C, while powered off, and −26 °C and +36.5 °C, while powered on [14]. When powered on, health checks were performed to ensure all subsystems functioned nominally under TVAC conditions.

Excluding GMOD (for which health checks were modified to better assess the scope of the damage experienced during vibration testing), the EQM largely performed as expected throughout TVAC testing, providing confidence that the EIRSAT-1 spacecraft can survive the space environment. Minor anomalies that were encountered were either related to the test set-up or functions of the flight software which were impacted by the temperature conditions [14]. Crucially, the latter would likely not have been detected prior to launch without TVAC testing.

The EQM test campaign concluded on 15th October 2021 [13].

4. Road to Flight

Since concluding the EQM test campaign, the team's priority has been generating non-conformance reports (NCRs) which document anomalies experienced during the campaign, suggest a root cause and, if required, propose mitigating solutions going forward. NCRs are then reviewed by FYS!, with input from ESA experts, and eventually closed when the anomaly is well understood and/or the mitigating solutions are satisfactory.

The major NCR related to GMOD has required capacitors to be replaced and the provision of additional mechanical support following investigations which showed a capacitor solder joint was damaged during vibration testing. Once all NCRs are closed (or on track to close), the FM build will commence (Figure 6).

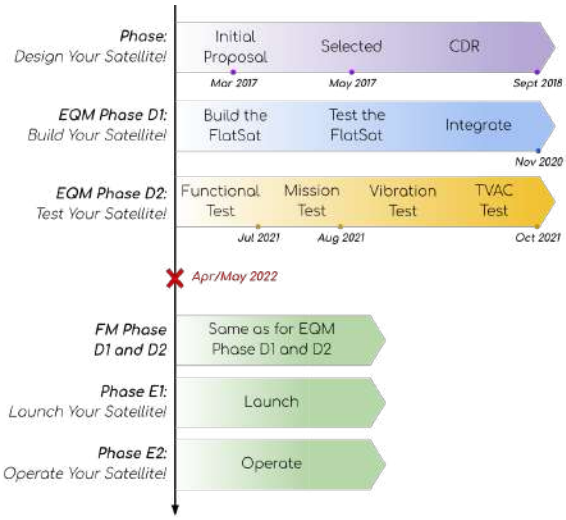

Figure 6. EIRSAT-1's project schedule.

In addition to EIRSAT-1, three other CubeSat teams are currently participating in FYS! 2 – LEDSAT, 3Cat-4 and ISTSat-1. LEDSAT was launched in August 2021 and is still in operation. 3Cat-4 and ISTSat-1 are in the process of preparing for launch in late-2022 [15].

5. Outreach & Dissemination

The EIRSAT-1 team primarily consists of students undertaking a masters or PhD, either as part of a module or as a more integral part of their degree, where the work forms part of their thesis. Information about the project is therefore

DOI: 10.5821/conference-9788419184405.052

regularly disseminated via conferences and publications. Involving a wider audience beyond academia is a key objective of EIRSAT-1. Not only do we want to inspire the next generation of students towards the study of STEM, but we also emphasise the key message that space is for everyone. The team has therefore undertaken a broad range of outreach activities (Figure 7) [16].

5.1. Talks

Team members frequently give talks at both primary and secondary level schools, as well as during themed events such as Space Week or National Science Week. During the pandemic, these talks have continued virtually.

5.2. Social Media

Updates on the status of the project and the team's activities are provided on the website (www.eirsat1.ie) and on social media, including Twitter, Facebook and Instagram (@EIRSAT1).

5.3. Informational Materials

The project has produced a range of engaging informational materials that are available on the EIRSAT-1 website, including:

- A brochure describing the team and their backgrounds for use during National Space Week careers roadshows for secondary school students: https://www.eirsat1.ie/post/eirsat-1-brochure
- A YouTube video: https://www.youtube.com/watch?v=EJqQdU4DNkY
- A comic book for 9-10 year olds that has been distributed to every primary school in Ireland: https://www.eirsat1.ie/comicbook

5.4. Other

- *10 Things to Know About*

Throughout the project, EIRSAT-1 has gained attention from many national media outlets. For example, in addition to online and newspaper articles, EIRSAT-1 featured in '10 Things to Know About', a TV series produced by Ireland's national broadcaster, RTE.

- *Space Poem and Space Art Challenge*

In 2021, two online outreach activities were held, aimed at secondary school students, and focused on art and poetry. In both cases, students' creative works were showcased on the EIRSAT-1 social media accounts. The space poem was co-created by school pupils from diverse backgrounds, in collaboration with the JCSP library demonstration project, UCD creative writers and the Museum of Literature Ireland. The space-themed poem, called 'All Ways Home', will be etched onto the EIRSAT-1 FM.

6. Conclusions

Following the EQM test campaign, the project now advances to the FM, a significant step towards launch. Building on the outreach efforts, public engagement will continue to be a major feature during the upcoming milestones.

Acknowledgements

The authors acknowledge all students who have contributed to the EIRSAT-1 project. EIRSAT-1 is supported by ESA's Education Office under the FYS! 2 programme. MD, DM, JT, RD and LS acknowledge support from the

Figure 7. Examples of EIRSAT-1's outreach activities taken from the @EIRSAT1 social media accounts.

Irish Research Council under grants GOIPG/2018/2564, GOIPG/2014/453, GOIPG/2014/684, GOIPG/2019/2033 and GOIPG/2017/1525, respectively. GF acknowledges support from a scholarship associated with the UCD Ad Astra fellowship programme. DM, AU, JM and SMcB acknowledge support from Science Foundation Ireland (SFI) under grant 17/CDA/4723. SW acknowledges support from ESA under PRODEX contract number 400012071. JE and JR acknowledge scholarships from the UCD School of Physics. FM acknowledges support from the UCD School of Computer Science. LH acknowledges support from SFI under grant 19/FFP/6777 and support from EU H2020 AHEAD2020 project (grant agreement 871158). This study was supported by ESA's Science Programme under contract 4000104771/ 11/NL/CBi and by ESA's PRODEX Programme under contract number C 4000124425.

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Establishing Thriving University-Level Space Education

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Abstract
Recent analyses of the UK National Space Strategy [1], Space Sector Skills Survey [2] and The 2020 Space Census [3], have investigated and highlighted many of the established strengths and weaknesses of the current UK Space Sector and the role of training and educational programs supporting it. Furthermore, there is additional research into what self-reported roadblocks early career students and workers (and employers) consider important in this journey [4]. Academia, employers, schools, colleges, and museums all have considerable roles to play in shaping the future science capital of our populace and establishing people on the tech workforce pipeline. Rising to meet this challenge, The University of Nottingham wants to develop the UK's space workforce and is proud to have begun its first dedicated aerospace undergraduate course in 2016. In addition to the core lecture modules, added project experience is available in the form of group and individual supervised projects. These practical activities are a rare opportunity to learn unique space skills and work hands-on with spacecraft technology, something in short supply in the UK at the undergraduate level [2]. The practical, hands-on components are an important part of the space education programme and involve different platforms and projects going from simple electronics workshops to CanSats, FlatSats and experimental Rockets.

These activities culminate in the CubeSat Program: a student-led group of projects to develop, build and fly CubeSat missions with a variety of payloads. The students have the possibility to present their own mission idea or join existing ones of interest to the research community. To support these high-fidelity opportunities for students and early career workers, a permanent on-site COTS Ground Station will serve as a control center for all these student-built satellite missions. To help with the establishment of this facility, The University of Nottingham has been cooperating with the local amateur radio community to train and license the student team.

This paper deals with the description of the different projects and presents the University's point of view about the strengths and weaknesses of our Space educational programme.

Keywords
Space Education, CubeSats, Hands-On Activities.

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Acronyms/Abbreviations:

ADCS	*Attitude Determination and Control System*
AITV	*Assembly Integration Test and Verification*
COTS	*Commercial Off The Shelf*
M3	*Department of Mechanical, Materials and Manufacturing Engineering*
GS	*Ground Station*
GNSS	*Global Navigation Satellite System*
HWIL	*Hardware In the Loop*
UnB	*University of Brasilia*
UoN	*University of Nottingham*

1. Introduction

Hands-on education and students' engagement are two vital aspects of The University of Nottingham (UoN) Space program. The program is part of the Aerospace Course established in 2016 and offering four different courses at both BEng and MEng levels. As evident in the space sector, interdisciplinary learning and collaboration as at the heart of a successful project. Hence the University and supporting staff are actively supporting the growth of space related teaching and extra-curricular projects to other interested technical departments and research groups, with the hope that their students will be excited to take part too.

This paper details some of the many ways UoN is supporting and encouraging its student training for careers in the space sector. It accompanies other publications at SSEA 2022 from the students themselves which describe their own views and educational achievements. Through formalizing University support for these programmes through official student societies, research groups, teaching and project based accredited modules, UoN hopes to improve the student experience and quality of their learning.

2. Facilities

Since 2019, and despite the pandemic, The University of Nottingham was able to establish and acquire new important facilities for learning and teaching space related activities. All the facilities are in the main University Park Campus in the so-called "Scientific area" and are accessible to all the students from different departments and faculties. The following sections summarise facilities available at UoN.

2.1. NottsSpace Lab

Opened in January 2022, this workspace is available to students for teaching and practical work. This area is used for different purposes: an office for students that are involved in PGR research related to CubeSats and small satellite, as a classroom for the practical workshops in different modules, and as a dedicated workspace for students and staff that contribute regularly to CubeSat design, construction, testing and mission operations. This well-equipped lab shall soon have all the proper equipment and simulators for building and testing small satellites.

The ability of using a permanent workspace has already improved the productivity and networking capabilities for the space program and provided a fantastic opportunity to showcase UoN's capabilities in space education; attracting new students during open days and other events open to the external public.

It also encourages further opportunities for teaching workshops for various groups to be led in the room using well-known equipment and facilities - and permanent staff.

2.2. Satellite Ground Control Center

A commercial off the shelf (COTS) ground station (GS) kit was acquired from Alen Space and is currently being installed on a roof at the main Nottingham campus. It will provide transceiver radio links with UHF, VHF and (receiving only) S-band channels.

The GS equipment, can be remotely controlled from any authorized UoN computer. All the students are encouraged to use the facilities and develop their practical skills in radiocommunications through supported training sessions. These include official courses conducted by the local radio amateur radio club, which is also an active partner of the space educational activities at UoN, as described later in the paper.

Licensed students, authorized by national OfCom laws to transmit and receive radio signal, are provided with a specific userID (callsign) and password that allow them to access the facilities from their personal computer and acquire data from orbiting satellites.

For the ones that are not yet authorized (hence unlicensed) there is the possibility to learn how to track and receive a satellite during dedicated practical lectures, extracurricular and outreach activities.

2.3. Attitude Determination and Control System (ADCS) Simulator

The University of Nottingham Space team is putting particular attention on teaching aspects related to the design, manufacturing, and testing of new ADCS hardware and software. To achieve this important goal the team decided to develop an in-house Helmholtz cage and air bearing table.

The equipment, which is being designed and manufactured by students as part of their credited module projects, is going to be installed at the end of spring semester 2022. The 2.5 m Helmholtz cage has a 3-axis square coils configuration and simulates Earth's magnetic field automatically at different altitudes.

The air bearing table can support single ADCS components or an entire satellite up to a 3U CubeSat within the Helmholtz cage.

The two systems in combination will be used to perform Hardware in the loop (HWIL) tests of ADCS Hardware and software developed by students at UoN, for example a 3-axis magnetotorquer solution for CubeSats designed this year by a BEng student. In addition, the testbed will be used to develop new lines of research in cooperation with national and international experts on the area.

2.4. Satellite simulators and software

As part of teaching activities, UoN staff now have the opportunity to use dedicated simulators to show the specific use of satellite subsystems or how to integrate a payload inside a real satellite bus using flight model equipment.

In 2019 the Department of Mechanical, Materials and Manufacturing Engineering (M3) acquired a commercial 1U CubeSat simulator developed by Theia Space [4]. The system is extremely useful for showing the students the functionalities of different subsystems, neatly packed within a complete 1U satellite including reaction wheel and magnetorquers. In addition, the university has also procured ground support equipment including a Sun simulator, a low-friction rotating platform, and a simple Earth magnetic field simulator based on two permanent magnets. The simulator kits are used as teaching tools for practical lectures in the lab but are accessible to student groups for self-studying sessions and extra-curricular projects to improve their knowledge of subsystem interfaces.

Another 3U simulator provided by OpenCosmos is also available in M3 and used by students to investigate the possibility to integrate their own payload in a commercial satellite bus.

Following the first student-led attempts at CubeSat avionics integration (section 4.2), members of NottsSpace team and M3 staff members decided to develop their own training workshops and kits to introduce skills related to hands-on space project assembly, integration, testing and verification. Several COTS components such as microcontrollers, cameras, battery packs, sensors and radios, have been procured in order to prepare different educational kits called “FlatSat”. These kits, are being used to teach microcontroller electronics and coding skills, with specific application and examples to how they're used in spacecraft. The components are assembled with breadboards and jumpers to replicate the avionics of more sophisticated satellites and are used in taught laboratory workshops and outreach events for the University. Students follow instructions to integrate the parts and complete pieces of code to enable basic functionalities typical of a satellite mission, such as taking temperature readings and send it through radio beacon to the local ground station. This solution has proven quite effective at levering up the enthusiasm of the students, while providing the rare chance to do space specific laboratory work – a key theme of UoN space teaching.

For developing software skills, M3 students have access to a series of platforms that allow them to simulate, analyse and operate satellite mission from the scratch. The most used software are: MatLab, Catia 3DExperienece, SolidWorks, Ansys, Abaqus, Orbitron, BeeApp, FreeFlyer. The use of the software is taught during different modules lectures but also during specific intensive courses. Similar to the FlatSat workshop, other PGR involved in teaching and space project development have created a suite of student-accessible software that is used for the design and analysis of CubeSat missions. Through several workshops, students are taught to develop such simulations themselves, for applications ranging from attitude control and orbital manoeuvres, to satellite telecommunications

2.5. Manufacturing Facilities

For manufacturing, University of Nottingham offers students free access to facilities with rapid prototyping with 3D printers, and different types of machining such as Milling, CNC turning, Electric discharge machining wire erosion, manual arc welding, material cutting, and metal fabrication, among others.

3. Collaborations

One of the key aspects of the space educational activities at UoN is to establish and promote internal and external collaborations. Space sector products naturally require understanding that the design is complex, requiring different expertise and extremely close, interdependent teamwork. Hence, establishing cooperation with different departments, faculties or with companies and other research centers opens up new possibilities and perspectives.

3.1. Internal Collaborations

Hands-on space activities at UoN are managed involving different experts inside the aerospace course, M3 Department and Faculty of Engineering. The CubeSat program also involves experts from other Faculties and research teams. Thanks to the support from these groups, the products developed by the student team can be developed according to requirements from these specific “customers” for science payloads. The students learn how to deal with product development alongside managing requests and expectations from the customers, as well as the rest of their team. At the same time, being a student directed mission, it also gives them the opportunity to develop their own innovative ideas and research. A practical example of this approach is the close collaboration with the Astropharmacy & Astromedicine Research Group at UoN. Because of the support and motivation from the interdisciplinary space community at UoN, two student CubeSat projects are currently in progress (WormSail & AstroJam). The team is also continuing to establish new collaborations in area including Geospatial research, Additive Manufacturing, Advanced Materials, Computer Science and, in the near future, hopes to develop links with the world class research from the UoN Rights Lab.

By integrating the CubeSat programme into the wider UoN network, the team gains beneficial access to additional facilities. The laboratory spaces at the School of Pharmacy, for example, include COTS incubators, instruments such as microscopes and fluorescent spectrometers (for controls), and vacuum chambers. There are also ultrasonic vibration cleaning instruments, although as these are intended for pharmaceutical apparatus it is not recommended, they be used for spacecraft parts cleaning. The Nottingham Geospatial Institute (NGI) leads the satellite navigation and positioning systems activities. Hardware-based and software-based Global Navigation Satellite System (GNSS) simulators have become available such as the Orolia (Skydel) GSG-8, used for RF front end validation. There are anechoic chamber facilities available at UoN, and instruments including spectrum analyzers, that can be used for TT&C testing of ground and space segments. Several shakers for structural tests and material characterizations are also available and accessible for the student projects.

3.2. External Collaborations

External collaborations mostly are with new space economy companies and start-ups, that have the dual aspect of offering new area of development and research but also the possibilities for the students to learn about the business approach used during industrial projects. Actually, the group is cooperating closely with an SME but in the near future the idea is to implement collaboration with big industrial players. Since the course and the activities are quite new, the team is aware that its capabilities should be proven before the big players can be attracted to cooperate with a new team. Considering the actual cooperation, collaborative projects are mainly devoted on the design and analysis of feasibilities studies dedicated to the confirmation that specific, novel technologies can be applied in space. These are mostly developed during individual projects with a duration of less than one year.

Another fruitful external cooperation, established in 2020, is the one with South Notts Amateur Radio Club (SNARC). The club, located in Nottingham, actively support the NottsSpace team offering students extra training. This extra training has not only complimented their studies on radio and electronics technology but helped them pass their Radio Society of Great Britain exams so they can legally operate the UoN ground station. SNARC’s expertise is supporting the inclusion of new TT&C technologies to the CubeSat and the CanSat project.

3.3. International Collaborations

In terms of international collaborations, the space program at University of Nottingham has already a solid network, that of course UoN aims to expand and grow.

NottsSpace is working elbow to elbow with University of Brasilia (UnB), in Brazil. Not only the two universities have twin GS and similar facilities but are closely cooperating in project such as Alphacrux, WormSail and AstroJam. The two teams are cooperating through sharing educational material and methods, and

DOI: 10.5821/conference-9788419184405.053

comparing the results obtained in order to better support their students and space projects.

In Brazil, UoN is cooperating also with INPE, the Brazilian National Space Research Institute, to develop new satellite missions such as RaioSat and supporting, as free consultancy, the UbaTubaSat II mission. That mission also involves students from the public secondary school Tancredo I, located in UbaTuba (SP).

In Europe the team is actively collaborating with University of Beira Interior in Covilha and University of Oporto, both in Portugal. This collaboration also involves a local SME and startup in a project called Antaeus, described later.

4. Projects

UoN has established a series of projects in the last 4 years dedicated to the direct involvement of the students in real space projects. The hands-on experience is priceless and give them a unique opportunity to realize something that will be operative. In the first two years a lot of effort has been focussed on finalizing collaborations and procuring dedicated spaces to develop the real missions. In the preliminary phases simple projects such as PocketQubes and high-altitude balloons have been developed up to the engineering model design stage. However, at the end of 2020, the possibility to get a real launch opportunity and with some supporting funds available, gave a real push to establish a more organized and consistent student space program. From this and the students commitment to formalise the projects for a better, wider involvement, the development of a student space society (SpaceSoc) and its project based arm (NottsSpace) was born. In the following sections some of the active complete projects are presented.

4.1. AstroJam

AstroJam is a 3U multipayload CubeSat mission designed and lead by UoN students, with payloads from the Nottingham Geospatial Institute and the Astropharmacy Research Group. The project is currently under evaluation for the 4th European Space Agency Fly Your Satellite competition. The core team is composed by PhD, MEng and BEng students from different faculties and departments such as M3, Astropharmacy and Computer Science and is expanding to involve students from other departments and faculties.

4.2. Wormsail

WormSail is a collaborative project between the University of Nottingham and University of Brasilia, with the aim to design, build and fly a small CubeSat to conduct experiments in space. These experiments include everything from the behaviour of tiny nematodes, to using the Earth’s magnetic field to steer the satellite and more. Once it’s launched, it could be the world’s first set of multi-cellular organisms on a CubeSat flight. Work began on WormSail in September 2020 and is currently ongoing as of 2022.

4.3. TemboSat

TemboSat is a mission proposed by third-year Mechanical Engineering students for their Group Design and Make module project. The mission’s aim is to use CubeSats to track elephants in the wild and help reduce their poaching through providing local authorities up-to-date elephants’ locations.

4.4. CC4CC

CC4CC (CubeSat Constellation for Climate Changes) is a collaborative project conducted with GSL Venture and EnduroSat. The project was firstly proposed by a BEng student [6] and aims to investigate sea level rising using a constellation of satellites. The mission design and analysis and the definition of the bus systems is the responsibility of UoN students.

4.5. Antaeus

Antaeus [7] is the acronym for Astrophysical Nanosatellite for Technological Advancement and high-Energy Universe Studies. It is a collaborative project between the University of Nottingham, University of Beira Interior and University of Oporto, with the aim of in-orbit demonstration of the use of a new high energy detector developed by University of Oporto. The UoN students will have the opportunity to cooperate with their colleagues from Portugal and at the same time be responsible for crucial subsystems such as the Structure and the TT&C.

4.6. RaioSat

RaioSat [8] is a satellite proposed by INPE and designed in collaboration with NottsSpace. The project has the aim of predicting severe weather phenomena using a Lightning Flashes Detection system developed by INPE and its partners. UoN's role is to act as the systems engineering team, developing the bus and taking care of all the AITV phases.

4.7. CanSat

In July of 2021, students took part in a CanSat competition that involved the design and development of a satellite mission. The mission was assessed through design reviews following ESA Standard Project Management and were presented to UK Launch Services Ltd (UKLSL) and OneWeb judges. The CanSat was designed to be launched using a small-sounding rocket up to 450 meters. Once ejected it was recovered using a recovery system based on a parachute. The team was part of the "Peake CanSat Category" which used a 66mm diameter and 160mm tall CanSat. The proposed mission was to collect air pollution data around the launch site, and record and track the flight path in real-time. The team was awarded with the second prize in their category in 2021 during the Mach-21 competition. A new mission is under development to compete at the MACH22 competition with the launch scheduled in July 2022.

4.8. Small Rockets

The UoN is also active in the design and test of model rockets. Following the interest and enthusiasm of the students from CanSat and CubeSat missions, in 2022 funding was allocated to support their extra-curricular activities and their participation in student competitions. This year they have been selected to attend the Mach-22 competition organised by UKLSL (UK Launch Services Ltd) and UKSEDS (the National Student Space Society). During the competition teams have to design, manufacture and launch a model rocket to achieve an altitude as close to 1km as possible, and deploy a CanSat (upgraded from the Mach-21 entry). The team would gather data from the launch, such as measuring and transmitting altitude, inertia and position during flight and recovery to a ground station.

5. Conclusions

In just a few short years, UoN has built a thriving space educational program, thanks to the involvement and enthusiasm of its staff, students, and collaborators. From its first few simple projects, it has grown and organized to support a wide-range of student led groups and research topics, while including plenty of teaching elements and laboratories – some of which are designed and run by the students themselves!. The authors hope the lessons and examples presented in this paper are of interest and use to students and staff elsewhere in the world, also hoping to promote space as a fantastic opportunity for technical education, and an important part of future global science economy, infrastructure, and diplomacy.

Acknowledgements

The authors wish to thank the students and staff who have been such a vital part of these projects and their enthusiasm for encouraging others to join in and learn more about space.

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The Student Aerospace Challenge: a European multidisciplinary contest and tertiary educational programme

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Abstract

Inspired by the first successful tests of a private manned spaceplane in 2004, the Student Aerospace Challenge was created in 2006 by the European Astronaut Club and its partners - Dassault Aviation, the European Space Agency, the International Astronautical Federation, Safran and Thales at the time - to allow European university students to explore some aspects of manned suborbital vehicles. Until 2020, the Challenge focused on a local reusable vehicle reaching Mach 3.5 and an altitude of 100 km. Since the 15th edition, to better respond to the evolution of the sector, a second vehicle is proposed: a hypersonic vehicle dedicated to point-to-point transportation taking, for example, less than two hours to travel from Barcelona to Tokyo.

Each year, the Steering Committee defines several work packages corresponding to a large variety of study domains realistically related to this type of innovative vehicles like aerodynamic and flight control, structure, reusable propulsion, airworthiness, promotion, market analysis, legal frame & medicine. The introduction of a second vehicle having a quite different mission led the Committee to introduce dedicated topics. In addition, for the current edition, a new work package was proposed to cover potential applications of suborbital flights other than carrying passengers.

In function of their background and interest, European University students have the opportunity to work, during several months, on a topic related to one of the work packages and to explore new solutions. Proposed projects should be technically realistic, economically viable and environmentally friendly. Reports and posters issued by student teams are evaluated by the Steering Committee some weeks before the “Suborbital Day”, a dedicated event organised like a mini-symposium, usually on-site where students present orally their projects and meet representatives of the different partners. The best-quoted projects are rewarded with prizes, among them, the ESA Grand Prize offering the winner team the unique opportunity to present their project in an appropriate European space-related event.

To date, 216 teams and 998 University students coming from all over Europe already took part in the Student Aerospace Challenge, a motivating and ambitious multidisciplinary educational programme. Their participation allowed them to complement their knowledge, learn new skills and enlarge their network in the space sector.

Keywords

Challenge, Education, Manned spaceplane, Project-based learning Suborbital

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Acronyms/Abbreviations

ACE	*Astronaute Club Européen (European Astronaut Club in English)*
CV	*Curriculum Vitae*
EADS	*European Aeronautic Defence and Space*
ELGRA	*European Low Gravity Research Association*
ESA	*European Space Agency*
IAC	*International Astronautical Congress*
IAF	*International Astronautical Federation*
ISS	*International Space Station*
MAE	*Musée de l'Air et de l'Espace of Paris – Le Bourget*
RISpace	*Reinventing Space Conference*
VSH	*Véhicule Suborbital Habité (Manned Suborbital Vehicle in English)*
WP	*Work Packages*

1. Introduction

The Student Aerospace Challenge [1] was created following a meeting between the promoters of a manned suborbital vehicle project and tertiary education students from some French "Grandes Écoles" at a Job Fair in June 2006. The professionals wanted to find some "young talents" for their "Véhicule Suborbital Habité" (VSH) project, and the students were looking for concrete innovative and motivating projects they could contribute to.

Schools and Universities were more and more pushing their students to invest themselves in intra or extra-curricular projects to complete their academic studies and in parallel aerospace industry wanted to hire young professionals with hands-on experience, teamwork, and project management skills in order to accelerate their professional insertion. It was thought that an ambitious federating multidisciplinary education programme would be the best way to provide a framework of cooperation and innovation.

The Challenge initially brought together Dassault Aviation, Safran and Thales, three French aerospace companies, with the support of the International Astronautical Federation (IAF) and the European Space Agency (ESA). The European Astronaut Club (French acronym ACE), which was the official promoter of the VSH, was asked to pilot this student competition. The creators of the Challenge were very confident about the future success of this initiative because of a buoyant suborbital context where projects were multiplying (especially in the United States). Indeed, SpaceShipOne, built by the famous aerospace designer Burt Rutan of Mojave-based Scaled Composites, had carried out the first private human suborbital flights in history and won the XPrize in 2004 by reaching the edge of space (at an altitude above 100 km). This amazing success was a key milestone in space access story and for private space explorers' future journeys. It showed that a small, motivated team was able to design and to build a manned space vehicle without governmental support. It marked the beginning of New Space.

During summer 2006, a first edition of the Student Aerospace Challenge was launched. The Challenge evolved from the second edition with the participation of the Musée de l'Air et de l'Espace of Paris – Le Bourget (MAE) which started hosting the annual Suborbital Day. In the third year, the VSH project of the initial partners having evolved, EADS (now Airbus) also joined the Challenge. For the current 2021-2022 edition, the partners are the ACE, ArianeGroup, Dassault Aviation, ESA and MAE.

Not only had the partners evolved over the years but also the participating students. Initially the Challenge was dedicated to French students only but from 2014-2015 edition, some teams from other European Universities started applying and nowadays students are applying from all over Europe. It is worth to be noted that the Europeanization of the Challenge was an initial goal of its founders.

After 15 years, the Challenge is still existing thanks to the strong commitment of the partners and the interest of the students. It is a very successful tertiary education activity thanks to the continuous adaptation and improvement of the competition according to the expectations of the partners and students, but also the evolution of the aerospace sector.

2. Suborbital vehicles

Initially, the partners' objective was to imagine solutions directly applicable to the VSH, a manned airborne suborbital vehicle studied by Dassault Aviation to transport six people at the edge of space. From 2012-2013 edition, three other vehicles were proposed to the students: SpacePlane (ArianeGroup), SpaceShipTwo (The SpaceShip Company/Virgin Galactic) and Lynx (XCor). New Shepard (Blue Origin) was added for the 2016-2017 edition allowing the teams to expand their projects which could be airborne or not and taking-off horizontally or vertically. Nevertheless, students were always given the opportunity to design their own vehicle shape and configuration.

For the 2018-2019 and 2019-2020 editions, only one reference vehicle was proposed to have all teams working on the same basis. The

DOI: 10.5821/conference-9788419184405.054

shape was chosen independent from existing professional projects (see Figure 1) and its main characteristics were the following ones:

- Length: 18 m,
- Wing span: 13 m,
- Empty weight: 10 t,
- Propellant mass: 10 to 15 t,
- Max altitude: 110 km,
- Max Mach: 3.5,
- Weightlessness duration: about 5 min,
- Max acceleration: 4 G,
- Total mission time: about 90 min from take-off to landing.

Figure 1. Student Aerospace Challenge's reference vehicle ©ACE

However, for the 2020-2021 edition, because of the evolution of the sector, partners found it important to offer students to work on another use of the suborbital flight: a vehicle able to transport passengers or freight on intercontinental distances at very high speed. This vehicle:

- Is dedicated to regular passengers' transportation (10, 50 or 100 people),
- On a distance greater than 10,000 km (Barcelona to Tokyo, for example) in 2 h max,
- Is equipped with liquid hydrogen and oxygen rocket engines.

The stakes being very different from technical and business points of view, it seemed urgent to the partners to approach in parallel vehicles for local suborbital flights (tourism and sciences) and those for intercontinental suborbital flights.

3. Work Packages

In order to provide students with a clear working basis and to offer a large variety of topics to attract students with different backgrounds, the partners decided, from the first edition, to adopt a work principle based on annual work packages (WP). Each WP describes shortly the context and proposes some topics of investigation. The number of annual WPs, domains and topics of investigation have evolved over the years taking into account the interest of the partners and the evolution of the aerospace sector. In average, nine different WPs are proposed every year out of which six are chosen by the student teams. Only two WPs have been proposed throughout all editions of the Challenge: Propulsion and Legal aspects. Propulsion is also the most studied WP with 59 student projects and Legal aspects the only WP studied by a team every edition. Other non-technical WPs like Promotion/Communication and Market Analysis are proposed since several editions but do not attract yet many non-STEM students.

For the current 2021-2022 edition, students could choose between the following 13 WPs:

- WP1 - Applications,
- WP2 - Promotion / Communication,
- WP3 - Legal frame,
- WP4 - Medicine,
- WP5 - Reusable propulsion / Maintenance,
- WP6 - Suborbital flight history,
- WP7 - Market analysis,
- WP8 - Structure suited to suborbital flight,
- WP9 - Aerodynamic and Flight Control,
- WP10 - Airworthiness,
- WP11 - Mission profile and Concept,
- WP12 - Infrastructures for fuel supply,
- WP13 - Commercial operations.

WPs 1 and 9 address topics related to vehicles performing local suborbital flights. WPs 11, 12 and 13 are proposed for the second time, because topics are linked to ultra-long range vehicles. For other WPs, students must select the vehicle family they want to work on. Partners are looking for economically viable and environmentally friendly solutions as these criteria are becoming more and more important in aerospace projects whether they are commercial endeavours or agency programmes. Nevertheless, proposed solutions shall remain technically realistic. The most iconic results obtained during the first twelve editions are presented in paper [2].

4. Organisation of the Challenge

4.1. Application Process

4.1.1. Eligibility criteria

All students enrolled in a European university located in one of the ESA Member or Cooperating States [3] can participate in the Challenge and, since 2014-2015 edition, teams should be composed of 2 to 5 students. For some specific WPs where multidisciplinary knowledge is needed (Medicine for example), students from two different institutions are authorized to create a single team.

DOI: 10.5821/conference-9788419184405.054

4.1.2. Application Form

Teams wishing to participate in the Challenge should get an oral authorization by an official of their institution, fill in an application form, choose a WP and provide a motivation letter.

4.1.3. Application Validation

Following a selection process by the Challenge's partners, selected teams have to get their participation officially endorsed by a representative of their institution.

4.2. Project preparation

Each team receives an access code to a download platform where previous reports are stored. Students have around 6 months to work on their project. Two progress reports should be submitted by the teams and are reviewed by aerospace experts before the delivery of the final report, abstract and poster.

4.3. Suborbital Day

Each edition of the Challenge is concluded by a one-day event called the Suborbital Day, which takes place at MAE. It is organised like a mini-symposium with sessions per WP chaired by partners' representatives. Each team delivers a 10-minute oral presentation of its project followed by a short discussion. Moreover, a European astronaut is invited to join this educational event and offer an inspirational lecture. It is a unique opportunity for the students to network with aerospace experts from partner institutions and industry as illustrated on Figure 2.

Figure 2. Students and aerospace experts networking during the Suborbital Day 2018 ©DAE

4.4. Awards

As the Challenge is a contest, the partners rank final reports and posters. "ESA Grand Prize" offers the best-ranked team the unique opportunity to present its project in an appropriate European space-related event such as the International Astronautical Congress (IAC) as illustrated on Figure 3, the Reinventing Space Conference (RISpace) or the European Low Gravity Research Association (ELGRA) Symposium. The two following ranked student projects are granted with "ArianeGroup Prize" and "Dassault Aviation Prize". The team having produced the best poster is awarded through the "Communication Prize" sponsored by ACE. Finally, as oral presentations are evaluated during the Suborbital Day, the team whose performance is the most appreciated receives the "Suborbital Day Special Prize" offered by MAE.

Figure 3. IDEST-DAST team presenting their Challenge project at the IAC 2018 ©ESA

4.5. Closing Ceremony

In addition to the Suborbital Day, every two years, during Paris Air Show at Le Bourget (France), partners organise a special closing ceremony for the awarded teams in the ESA's pavilion. This is another unique opportunity for the students to meet with ESA astronauts and to benefit from a VIP visit of the exhibition. It allows them to learn more about the aerospace domain and to exchange with the main actors.

5. Result

5.1. Participants Overview

Since 2006, 15 editions of the Challenge have been organised and 216 teams have participated to the entire contest totalling 998 students. On average, 14 teams representing 66 students participate to each edition. 27 students have participated to two editions and one student participated to three, working on different WPs and winning a prize each time!

The number of females has been fluctuating over the years, as shown on Figure 4, with an average representation of 20.4%.

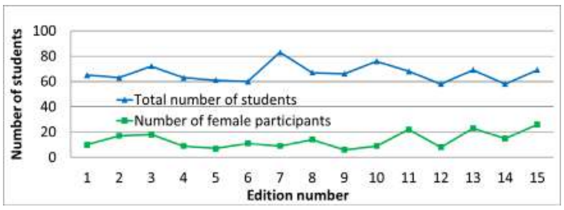

Figure 4. Comparison of the total number of students versus the number of female participants per edition of the Challenge

As illustrated on Figure 5, during the eight first editions of the Challenge, only French teams participated but from the 9th edition in 2014-

DOI: 10.5821/conference-9788419184405.054

2015, the contest became slowly European with teams applying from other countries.

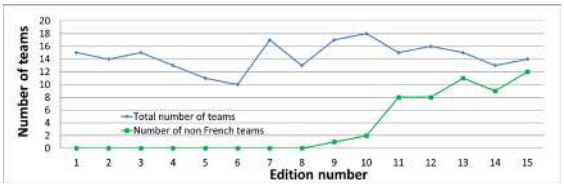

Figure 5. Comparison of the total number of teams versus the number of non-French teams per edition of the Challenge

The number of countries has been growing over the years to reach a record of 8 different countries for the 12th edition in 2016-2017. Table 1 shows the represented countries and the respective number of teams and institutions.

Table 1. Countries represented in the Challenge, corresponding number of teams and institutions

Country	Number of teams	Number of different institutions
Bulgaria	3	1
France	165	41
Germany	4	2
Greece	2	2
Italy	9	2
Poland	5	2
Portugal	3	3
Romania	5	2
Spain	5	2
Sweden	1	1
Switzerland	1	1
The Netherlands	2	1
United Kingdom	11	6

5.2. Feedback

The partners recently conducted a survey among former participants to assess the impact of the Challenge on their studies and careers. 92 of them answered the anonymous online questionnaire, so around 9% of the total number of participants (many e-mail addresses were no longer valid). As illustrated on Figures 6 and 7, even if most of them participated recently in the Challenge, they represent participants from the first to the latest edition of the Challenge who worked on a large variety of WPs. At the time of their participation, 37% of them were Bachelor students and 67% Master students.

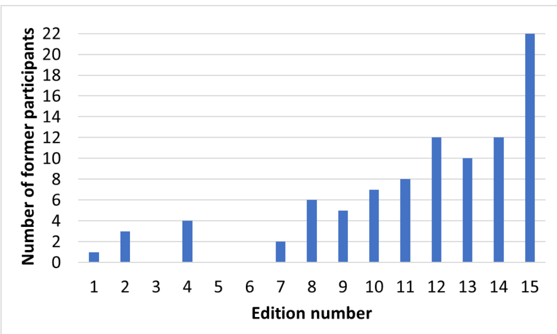

Figure 6. Distribution of the former participants who answered the survey over the different editions of the Challenge

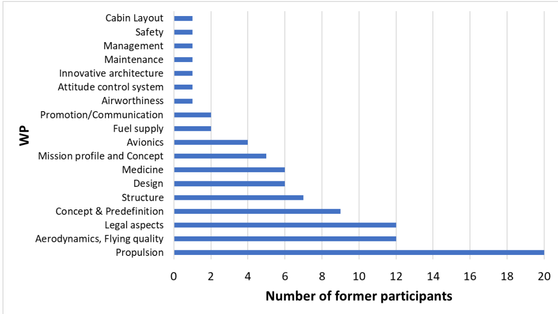

Figure 7. Distribution of the former participants who answered the survey over the WPs

As shown on Figure 8, most of them in an engineering field but some in legal, business, design, medicine, and science fields.

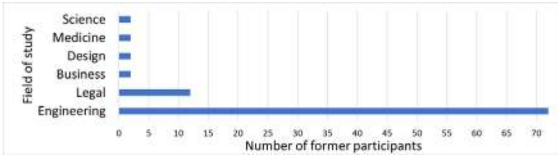

Figure 8. Fields of study of the former participants who answered the survey

71% of these former participants are still in touch with other participants and 26% made contacts during the Challenge who served them later in their studies and/or career. 75% promoted the opportunity after their participation and 87% added their participation to their C.V. The participation to the Challenge was part of the studies of 46% of these former participants. Table 2 shows how their participation in the Challenge influenced decisions regarding their studies and/or career.

Table 2. Answers from the former participants to the question: Did your participation in the Challenge influence decisions regarding further studies/career?

43 %	Yes it influenced my decisions, it confirmed/reinforced my opinion on what I want for my future studies/career
42 %	No it did not influence my decisions, I already knew what I wanted to do in the future
9 %	No it did not influence my decisions, it was not really helpful
4 %	Yes it influenced my decisions, it made me realise I want to change my plans as I
1 %	Yes it influenced my decisions, it made me realise the aerospace sector was not where I wanted to work

92% of the former participants confirmed that their participation in the Challenge allowed them to complement the skills and competences they gained during their studies and 77% already applied what they learned. Figure 9 shows that in addition to acquiring knowledge in a specific domain, former participants also developed some skills, in particular teamwork and project management but also interdisciplinarity.

62% of these former participants are now working, 33% are still studying and 5% are currently looking for a job. 65% in the aerospace domain and 58% in a field related to the WP they selected during the Challenge.

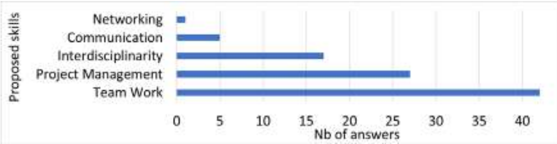

Figure 9. Answers from the former participants to the question: What was the most useful skill you developed during the Challenge?

6. Impact of Covid-19 situation

As many activities throughout the world, the Challenge was impacted by the Covid-19 pandemic. During the 2019-2020 edition, being not able to organise the Suborbital Day at the MAE in June, partners first postponed the event for several months and finally decided to organise it online as it was important to maintain an event. For the 2020-2021 edition, the same situation occurred, and the Suborbital Day was again held online. Both events were delivered using collaborative tools as illustrated on Figure 10. Connection tests were made one week prior with all participants to avoid technical issues. The virtual Suborbital Day allowed student teams to present their projects and receive their prizes but meeting with an ESA astronaut and exchanges with the partners' representatives and experts were not as easy as usual despite a nice virtual environment.

Figure 10. Some experts and students participating to the 2020 virtual Suborbital Day

In 2021, Thomas Pesquet recorded from the ISS, during his Alpha mission, a welcome video for the participants of the online Suborbital Day as illustrated on Figure 11. This was a very nice surprise!

The partners of the Challenge strongly hope to organise again the Suborbital Day at the MAE in June 2022. Even if the two online editions were successful interaction between the students and the professionals was limited whereas it is a key element of the Challenge.

Figure 11. Capture of Thomas Pesquet's Welcome video recorded from the ISS for the 2021 online Suborbital Day

7. Conclusions

The Student Aerospace Challenge is a unique European multidisciplinary contest for university students allowing them to work in teams for several months on a space-related project while getting feedback and meeting with professionals from the sector. Since 15 years, the Challenge has been successfully organised, even during the Covid-19 pandemic, allowing in one hand, students to complement their knowledge and network with aerospace actors and in the other hand, partners to meet students and identify future talents to maintain the appropriate workforce. For future editions, after the Covid-19 pandemic, partners would like to strengthen, the networking element of Challenge and to attract more non-STEM students into the Challenge to better support the evolution of the European space industry.

Acknowledgements

Thank you to all past and present Challenge's partners and experts as well as the European astronauts who took part to Suborbital Days and Closing Ceremonies: Jean-Pierre Haigneré, Patrick Baudry, Léopold Eyharts, Reinhold Ewald, Thomas Pesquet and Michel Tognini.

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UPC NanoSat-Lab - Past, Present and Future Activities

A. Camps[1]

Abstract

The Universitat Politècnica de Catalunya UPC NanoSat Lab is part of the CommSensLab-UPC Specific Research Center of the Department of Signal Theory and Communications, and counts with the support of the School of Telecommunications Engineering (Telecom Barcelona, ETSETB). It is located in the UPC Campus Nord. The lab was originally created in 2007 to promote the testing of novel remote sensors and techniques in space, taking advantage of CubeSats. Over time, the lab has also started the study of Earth-to-space IoT and RF intersatellite link communications, as key enabling technologies for the next revolution of Earth Observation.

At the time of writing this abstract, the UPC NanoSat Lab has developed and launched four CubeSats, and is working in three new missions that will be launched in Q4 2022 - Q1 2023. At present, the Lab is developing an "Open PocketQube Kit" for IEEE as a low-cost educational platform on space-related technologies.

The lab has also a Class 8 clean room equipped with a shaker and thermal vacuum chamber, and Helmholtz coils, air bearing system, and Sun simulator for attitude determination and control system testing to conduct the environmental tests.

Finally, in the MontSec Astronomical Observatory (OAdM),which is managed and operated by IEEC, hosts the UPCNanoSat Lab VHF/UHF and S-band ground station [3], where the data from the ^{3}Cat-5/A satellite where downloaded.

Since its inception in 2007, about 300 students have been trained in the lab, either as undergraduate students in the "Advanced Engineering Project" of the ETSETB, as Final Degree or Master Thesis projects, as graduate students, or just for an internship.

This paper presents a quick overview of the past, present and future activities of the UPC NanoSat Lab.

Keywords

CubeSats, Laboratory, Testing facilities, Ground Station, Education, Research

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1. Introduction - A quick historical review

The UPC NanoSat Lab was created in 2007 after UPC Chancellor, Prof. Antoni Giró, tasked Professors Juan Ramos and Adriano Camps the development of two tractor projects: one in the field of "aeronautics," and another one in the field of "space" to collimate the efforts and know-how of several UPC engineering schools, and notably the Aeronautics schools that had been recently created in Terrassa and Castelldefels. Since no specific budget was allocated for these tasks, the beginnings were slow, as activities were conducted in a best effort basis "in the cracks" of the usual projects, using project remnants to feed the new space activities.

The first project was the UPCSat-1, renamed later as ^{3}Cat-1 (pronounced /Cube-Cat One/), a 1 unit (1U) CubeSat including a number of technology demonstrators coming mostly from the Department of Signal Theory and Communications, and the Department of Electronics Engineering, the two that at that time had more background on space-related activities. The project started as a mix of subsystems that were purchased, those that we considered critical such as the On-Board Computer (OBC), the Electrical Power System (EPS), the structure itself etc. and subsystems developed in-house. However, it was soon realized that neither the CubeSat "standard" was a complete standard (as it only defined the mechanical requirements, but not electrical ones, so there were incompatibilities in the connectivity of some of the subsystems purchased), nor some of the subsystems purchased really deserved the name of space qualified (e.g. EPS with some components not really ready for space, or others with serious design "issues" etc.).

In these circumstances, it was decided to step back and start designing the different subsystems inhouse, as the only way to make sure that we knew what was inside… It was somehow a sort of "vertical integration," because of the severe budget constraints. In our way to try to use commercial off-the-shelf (COTS) components we, little by little, started creating what is now called the UPC NanoSat Lab, and in the office space we occupied in 2007 in the Omega-3 building of UPC Campus Nord, we started bringing in a customized Thermal Vacuum Chamber (TVAC) for the bake-out and thermal cycling tests, a Sun simulator with a COTS Xenon lamp (whose spectra was cross-checked against an Oriel Top of the Atmosphere Sun simulator).

In 2013 we received co-financing to purchase a long-waited electro-dynamic shaker to conduct all the vibration tests. Because of the special requirements (too heavy) the UPC NanoSat Lab was migrated to a basement between the A3 and B3 buildings at UPC Campus Nord.

In May 2018, thanks to a "María de Maeztu" grant awarded to the CommSensLab Research Center (Dept. of Signal Theory and Communications) an ISO 8 clean room was going to be installed. At that time, we were "invited" to move, and thanks to the school of Telecommunications Engineering (ETSETB-UPC) dean, Prof. Ferran Marqués, and UPC Chancellor, Prof. Francesc Torres, a new location was provided in the basement of the C4 building, in the same UPC Campus Nord. Today's UPC NanoSat Lab was inaugurated on November 2018 [1]. At the time of writing this paper, we are expecting to receive a bigger shaker, to be granted by a private company. This will allow the lab to grow, and also offer a better service to national and international companies, as the original facilities were dimensioned according to the needs of a University lab, with limited budget.

To put things in the historical context, in March 2010, on the occasion of the 10th anniversary of the Bologna Process, the European Higher Education Area (EHEA) was launched. As the main objective of the Bologna Process since its inception in 1999, the EHEA was meant to ensure more comparable, compatible and coherent higher education systems in Europe. It implies the establishment of new teaching methodologies, to the detriment of traditional master classes: Continuous Assessment, and Practical Teaching. After having compared several models for the definition of the new curricula, the ETSETB-UPC identified the Conceive-Design-Implement-Operate (CDIO) initiative as the most complete and coherent model. In the new curricula, the CDIO initiative is implemented with four subjects: Introduction to Information and Communication Technologies (ICT) engineering (or ENTIC), Basic Engineering Project (or PBE), Advanced Engineering Project (or PAE, the capstone project), and the Final Degree Project. Since its inception, a PAE subject called under the generic term "^{3}Cat-NXT" has been offered to the students willing to learn more about space activities, electronic design, programming, testing etc. [2]. The course starts with an intense 11 hour tutorial on different aspects related to spacecraft systems engineering that levels the different student backgrounds, depending on their majors, and provides some basic understanding on the main design considerations that apply to spaceborne systems, that do not apply for -for example- consumer electronics. The topics change every semester according to the UPC NanoSat Lab's main activity, but typically they are connected along 3-4 semesters. This creates a bit of extra overhead to the students, because of the extra work to document and report for the next semester students, but also helps them to understand how a real project in a company is, including internal reporting to a team leader, weekly oral presentations and progress meetings with the faculty, taking minutes of the meeting (MoM), with action items, as well as three main project meetings including Preliminary and Critical Design Review meetings, and Final Review meeting.

Since the ^{3}Cat-NXT PAE subject started, we estimated that about 300 students have followed this course, and many of them have continued space-related activities in the lab during their Final Degree project, and some of them in their Master's Thesis, or even Ph D Thesis. And more interestingly, the lab is not restricted to students from the ETSETB-UPC, students from other UPC Schools or from different countries are welcome to join an international multi-disciplinary, and "multi-generation" (from freshmen to post-docs) working environment.

In the next sections, the UPC NanoSat Lab facilities, and main missions will be explained.

2. UPC NanoSat Lab: Facilities

The facilities of the NanoSat Lab are designed to carry out the assembly, integration and test procedures of up to 6U CubeSat spacecrafts and subsystems. An ISO 8 cleanroom area that includes all the necessary instrumentation and testing equipment to perform verification and validation procedures (Fig. 1).

Fig. 1. UPC NanoSat Lab clean room with TVAC and shaker

2.1. Thermal Vacuum Chamber

A custom cylindrical Thermal and Vacuum Chamber (TVAC) that emulates the outer space conditions is also available. It is mainly used for the environmental test campaigns in CubeSat missions. It has a heating system based on three infrared lamps and a cooling system based on liquid nitrogen that circulates around the thermal shroud. Internal temperature can be controlled from -196 ºC to +300 ºC, while the minimum pressure is 10^{-5} mbar. This allows to simulate the pressure and thermal cycles of a satellite in orbit. The facility is operated by a centralized computer that controls the temperature and vacuum levels depending on a target reference. 2.92 mm (K-type) RF connectors, DB-9, and thermo-couples are available at the feedthroughs. The Device Under Test (DUT) can be hanged from the top of the TVAC or placed on a plate thermally insulted from the shroud, which can rotate thanks to a magnetically coupled motor. The TVAC also features a large quartz window to allow the light from a Sun simulator to illuminate the DUT, and a Germanium lens to observe the temperature distribution in the DUT.

2.2. Shake table

Vibration tests in all three axes can be carried out in the electrodynamic shake table model Data Physics GW-V400 [3]. Sine (frequency sweep), random and some shock tests can be conducted.

2.3. Helmholtz Coils and air bearing

The Helmholtz Coil System is a set of three pairs of coils manufactured by Serviciencia SL, that generate an arbitrary magnetic field which is uniform in a cubic of ~40 cm side. The system includes an air-bearing to test attitude determination and control systems (ADCS) in near zero-g conditions. The current that flows through the coils is generated by a triple power supply controlled by a computer, and it can mimic the Earth's magnetic field while the satellite is orbiting around the Earth (Fig. 2).

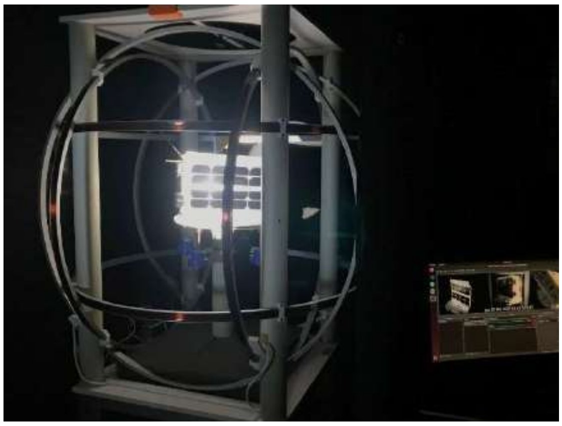

Fig. 2. Helmholtz coils during ADCS testing of a 6U CubeSat

DOI: 10.5821/conference-9788419184405.055

2.4. Ground Station

The UPC NanoSat Lab also designed, manufactured, and operates its own ground station (Fig. 3). It includes quad-antennas at Very High Frequency (VHF) from 144 to 145 MHz; Ultra High Frequency (UHF) from 435 to 438 MHz; and a 3-m dish at S-Band from 2200 to 2290 MHz. It si located at the Observatori Astronòmic del Montsec (OAdM) premises, which is owned and operated by the Institute of Space Studies of Catalonia (IEEC). VHF and UHF are transmit/receive, and exhibit a G/T of - 16 and - 14 dB, respectively. S-band is receive only, and exhibits a G/T of + 9 dB.

Fig. 3. IPC ground station at IEEC Observatori del Montsec Premises.

3. UPC NanoSat Lab Main Projects

In this section, the main satellite missions developed by the lab are explained.

3.1. ^{3}Cat-1

^{3}Cat-1 (Intl. designator 2018-096K) was the first project of the lab: a 1U educational and techdemo mission [4]. It was started in 2007, and it was ready for launch in 2014, but the first Russian invasion of Ukraine prevented it from being launched using a Dnepr rocket. After this failed attempt, it was re-scheduled for a launch in a Falcon 9, but for two occasions the previous launch exploded (June 2015 and September 2016). It was finally launched from Sriharikota Launching Range (India) using a PSLV in November 2018.

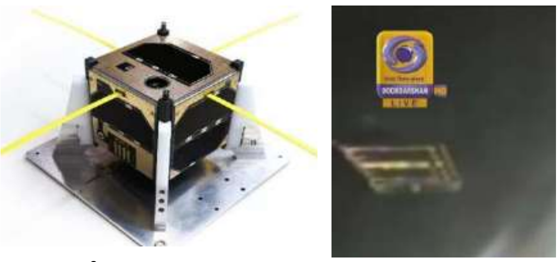

Fig. 4. ^{3}Cat-1 (left), and moment in which it was injected in orbit (right)

^{3}Cat-1 included the following payloads: 1) an "eternal" self-powered beacon using a Peltier cell to generate electricity thanks to the temperature gradient between the inner and outer parts of the satellite, 2) a CellSat photovoltaic solar cell developed by the Micro- and Nano-Technologies group from the Electronics Engineering Dept at UPC, 3) a monoatomic oxygen detector based on the analysis of the resonant frequency of a MEMS device covered by a sensible polymer, 4) an experiment to characterize a Graphene Field Effect Transistor (GFET), 5) an experiment to test the effects of plasma in Wireless Power Transfer (WPT) links, 6) a VGA-resolution CMOS camera, and 7) a Geiger counter.

3.2. ^{3}Cat-2

^{3}Cat-2 (Intl. designator 2016-051B) was a 6U Earth Observation mission [5]. It was launched from Jiuquan Satellite Launch Center using a Long March D2, in August 2016. ^{3}Cat-2 payload was PYCARO, a dual-frequency (L1 and L2), dual-polarization (RHCP and LHCP), and dual-constellation (GPS and Galileo) Global Navigation Satellite Systems-Reflectometer (GNSS-R).

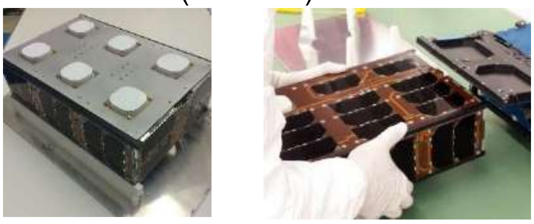

Fig. 5. ^{3}Cat-2 nadir looking antenna array (left), and ^{3}Cat-2 during integration in the DuoPack deployer at ISIS premises.

3.3. ^{3}Cat-3

Leveraging on the ^{3}Cat-2 experience, ^{3}Cat-3 was meant to be a multi-spectral imaging mission for the Cartographic and Geologic Institute of Catalonia (ICGC) [6]. Unfortunately, despite being included in its Strategic Plan, political issues at Catalan and Spanish levels prevented it from being approved, and the mission stopped after a Phase A study. This mission is reincarnated as GenEO, the second mission of the New Space strategy of the Catalan government.

3.4. ^{3}Cat-4

^{3}Cat-4 mission aims at demonstrating the capabilities of smallest nano-satellites for Earth Observation (EO), in particular using GNSS-R and L-band microwave radiometry, as well as for Automatic Identification Services (AIS) [7]. The goals of this mission are mainly educational, technology demonstrator of the Flexible Microwave Payload-1 (FMPL-1) which implements the three RF payloads in a single software defined radio, and scientific, including dual-frequency (L1 and L2) GNSS-R and assessing the required ionospheric corrections, and the creation of RFI maps.

^{3}Cat-4 was selected by the European Space Agency (ESA) Academy for the "Fly Your Satellite!" program (second edition). Its launch is foreseen for Q4 2022 in the maiden flight of Ariane 6.

Fig. 6 shows an artist's view of the satellite with the ~50 cm antenna deployed,

Fig. 6. ^{3}Cat-4 nadir looking antenna in stowed configuration (top left), fully integrated (top right), and artists' view.

3.5. FSSCat: ^{3}Cat-5/A and ^{3}Cat-5/B

^{3}Cat-5/A (Intl. designator 2020-061W) and ^{3}Cat-5/B (Intl. designator 2020-061X) were the two 6U CubeSats forming the FSSCat mission. The "Federated Satellite Systems/^{3}Cat-5" (FSSCat) mission was the winner of the 2017 ESA S^3 (Sentinel Small Satellite) Challenge and overall winner of the Copernicus Masters competition. FSSCat was launched from Kourou Space Port (Guiana Space Centre) using the VEGA 16 SSMS PoC on September 2020. The primary goals were the generation of coarse resolution soil moisture, sea ice extent and thickness maps using L-band microwave radiometry and GNSS-Reflectometry, enhanced resolution soil moisture maps applying pixel downscaling techniques, and the test of techniques for future satellite federations. Secondary goals were sea surface salinity and wind speed maps. ^{3}Cat-5/A carried UPC's Flexible Microwave Payload–2 (FMPL-2), a software defined radio payload implementing an L-band microwave radiometer and a GNSS-Reflectometer [8]. ^{3}Cat-5/B carried Cosine's HyperScout-2 visible and near infrared + thermal infrared hyperspectral imager [9], enhanced with the PhiSat-1 board, an onboard Artificial intelligence experiment for cloud detection [10]. Both CubeSats include an optical inter-satellite link from Gölbriak Space, and a UHF inter-satellite link tech-demos from UPC to test the concept of satellite federations. FSSCat scientific results can be seen in [11].

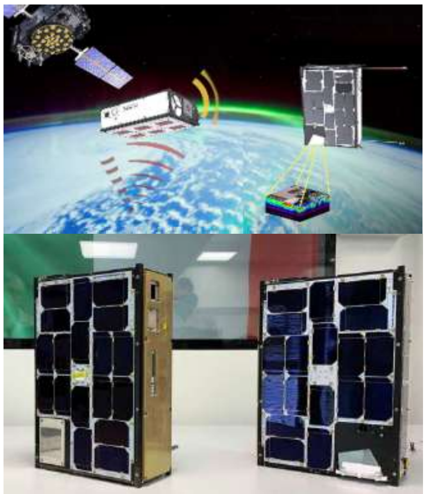

Fig. 7. ^{3}Cat-5/A left and ^{3}Cat-5/B right: FSSCat mission concept (top) and spacecrafts (bottom, courtesy of Tyvak).

3.6. ^{3}Cat-6

^{3}Cat-6/FMPL-3 is an L5/E5a GNSS-R reflectometer hosted payload onboard the GNSS augmentation Signaling (GNSSaS) mission a 6U CubeSat from NSSTC/UAEU (Fig. 8, [12]). It also includes VHF and UHF

DOI: 10.5821/conference-9788419184405.055

receivers for ionospheric scintillation studies. It was shipped on October 2020 to UAE, and it is waiting for final integration and launch in Q4 2022.

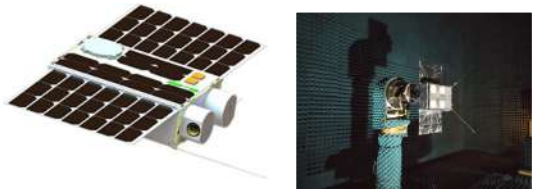

Fig. 7. GNSSaS satellite, and ^{3}Cat-6/FMPL-3 2x2 L5/E5a antenna array for GNSS-R.

3.7. ^{3}Cat-7

^{3}Cat-7/RITA is a combined hyperspectral imager, L-band microwave radiometer, and LoRa IoT communications techdemo hosted payload onboard the AlainSat-1 mission, a 3U CubeSat from NSSTC/UAEU, and one of the winners of the 2nd IEEE GRSS Student Grand Challenge (Fig. 9). It will be shipped to UAE in summer 2022, and launch in expected for Q2 2023.

Fig. 8. AlainSat-1 artist's view (left) and flight model of the ^{3}Cat-7/RITA payload.

3.8. ^{3}Cat-8

^{3}Cat-8 is the newest UPC NanoSat Lab project. It is a 6U CubeSat mission featuring a number of technology demostrators: a deployable Fresnel Zone Plate antenna for GNSS-Radio Occultations, a polarimetric camera for ionospheric studies, an electrospray ionic motor, a PocketQube deployer, and an autonomous beacon for improved satellite identification. At the time of writing this paper the final configuration of the satellite is being defined.

3.9. ^{Po}Cat's

The UPC NanoSat Lab is also developing an "Open PocketQube Kit" for the Institute of Electrical and Electronic Engineers (IEEE). These PocketQubes, generically named "^{Po}Cat's" (pronounced /PoCat/), will be delivered by the end of 2022, together with all designs and oftware as an educational tool and to lower the entry barrier of new actors in the space. The payloads of the three PocketQubes are: a VGA camera, an L-band and a 24.25-25.25 GHz RFI monitoring receivers. Two replicas of these ^{Po}Cat's will be deployed from ^{3}Cat-8 and will be used to test Satellite Federation Concepts among them, the mother satellite (^{3}Cat-8), and ground.

4. Conclusions

This paper has presented a brief historical review of the UPC NanoSat Lab, its facilities, and main projects. Apart from the physical space, all these activities have been developed without a specific institutional support, but with the remnants of other projects, or some specific projects financing them, such as FSSCat and ^{Po}Cat's. More than 300 students have followed the Advanced Engineering Course at the ETSETB curricula linked to the UPC NanoSat Lab, while many others from several degrees have developed their Bachelor or Master's final degree project in the lab. The lab is also a foal point of the Catalan New Space Strategy [13]

Acknowledgements

We want to thank to ETSETB deans Prof. Elisa Sayrol, Ferran Marqués, and Josep Pegueroles, and UPC Chancellors Antoni Giró and Francesc Torres their support to the UPC NanoSat Lab.

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Deployable Fresnel Zone Plate antenna for CubeSats

Alejandro García [1], *Adrián Márquez* [2], *Luís J. Contreras* [2], *Adriano Camps* [2]

Abstract

Earth Observation satellite missions can provide global and frequent coverage. In the past decade we have seen an explosion of these missions based on three unit CubeSats, notably with Planet and Spire constellations of visible and near-infrared imagers and GNSS-Radio Occultations payloads. One of the most important parts of these type of payloads is the antenna, which is limited due to the dimensions of the CubeSats. Today, the largest deployable antenna for CubeSats has a diameter of 50 cm and it was part of RainCube rain radar. ESA is currently sponsoring two studies to develop a 1 m deployable reflector antenna for CubeSats. Although the most common solutions are the deployable reflectors, Fresnel Zone Plate antennas are a simple type of antennas that can overcome some of the technical limitations of these reflectors.

In this paper we will present the design and tests of a deployable Fresnel Zone Plate antenna with 155 cm diameter, at a distance of 58 cm from the feeder. During the design, the modularity of the system has been considered, so that other antenna types can also be deployed. This antenna has a triangular shape, and each end is attached to a telescopic carbon fiber rod, which is deployed by means of a toothed belt that pushes them from its inner part. Each toothed belt is pushed with a DC motor.

If accepted for a launch of opportunity, this antenna will be used in a GNSS-Radio Occultations payload onboard 3Cat-8, one of the future satellite missions of the UPC NanoSat Lab.

Keywords

Fresnel Zone Plate, Deployable antenna, CubeSat

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Acronyms/Abbreviations

GNSS *Global Navigation Satellite System*

U *Unit*

FZP *Fresnel Zone Plate*

PCB *Printed Circuit Board*

1. Introduction

During the last years, Earth Observation satellite missions have gained a lot of interest basically using three different techniques. Some use hyperspectral cameras, other satellites use Microwave Radiometry or Global Navigation Satellite System (GNSS) - Reflectometry and other spacecrafts use radars. Although, these satellites have considerable dimensions, the current trend in this industry is the miniaturization of the payloads and the whole spacecraft as much as possible.

The appearance of the CubeSat [1] form factor standardized the satellites envelope and weight, and has played an important role in the miniaturization process. These satellites are described by Units (U), so a 1U satellite is 10 cm x 10 cm x 10 cm, with a weight of no more than 2 kg. Depending on the number of units that are used, there are different types of CubeSats. With CubeSats, opportunities of faster and more cost-effective development and launch have appeared.

One of the main requirements of these payloads is to have a high spatial resolution, since the resolution is too low, the area covered is large, and the small features cannot be identified. In the case of radio frequency payloads, this spatial resolution is directly related to the directivity of the antenna in the following way: the higher the directivity, the smaller the beamwidth, and the better the resolution. The antenna directivity is proportional to the effective area, and this one is proportional to the antenna dimensions. For example, for a reflector antenna, the directivity increases with the square of the radius of the reflector, or for a Yagi antenna it increases with the number of passive elements. Thus, there is a trade-off between the directivity of the antenna (i.e. having a large antenna) and space available inside a CubeSat, making it difficult to allocate them.

This work is focused on the development of a deployable Fresnel Zone Plate (FZP) antenna for GNSS radio occultations that will be carried in the 3Cat-8 mission, a 6U CubeSat under development by the NanoSat Lab in collaboration with some other research groups. The idea is to have the antenna completely stowed inside the CubeSat during the launch in order to take profit of the standardized deployers for this type of satellites and once the satellite has been put in orbit the antenna must be deployed achieving big enough dimensions to increase the performance of the subsystem in comparison of what has been used until now. This work pretends to cover both the electromagnetic design of the antenna and also the deploying mechanism which is intended to have a certain level of modularity in order to be adapted for different types of antennas or even other type of payloads.

2. Antenna – Electrical design

It is known that, from the Huygens principle [2], any point of a wavefront, can be considered as a source of new waves that expand from that point. Having said that, Fresnel Zones theory says that, having two antennas, positioned in two points, A and B, and working one of them as transmitter and the other one as receiver, the transmitted waves can travel directly from A to B in a straight line, or can arrive the receptor following other paths by reflection, that means, a longer path that introduces a phase different between the direct and reflected beams which, in some cases is destructive, giving place to the destruction of the waves. Nevertheless, the reflection can also cause that the waves arrive in phase at the receiver, enhancing the received wave.

Fresnel zone plates antennas are a type of flat antennas based on the Fresnel zones principle, and they achieve the focusing effect by controlling the phase shifting property of the surface using diffraction instead of refraction or reflection.

This plate consists of a set of concentric rings, known as Fresnel zones, which alternate between being opaque and transparent. Signal hitting the zone plate will diffract around the opaque zones. The zones can be spaced so that the diffracted signal constructively interferes at the desired focus since all radiation from each zone arrives at the focal point in phase within ±π/2 range, concentrating the power in the focal point.

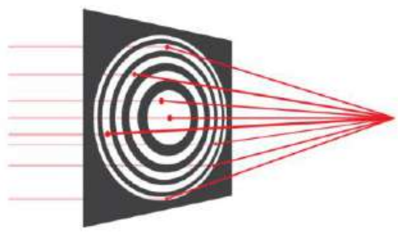

Figure 1. Fresnel Zone Plate [3]

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The radius of every zone is defined according to Eq 1, where F_1 and F_2 are the two focal lengths, λ is the wavelength at the operational frequency and n is the number of the ring.

$$r(n) = \sqrt{\frac{n\lambda F_1 F_2}{F_1 + F_2}} \qquad (1)$$

Knowing that most of the CubeSats are orbiting at LEO orbits, the first focal length (F_1) has been set to 500 km and departing from Eq 1 the rest of parameter values have been found trying to optimize the directivity of the antenna. To do the simulations, an electromagnetic analysis software called CST has been used, and basically with a simplified version of the antenna that had a patch antenna matched at 1575.42 MHz as a feeder, and metallic rings at a distance F_2.

The optimum configuration of the antenna is with a focal length of 580 mm, and with four zones with the radius that can be seen in Table 1 and obtained from Eq 1.

Table 1. Radius of the FZP rings

Zone	1st	2nd	3rd	4th
Radius (mm)	345.7	507.1	642.6	766.1

The obtained radiation pattern for a given plane can be seen in Figure 2 which will be the same for any other plane due to the symmetry of the antenna. It achieves a directivity of 18 dBi and a beamwidth of 8.2º.

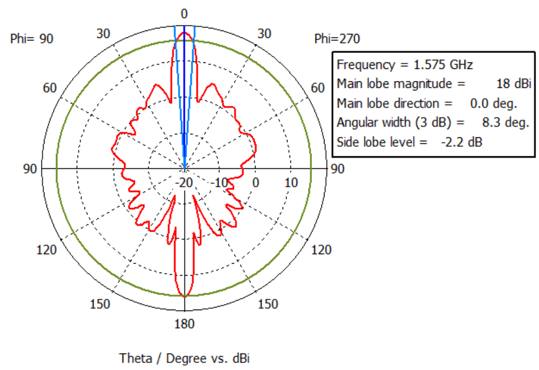

Figure 2. FZP radiation pattern

The real prototype from Figure 3 was designed with three carbon masts that were holding a single ring made with metallic tape. The design was done at 2.7 GHz with the intention of reducing the dimensions of the antenna and measure it in the anechoic chamber.

Figure 3. FZP prototype with two zones

3. Deploying mechanism

As commented in the introduction, the antenna must be stowed during the launch so a deploying system needs to be designed.

Having in mind the triangular shape of the FZP antenna, the idea is to have its three corners attached each one to a mast that will hold it in a flat shape, similar to the one designed for the measurements in the anechoic chamber. Since the FZP is considerably large, the three masts will need to have some deploying mechanism in order to reach the desired deployed length. In Figure 4 it can be seen a simple concept design with which this system can be understood in a better way and all the parts can be identified.

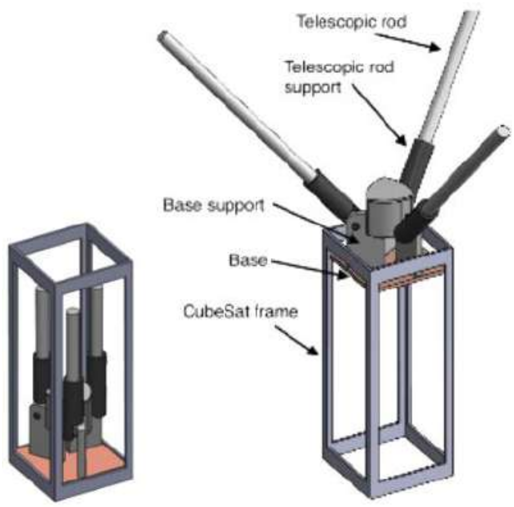

Figure 4. Deploying mechanism concept

In the left draw of Figure 4, it can be seen the stowed configuration with all the system completely inside the CubeSat structure. For the deployment, since the three masts need to rotate some degrees in order to achieve the triangular shape, the system needs to be lifted up from inside the CubeSat until it reaches the top surface of the spacecraft, as it could be seen in the right figure.

3.1. Lifting mechanism

DOI: 10.5821/conference-9788419184405.056

The implemented idea is based in how the CubeSat deployers work. The system should be pushed by a spring that is compressed under the base during the launch storing an elastic potential energy and when it is time to deploy, a mechanism should unblock it and the potential energy becomes kinetic energy which should be enough to lift up the base and all the deployment system until they reach the final position.

The final implementation, uses four springs located in the corners of the satellite structure. These 300 mm long and 12 mm diameter springs have inside an inner 6 mm diameter aluminum circular guide that is part of the satellite frame. Since these guides go from the low part to the top of the satellite structure, they give the frame a lot of rigidity, giving the possibility of considerably simplifying the side walls of the structure and thus freeing up space for the entire deployment mechanism. These guides are also used for the base guiding, which has four linear bearings through which the guides pass, and they make sure that the base doesn't move in the lateral directions.

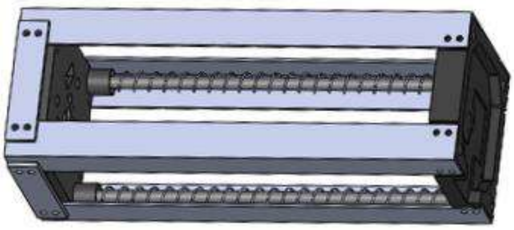

Figure 5. 3U CubeSat prototype frame with the lifting up system

3.1.1. Locking mechanism

Once the system has been lifted up to its final position, it must remain there fixed without no more vertical movement. To do so, three neodymium magnets are attached to the base and three more to the top part of the satellite frame ensuring that once the base has reached its final position, the attraction between the pairs of magnets make to the base not possible to return back and it stays fixed to the top part of the frame.

3.1.2. Holding mechanism during the launch

During the rocket launch, the system must remain stowed and the spring must be compressed. These springs have a considerable elastic potential energy and a robust system must ensure that it will not unlock the system, and cause any damage.

The used system is an adaptation of the one used in the NADS subsystem of the ^{3}Cat-4 mission [4], taking into account the differences between the two satellites. The implemented system is based in three Dyneema lines that are attached to the base of the deploying mechanism and also to the base of the satellite structure. This type of Dyneema wire has a diameter of 0.25 mm and can hold weights up to 23.5 kg, having enough strength to hold all the springs compressed. In the lower part of the satellite structure there is a Printed Circuit Board (PCB) with a burning system based in Kanthal wires. Kanthal is a family of iron-chromium-aluminum alloys with a special ability to withstand high temperatures and having intermediate electric resistance.

In this implementation, the Dyneema wires pass through this Kanthal wires and once it is a applied a 3.3 voltage to these Kanthal wires, the high amount of current makes the temperature of the wires increase with the result of cutting the Dyneema lines and allowing the system to be unlocked and lifted up.

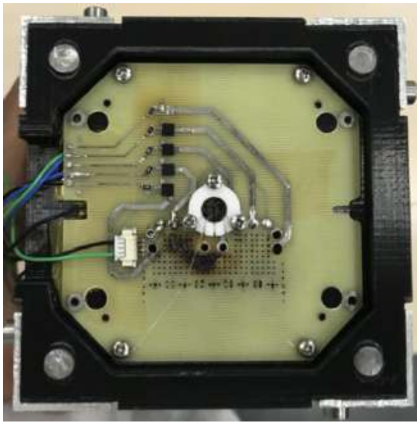

Figure 6. PCB for the Dyneema lines burning

3.2. Masts deployment

Once the deploying system has been pushed by the springs and has reached its final position in the satellite structure, it's time for the deployment of the FZP.

The three masts that hold the FZP are three telescopic carbon fiber rods composed of cylinders of different diameter. These cylinders have a folded length of 17 cm and a deployed length of 200 cm. The system is the same used as for the fishing rods.

3.2.1. Angular movement

Once the system has been lifted up, these rods need to rotate some degrees until they reach

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the appropriate angle. This rotational movement is ensured by means of a rotational spring located near the center of rotation of the rods as it can be seen in Figure 7.

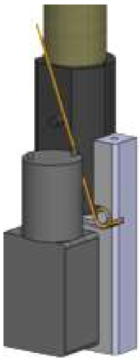

Figure 7. Rotational spring for the angular movement of the rods

Once these rods have reached their final position, they need to stay fixed without having any rotation. The forward movement is avoided in the final part of the deployment when the FZP starts making strength and avoids this movement. The backwards movement is avoided with a breaking system that has been designed minimizing as much as possible the occupied space. As it could be seen in Figure 8, the axis of rotation of the carbon rod supports, has a flange that is maintaining the break folded. Once the rod has rotated and the flange has also rotated, a small spring pushes the brake to its final position and this one fits with the flange shape avoiding the backwards movement.

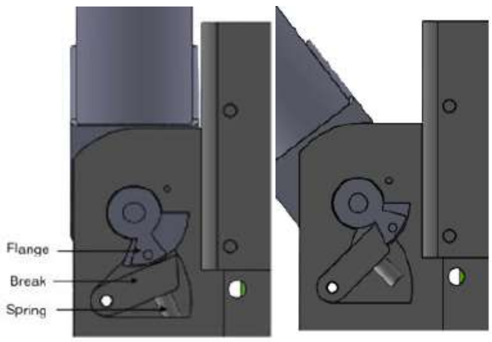

Figure 8. Angular movement brake

3.2.2. Telescopic deployment

The final part of the deployment is basically to deploy the telescopic rods until they reach their final length. To do so, there is a toothed belt that goes inside the rods and pushes them from its inner part. At the same time these toothed belts need to be pushed with a motor. The idea of using only one central DC motor was considered but then it was substituted by the idea of using three of them one per each rod. The use of three motors has several advantages like being able to deploy the three branches sequentially reducing the peak power consumption, it simplifies the gear system that is needed for the case of using a single motor and also increases the modularity of the system since each mast can be operated independently and have different deployed lengths. Each motor is attached to the pieces that hold the rods called base supports, and its axis of rotation is attached to a gear that pushes the toothed belts. This configuration can be properly understood in Figure 9.

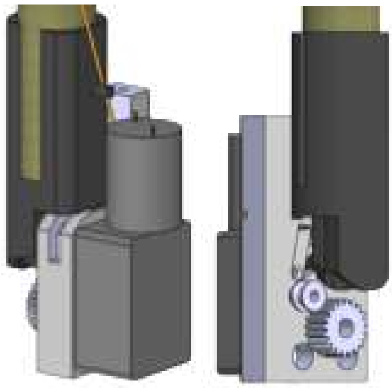

Figure 9. DC motors attachment

The three toothed belts are stored in the bottom part of the base and each one is rolled in a reel that has an inner hole with a strategic shape to guide the belt to the position of the gear where the motor pushes it.

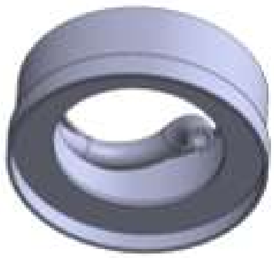

Figure 10. Toothed belt reel

4. Results and discussion

4.1. ·Electromagnetic analysis

After the measurements in the anechoic chamber of the prototype, the directivity results were compared with the ones obtained in the simulation. The measured one was 12.5 dBi and the one from the simulation was 14.8 dBi. There are 2.3 dB of difference which is a considerable amount taking into account the logarithmic scale. There are several factors that could have affected but the most important ones are the manufacturing imperfections, the non-perfect conductivity of the materials and the movement of the support of the anechoic chamber that caused some vibrations on the FZP among others.

4.2. Deployment

All the designed pieces for the deployment system have been 3D printed in order to make some testing on the deployment before start manufacturing with aluminum and all the space rated components that are needed like the motors, the PCB or the bearings. In Figure 11 there can be seen three pictures of the prototype system in the three stages of the deployment. The used FZP is a cloth without the conductor rings that has been used to simulate the tension that a similar and definitive one must be doing once the antenna is completely deployed.

Figure 12. Complete system prototype

As a first prototype the system performed well both for the lift up system and for the telescopic deployment of the rods.

5. Conclusions

Regarding the electromagnetic simulations, one of the points that needs to be improved is the Front to back ratio. As it could be seen in radiation pattern, the principal lobe has nearly the same radiation levels as the back one. One of the possible solutions that is being considered is to implement the conductor rings with a conductor material in the top part and an absorbent material in its bottom part to avoid the signals coming from the back part of the satellite to be also detected by the feeder.

Regarding the deploying system, a general conclusion would be that the prototype is performing well and achieving the expected goals but there is a lot of work to do until it is ready to be launched in a space mission. There are a lot of innovative ideas inside each part to cope with all the requirements and these ideas now need to be exhaustively tested under space conditions with a thermal vacuum chamber and a shake table to validate them.

One important aspect is that although the system seems to be really specific for this application, it has a lot of modularity. For example, in case that it is needed to deploy a specific sensor some distance away from the satellite, using a single rod and adapting the rest of the parts it could be done really easy. Another example could be the case of deploying a reflector with a certain offset respect to the satellite axis, it could be done by varying the length of the three branches and also modifying the angle of rotation of these branches.

Acknowledgements

I would like to express my special thanks of gratitude to the whole NanoSat Lab team and specially to the ones who have participated in this project and those who are still working on it.

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Space Games:
Evaluating Game-Based Virtual Reality in Higher Education

Lana Laskey[1]

Abstract

With increasing global dependence on satellite technology, space traffic has grown exponentially over the last decade. Enhanced education and training of future mission operators will be necessary to meet this growing demand. The complexity of satellite mission operations poses a challenge in education and training. Remote spacecraft are elusive and difficult for a trainee to visualize and involve a steep learning curve. However, the integration of *game-based virtual reality* into spacecraft simulation and training may assist in overcoming these challenges. This research study explored the integration of *game-based virtual reality* into a university course involving spacecraft operations. Virtual spacewalks allowed student participants to conduct visual inspections and interact directly with spacecraft components. The immersive virtual reality environment prolonged cognitive engagement and game mechanics influenced motivation, both cornerstones in learning. After completing the training scenarios, user experience was assessed with several validated scales measuring system usability, user satisfaction, cognitive loading, and any potential simulator sickness. Results revealed satisfactory scores in all categories with minimal simulator sickness. The integrated use of *game-based virtual reality* in the classroom provided an enhanced learning experience in a safe and repeatable environment that might be difficult with traditional teaching methods. This paper will evaluate *game-based virtual reality* when integrated into higher education or other training environments.

Keywords

Game-Based Virtual Reality, Instructional Design, Simulation, Spacecraft Operations, Training

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Acronyms/Abbreviations

CLS	*Cognitive Load Scale*
EL	*Extraneous Cognitive Load*
EL_vr	*Extraneous Cognitive Load due to Virtual Reality*
GBVR	*Game-Based Virtual Reality*
GL	*Germane Cognitive Load*
GUESS	*Game User Experience and Satisfaction Scale*
IL	*Intrinsic Cognitive Load*
MCLSVE	*Multidimensional Cognitive Load Survey for Virtual Environments*
SSQ	*Simulator Sickness Questionnaire*
SUS	*System Usability Scale*
VR	*Virtual Reality*
VRSQ	*Virtual Reality Sickness Questionnaire*

1. Introduction

Game-based instruction uses game mechanics for serious educational purposes [1] and has been found to increase learner satisfaction and motivation [2]. Additionally, virtual reality (VR) applications provide an immersive learning environment encouraging concentration and prolonged cognitive engagement [3]. These elements are essential for effective learning and have been found helpful in teaching complex disciplines [4]. Merging the two instructional strategies produces an enhanced pedagogical approach known as game-based virtual reality (GBVR). When developing instructional tools and techniques for a complex discipline such as spacecraft operations, employing GBVR may help encourage learner motivation and prolonged cognitive engagement necessary to achieve learning objectives. This study aims to integrate and evaluate an instructional design using GBVR in higher education and provide a quantified pedagogical assessment for educational practitioners, researchers, and industry personnel tasked with training complex disciplines.

2. Methodology

A quantitative experimental design was employed to examine the user evaluation of GBVR when integrated into a university course. Participants consisted of 15 university students enrolled in a spacecraft operations senior capstone course. The average age of all participants is 23.8 years (*SD* = 4.0), including 3 females and 12 males. All participants underwent the same treatment consisting of a 10-minute computer-based pre-training session (simulating spacecraft ground control) followed by a 10-minute GBVR training session (simulating an on-orbit spacewalk) and post-test surveys (see Figure 1). Participants were immersed in the VR environment using a software package titled *Mission ISS* [5] and worked from a seated position to minimize simulator sickness [6]. Participants were equipped with a *Valve Index VR kit* consisting of two hand-held controllers and a head-mounted display [7]. The independent variable is GBVR training, and the final survey scores serve as the dependent variable. Survey results were captured using four validated scales outlined in section 2.1.

Figure 1. Spacecraft Operations Laboratories: Computer-Based Pre-training Simulation (left) GBVR Simulation (right)

2.1. Validated Scales

Several previously validated scales were employed during this study to evaluate whether the instructional design of course material and laboratory tools met specific criteria. The list of criteria includes adequate system usability, appropriate user satisfaction, balanced cognitive loading, and minimal simulator sickness. The following subsections will describe the scales used to measure each attribute.

2.1.1. System Usability

The *System Usability Scale* (SUS) was developed in 1986 as a subjective assessment tool for evaluating user perception of hardware devices and software applications regarding

DOI: 10.5821/conference-9788419184405.057

system complexity, ease of use, functionality, and user confidence [8]. The SUS survey will be used to evaluate the laboratory setup and equipment. The SUS survey contains ten questions rated on a 5-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree). Final composite scores are ranked on a scale from 0 to 100 (0 = Worst Imaginable, 100 = Best Imaginable) [9], with a score of $M = 68$ being the published average standard [8].

2.1.2. User Satisfaction

The *Game User Experience Satisfaction Scale* (GUESS) [10] was developed in 2016 as a 55-question survey to measure user satisfaction and enjoyment during gameplay and later revalidated as an 18-question survey (GUESS-18) [11] to be used for this study. The questions are rated on a 7-point Likert scale (1 = Strongly Disagree, 7 = Strongly Agree) covering nine constructs: usability, narratives, play engrossment, enjoyment, creative freedom, audio aesthetics, personal gratification, social connectivity, and visual aesthetics [11]. Scores are tabulated by summing the averages across all nine subscales and dividing by the maximum score of 63, resulting in a final score ranging from 0 (worst) to 100 (best). Six popular video games tested with GUESS-24 produced an average score of $M = 78.7$ (49.6 raw score divided by 63) [12] and will be used as the standard for this study. Survey wording will be modified from “play/playing” and “game” to “operate/operating” and “sim,” respectively.

2.1.3. Cognitive Loading

The *Cognitive Load Survey* (CLS) was developed in 2013 to measure the interactions between the various types of mental loading imposed on the learner during exposure to instructional material, tools, and strategies [13]. The CLS survey is comprised of ten questions measuring the interaction between the various types of cognitive loading and rated on a scale from 0 (not the case at all) to 10 (completely the case). Final scores are averaged for each loading type and ranked on a scale from 0 (low) to 10 (high). According to cognitive load theory [14], there are three types of cognitive loading: intrinsic, extraneous, and germane. Intrinsic cognitive load (IL) relates to task complexity and should be kept in a medium to low range (Approx. 2-5) to avoid disengagement of the learner due to tasks being either overly complex or exceptionally easy. Extraneous cognitive load (EL) impedes the learning process due to nonessential instructional elements and should be kept to a minimal level (Approx. 0-2). On the contrary, germane cognitive load (GL) refers to instructional features beneficial to learning and should fall within the medium to high range (Approx. 5-10). Furthermore, the *Multidimensional Cognitive Load Scale for Virtual Environments* (MCLSVE) [15] was developed later in 2018, adding four EL questions to the original survey regarding virtual environments (EL_vr), and will be used for this study.

2.1.4. Simulator Sickness

The *Simulator Sickness Questionnaire* (SSQ) was developed in 1993 to measure simulator-induced symptoms of nausea, oculomotor eye strain, and disorientation [16]. The SSQ survey consists of 16 questions rating each symptom on a 4-point Likert scale (0=none, 1=slight, 2=moderate, and 3=severe). Later in 2018, the *Virtual Reality Sickness Questionnaire* (VRSQ) was derived from the SSQ by reducing the survey to 9 questions [17]. VRSQ researchers eliminated the 7-question nausea category due to low reporting of nausea symptoms during their research trials with VR applications [17]. Consequently, the VRSQ will be used for this study. Final composite scores are tabulated based on proportional weighting of each symptom and rated on a scale of 0 (no symptoms) to 100 (severest symptoms). Studies show that longer immersion time will likely increase self-reported post-test symptom severity [18]. Since the average time of participant exposure for this study was approximately 10 minutes, the 0-15 minute range will be used, indicating an average symptom severity score of less than $M = 9.5$ [18].

3. Results

One-sample t-tests were conducted to compare participant results to the benchmark standards for the SUS and GUESS-18 measurement scales (see Table 1, Figure 2, and Figure 3). For the SUS survey data, the results indicated significantly higher scores for the simulation group ($M = 88.2$) compared to the accepted average score ($M = 68.0$), $t(14) = 5.88$, $p < .001$. A large effect size of $d = 1.52$ was revealed, demonstrating that the participants found the simulation relatively easy to use. For the GUESS-18 survey data, the results indicated significantly higher scores for the simulation group survey score ($M = 86.7$) compared to the average popular game score ($M = 78.7$), $t(14) = 3.87$, $p < .001$. A large effect size of $d = 0.99$ was indicated, signifying a high level of user enjoyment and satisfaction.

The mean comparisons for the MCLSVE and VRSQ results to the benchmark standards can be found in Table 1, Figure 4, and Figure 5. The mean MCLSVE scores (M_{IL} = 2.4, M_{EL} = 1.6, M_{EL_vr} = 1.4, and M_{GL} = 8.7) placed within the approximate accepted ranges ($0 < M_{IL} < 2$, $2 < M_{EL} < 5$, $2 < M_{EL\_vr} < 5$, and $5 < M_{GL} < 10$) [13]. Finally, the average VRSQ scores (M_{Avg} = 6.2, M_{Dis} = 5.8, M_{Ocu} = 6.7) also placed within the accepted range ($0 < M < 9.5$) [18].

Table 1. Study Results vs. Standard Benchmarks [8] [11] [13] [18]

	N	Min	Max	*M*	*SD*	Standard (*M*)
SUS	15	50.0	100.0	88.2	13.3	68.0
GUESS-18	15	73.0	99.2	86.7	8.0	78.7
MCLSVE IL	15	1.0	5.3	2.4	1.5	Approx. 2-5
MCLSVE EL	15	1.0	4.7	1.6	1.0	Approx. 0-2
MCLSVE ELvr	15	1.0	4.0	1.4	0.8	Approx. 0-2
MCLSVE GL	15	6.5	10.0	8.7	1.2	Approx. 5-10
VRSQ	15	0	25.8	6.2	8.0	0-9.5

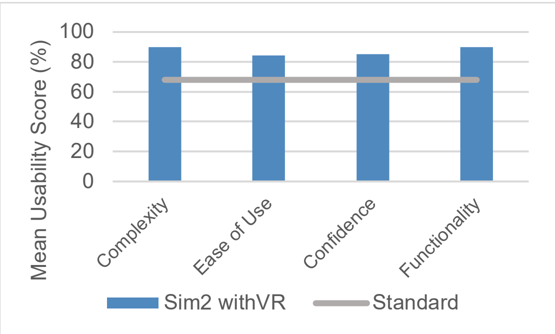

Figure 2. System Usability Scale (SUS) [8]

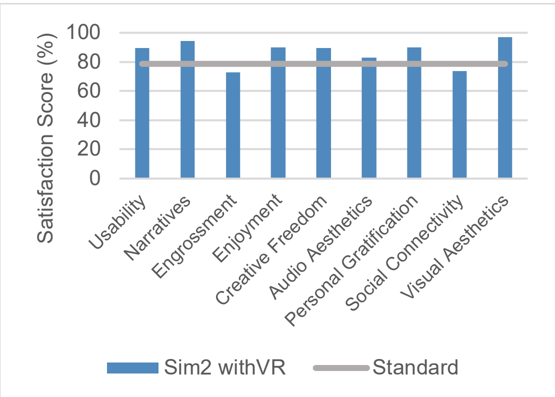

Figure 3. Game User Experience Satisfaction Scale (GUESS-18) [11]

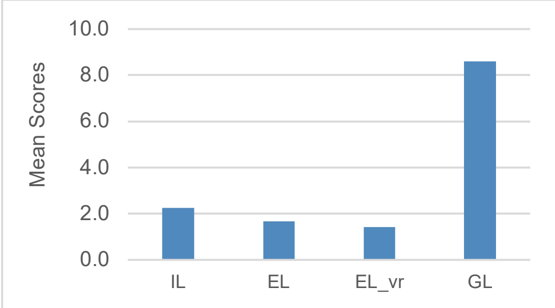

Figure 4. Multidimensional Cognitive Load Scale for Virtual Environments (MCLSVE) [15]

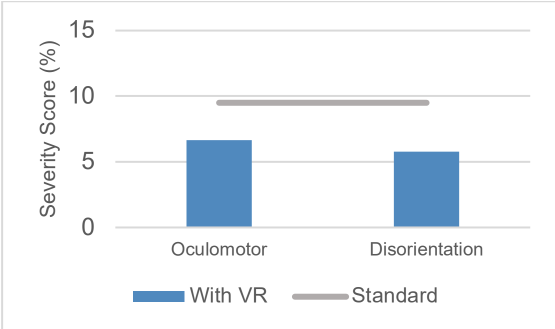

Figure 5. Virtual Reality Sickness Questionnaire (VRSQ) [17] [18]

4. Discussion

Compared to accepted benchmark standards, the GBVR instructional design employed in this study demonstrated satisfactory results in all categories, including system usability, user satisfaction, cognitive loading, and simulator sickness. As shown in Figure 2, system usability scores rated excellent along the SUS adjective scale [9] in complexity, ease of use, user confidence, and functionality. Successful usability scores are likely due to the effective laboratory setup, including the virtual reality simulation software (*Mission ISS* by Magnopus, 2019), game controllers, and head-mounted displays (*Valve Index* by Valve Corp., 2022).

Overall GUESS-18 user satisfaction scores (M = 86.7) in Table 1 scored significantly higher than the benchmark standard (M = 78.7). As shown in Figure 3, high scores in enjoyment and personal gratification indicate user motivation and interest in completing tasks skillfully, which are fundamental to student learning. The high level of user satisfaction is likely due to effective game mechanics such as game narrative, aesthetics, and goal accomplishment, including immediate feedback and reward. All categories exceeded the average popular game score (M = 78.7) except for social connectivity (M = 73.8) and play engrossment (M = 72.9) (see Figure

DOI: 10.5821/conference-9788419184405.057

3). This is likely due to the single-player educational activity offering no in-game social connection, like in the case of mainstream gaming communities. Conversely, during gameplay, the instructor gave verbal direction from outside of the GBVR environment. This interaction with someone outside the game may have slightly deterred play engrossment.

Notably, the SUS and GUESS-18 scales illustrate convergent validity regarding system usability. The overall SUS usability score (M = 88.2) and the GUESS-18 usability subscale score (M = 89.5) differ by only 1.3%, depicting converging scales (see Table 1, Figure 2, and Figure 3). This similarity further validates that survey questions from both scales accurately capture participant perceptions of system usability along with neighboring constructs of each scale.

The MCLSVE results displayed in Table 1 and Figure 4 indicate that appropriate cognitive balancing was imposed on the participants. Intrinsic loading ranked properly above 2.0 (M_{IL} = 2.4), while extraneous loading ranked appropriately below 2.0 (M_{EL} = 1.6, M_{EL_vr} = 1.4). Based on the accurate balancing of IL and EL, the remaining availability of participants' mental processing capacity contributed to high levels of germane loading, above 5.0 (M_{GL} = 8.7). Successful cognitive balancing is likely due to the proper instructional design of the curriculum content. Task complexity adequately matched the learner's skill level, while nonessential extraneous loading was kept to a minimum.

Lastly, the VRSQ scores indicate low severity of symptoms due to VR simulation (see Table 1 and Figure 5). The average disorientation score (M_{Dis} = 5.8) ranked well below the known average limit (M_{Avg} = 9.5) [18]. Likewise, the average oculomotor score (M_{Ocu} = 6.7) ranked well below the known average limit (M_{Avg} = 9.5) [18]. These results are likely attributed to effective lab equipment and students performing VR activities from a seated position [6].

A limitation of this study was the small sample size (n = 15), as this could restrict generalizability over the target population. Although the sample was small, the results were significant, and large effects were generated within the group of participants. However, repeating the study with a larger sample could further improve generalizability and external validity.

5. Conclusions

The integration and evaluation of GBVR in the classroom revealed noteworthy results. First, based on proper laboratory setup, system usability rated excellent along the SUS adjective scale [9] in complexity, ease of use, user confidence, and functionality. Second, based on effective game mechanics, overall user satisfaction ranked significantly higher than six popular video games analyzed by Shelstad et al. (2019). Third, cognitive loading was adequately balanced based on proper instructional design, facilitating student learning. Lastly, simulator sickness did not exceed acceptable minimums due to an effective laboratory format. These positive results set the foundation for potentially enhanced student learning. With GBVR correctly integrated into the classroom or training environment, learner enjoyment and satisfaction may be amplified, likely leading to increased motivation, cognitive engagement, and skill retention [1] [4].

Acknowledgements

I recognize all student participants for their contributions and excitement for spacecraft operations.

Thank you, Trevor Goodwin and the XR lab team, for their support and assistance with VR laboratory equipment and activities.

Thank you, Embry Riddle Aeronautical University, College of Aviation leadership for the development and continued support of the XR laboratory facilities available to all faculty and students.

Thank you, Dr. Stephanie Fussell, for sharing your expert knowledge, guidance, and research in education and training with virtual reality applications.

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Space Education: Challenges and Strategies in Teaching Space Policy to Technical University Students

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Abstract
Law and policy provide the foundation for space actors engaging in space activities. Likewise, various levels of policy and regulation apply internationally, domestically, and even institutionally to both governmental and nongovernmental entities. Consequently, teaching the policy frameworks for space regulations and best practices is essential for a comprehensive university curriculum in space education. Challenges arise, however, when instructing technical and non-policy university students in humanities-centered topics. *Reading comprehension, writing ability, critical thinking*, and *communication skills* are critical elements of policy education, yet many technically oriented students struggle with these requirements. Given these are fundamental skillsets necessary for success in both academia and a dynamic space work force, adapting traditional teaching methodologies may be required to optimize desired learning outcomes for technical student audiences. Customizable strategies exist that can combine and scale these fundamental skillsets with substantive content and materials, providing a range of teaching and learning modalities for study, assessment, and experience. This presentation will highlight potential learning approaches tried at one aeronautical university to address these challenges.

For instance, overarching strategies may include commencing with a visual of the student journey (much like a user journey in an investment pitch) delineating the value-added experience for students engaging in course content, and building substantive skill-based learning components which are introduced sequentially and with increasing level of difficulty. Examples of learning methodologies include applying Bloom's Taxonomy in assignment creation. Most importantly: 1) *Knowledge*: involves identifying, understanding and remembering core content (e.g. pop quizzes, reading quizzes, cumulative review quizzes, question bank assessments); 2) *Analysis*: involves reading comprehension, interpretation, evaluation, analysis (e.g. essays, summaries, case studies); 3) *Application*: involves investigation, research and designing research projects (e.g. research articles, posters, digital presentations, short videos). Scaffolding assignments and artifacts into manageable pieces throughout the semester is key to guiding students towards success and reducing potential for 'expert blind spots.' Lastly, an end-of-course review and self-reflection of the student journey is helpful in underlining the critical thinking process and provide a visual review of the student journey in acquiring substantive knowledge, skills, and experience throughout the term.

Keywords
Space Policy, Space Education, Critical Thinking, Taxonomies of Learning

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1. Introduction

Course subjects in space law, policy and ethics form a unique but integral part of the Spaceflight Operations program at Embry-Riddle Aeronautical University (ERAU). Given the interdisciplinary nature of the program, course student enrollment comprises of Science, Technology, Engineering and Mathematics (STEM), as well as non-STEM and technical aviation students. Two introductory and mid-level law and policy courses are mandatory for majoring in the Spaceflight Operations program, which also attracts students outside the program seeking elective fulfilment in space related topics. Another two advanced courses are offered to Senior undergraduates and graduate students in applied space policy and regulation with requirements for original research and written analytical outputs.

As a technical institution, education is necessarily bifurcated into developing knowledge and applied skillsets at ERAU. In the policy and law courses students are educated in general law and policy concepts, specific international space treaty regimes, development of national space laws, space related agencies, and pertinent regulations. In addition, students conduct research; draft industry style reports and documents; discern the practical components and regulatory requirements for acquiring a license/permit for conducting spaceflight activities; compare/ contrast spaceflight activities and law/ policy implications across space companies, technologies, and mission architectures. Furthermore, students learn to identify and distinguish the pertinent values, interests and objectives impacting industry and government interrelationships and informing space policy development. So, while the core objective of the curriculum is knowledge based, inherent skillsets are required for both knowledge acquisition and practical application to successfully demonstrate competence in the course subject matter.

2. Teaching Challenges and Learning Strategies

Several challenges exist for industry experts and academics teaching professional and advanced policy related topics at a technical university. First, teaching humanities focused substantive content, even in a simplified format, is challenging without assessing and honing student core skillsets (significantly, reading and writing abilities). Secondly, student openness and willingness to adapt to new learning modalities as well as new substantive content, outside their comfort zone, is likewise challenging but essential. Ordinarily, law and policy courses are reading and writing intensive seminar classes, with critical analysis and discussion being central to the learning experience (e.g. Socratic Method). However, this traditional teaching method was not successful here and required adaptation given the university's program objectives and refocus on educating and training industry ready technicians, not academics or policy professionals. Course redesigns were therefore warranted utilizing Bloom's Taxonomy [1] in redefining course content and developing learning assignments and assessments in line with other technical courses in ERAU's College of Aviation. Ultimately, streamlined teaching approaches appealed more to students given their familiarity with this course structure and digital assessment formats. Student performance and satisfaction increased overall within a year of implementing these teaching modalities. The student learning experience and assessment plan was formatted around the core taxonomies of *knowledge, analysis,* and *application.*

2.1. Knowledge

Knowledge acquisition involved identifying, understanding, and remembering core content. Strategies to achieve knowledge retention included in-class pop quizzes (time restricted but open book); weekly reading quizzes (complete within multi-day window, two attempts permitted), based on current lectures and reading assignments; periodic cumulative practice quizzes based on course readings provided for memory review and retention at the end of each course section; and structured online assessments with the ability to test categories of knowledge using randomized questions from question banks to objectively gauge substantive learning. In summary, increasing opportunities for content repetition and recall were beneficial to student knowledge acquisition as demonstrated through objective grading of assignments.

2.2. Analyses

Analyses involved reading comprehension, interpretation, evaluation, and analysis. In these courses, analytical writing was best suiting to take home assignments, such as drafting analytical reports, synthesis and summary briefs, weekly reflections on news and policy developments, examing case studies, and reading and critical thinking exercises etc. Higher level and graduate course requirements increasingly incorporate case studies/ scenarios with written assessments. Significantly, written analytical assignments were scaffolded for level of difficulty and in alignment with weekly course topics.

2.3. Application

Application involved individual and small group investigation, conducting research, expert interviews, and designing research projects. Applied assignments were particularly feasible and successful at the senior and graduate level. Assessments here included substantial hands-on outputs and artifacts including drafting an original conference-worthy research article, creating and delivering research posters, digital presentations and filming short student videos summarizing the students works on industry issues, scenarios, and policy issues.

3. Skill Set Requirements

The requisite skills required to address substantive learning in law, policy and ethics for spaceflight include: 1) critical thinking, 2) active reading, 3) analytical writing, 4) research skills, and 5) effective communication. These skillsets are focal to the core curriculum in both fundamental and advanced coursework. Furthermore, these skillsets are developed in tandem with substantive knowledge and scaffolded to improve on inherent weaknesses and build competencies. Examples of the skillset requirements with correlating learning challenges and applied learning strategies and assignments implemented are attached in Appendix A. The purpose, objectives and outputs of these skills sets were intentionally tiered throughout the course and developed by combining the seven learning strategies advanced by Ambrose et al. [2] and concepts from Martha Stassen's Program-Based Review and Assessment [3].

3.1. Critical thinking

Critical thinking is defined as reflective thought [4] and is essential here to both understanding law/ policy and being able to foresee implications of applied law, decision-making, and choosing courses of action/ inaction. In addition, critical thinking is key to understanding core issues and learning how to frame a question appropriately to find a valid answer.

3.2. Active Reading

Focused and active engagement in reading and class preparation is a challenge for many students. Learning strategies adopted here (e.g. reading guides, quizzes) aimed to motivate and encourage student engagement and prepare for class meetings. Allowing two attempts at reading quizzes with pinpointed answers following the final attempt provided students with an opportunity to reflect on mistakes and ultimately be able to locate the correct answers in the assigned readings.

3.3. Analytical Writing

Analytical writing incorporated the prior two skillsets of substantive reading comprehension and reflective thought capabilities. Here correct knowledge must be applied and is evaluated for accuracy in form and substantive validity. Analytical approaches and exercises included variations on the analytical formula of issue, rule, analysis, conclusion (IRAC), and integrating evaluative approaches (comparing, contrasting, and distinguishing facts, issues, rules, cases) as used in law and policy. This analytical mindset/ skillset is taught in a manner that can be applied ubiquitously to any discipline or industry.

3.4. Research Skills

Developing strong and efficient research skills is universally key to any practice or discipline. Furthermore, this skillset inherently incorporates the skillsets of critical thinking and reading, and adapts analytical writing to creating concept maps, brainstorming research paper topics, formulating topical searches, evaluating sources, drafting research queries, and develops communication abilities with librarians and external experts for research purposes.

3.5. Effective Communication

This cumulative skillset is present in the previous skill tiers and culminates with the presentation of the acquired knowledge, and application of that knowledge. Effective communication, information and feedback provided on assessments to students were collated based on this author's experience and training with legal presentation skills, interpersonal communications, and drafting a wide range of academic, legal, and business documents. For instance, students are provided with a professional email template, complete with explanations for each line component and full sample communication, for applying in class communications and also for use in external professional communications.

DOI: 10.5821/conference-9788419184405.058

3.6. Demonstration of Mastery

Ambrose et al. explain knowledge mastery as a three-tier learning process incorporating the acquisition of component skills, practice in integrating skills, and knowing how to apply skills [2]. Given the nature of law and policy as applied to an inherently unique and specific topic of spaceflight, this author takes the Mastery diagram one step further. Acquisition of knowledge and skills is impossible without the ability to also think out-side-the-box and understand the underlying values and concepts both informing space policy and law development and being impacted by the legislative process and industry objectives. Hence, the spheres of Mastery [Figure 1] have at their core the underlying values and concepts informing the perceptions for knowledge interpretation and application.

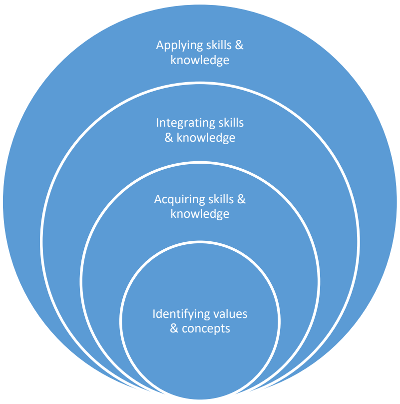

Figure 1. Mastery Diagram [1]

4. Further Considerations

Revising law/ policy curriculum and teaching strategies courses to suit a young technical audience can be daunting initially. Applicable course materials are limited for teaching at this level and forum, which means creativity and professional expertise are required simultaneously to teach the subject matter, and connect it to relevant forms (e.g. analogous examples, issues, rules, interpretations and authorities) for future applications. Lack of standardized textbooks or course materials for these courses also potentially leads to expert blind spots which must be identified and addressed. In addition, all materials must be sourced, evaluated and/or created by the instructor. This can present a heavy burden up front. Once the revision is completed, student assessments must also be monitored to ensure teaching effectiveness, taking into account class dynamics can impact overall performance outcomes and differ from term to term.

4.1. Expert Blind Spots

Expert blind spots are where the educator is not consciously aware of skills or knowledge required to complete a task [2]. This can manifest in omission of substantive information or failure to provide procedural steps to complete complex tasks. For example, unpacking core concepts and elements of law (e.g. negligence vs strict liability regimes) or utilizing professional language without explanation (e.g. legalese, industry terms of art, speed of articulation and comprehension). What is evident to an expert will not necessarily be clear to the student. Even ordinary terminology may lack clarity. For instance, one class struggled with the concept of a 'full sentence outline' and required a draft sample to follow before they understood the scope and purpose of the assignment. As a result, subject matter guides and sample provisions for even perceived basic skills are now provided to ensure student clarity and to demonstrate expectations (e.g. how to draft a paragraph, bibliography, abstract, brainstorm a mind/ concept map).

4.2. Evaluating and Curating Resources

Sourcing a range of digital resources is also an ongoing task for reinforcing lectures, course content and knowledge retention. Videos, podcasts, e-books, and digital products provide additional supplementary education. For instance, the United Nations' audiovisual library of international law space law series. Up to date authoritative publications and handbooks on space policy and law considerations for new space actors are limited, however, given the dynamic nature of policy and geopolitical support for national and commercial space objectives. However, recent resources help to simplify and highlight complex topics in space policy and law in digestible segments.

The benefit of curating these resources include making the overarching topics publicly accessible, available in a variety of consumable formats, and understandable to the ordinary layman. The challenge in surveying publicly available resources is that they tend to be very broad which may render superficial knowledge for the average student, and the illusion of knowledge can present a liability in practice. Conversely, if the content is too high level or dense the student loses interest quickly and has difficulty learning. Additionally, in conducting a search for quality educational space law and policy resources, it is clear that while some relevant space law/ policy resources exist, careful evaluation must be made to filter

DOI: 10.5821/conference-9788419184405.058

through myriad opinion to provide accurate and objective informative for educational purposes. This is an ongoing examination for professionals and students alike. Not all publications or opinions are true, valid, or accurate. Consequently, “Evaluating Sources” has become a mandatory online training program required here to teach students how to effectively conduct research and screen current events, policies and evaluate source credibility and authority.

4.3. Additional Strategies

Three additional overarching strategies were initiated to help connect the dots in the student learning experience. First, presenting a visual demonstration of the student journey through the course. Secondly, articulating and explaining the class teaching philosophy, identifying key ethical approaches applicable to both life and educational learning. Lastly, creating an opportunity for students to reflect on their entering objectives and concluding self-assessment in the course.

4.3.1. Visualizing the Student Journey

Commencing each term with a visual aid or flow chart of the student journey has been helpful for delineating the value-added experience to encourage students to engage in the course, much like a user journey in an investment pitch. Here, the visual journey incorporated the substantive course content and milestone markers (e.g. assessments) demonstrated the consistent scaffolding of substantive knowledge and skill-based learning components which are introduced sequentially and with increasing level of difficulty.

4.3.2. Teaching Philosophy

Providing students in the introductory class with a chart identifying the professor’s teaching philosophy and ethical values for the course, along with the rationale of those values and how they serve to improve quality of life experience both inside and outside the classroom (e.g. accountability, self-responsibility, openness to learning/relearning). While this knowledge is not new, the format and unpacking of the core values is often new information for students.

4.3.3. Student Reflections

Students are also asked to complete intake surveys identifying their academic status, career interests, and learning objectives in the course. Upon end of term, students are asked to reflect on their entrance surveys and articulate their self-evaluation of earlier goals and ultimate success. This student ‘reflection’ is distinguishable in form and purpose from the marketing style end-of-term student evaluations provided by the institution. The aim here is to provide the opportunity for students to think critically and reflect ethically on their learning journey, see how far they have come in their knowledge and skill development, and/or hold themselves accountable for their performance in the course. These reflections are graded but designed as a pass/fail assignment to provide an incentive for participation.

5. Conclusions

In conclusion, teaching law and policy at a technical university is still an ongoing challenge. Adapting traditional and disciplinary teaching methods for a less humanities centered and more technically focused audience is inevitable. However, core taxonomies centered around knowledge acquisition, integration and analysis, and knowledge application to novel scenarios can provide an optimal structure for a curriculum redesign. Clearly identifying the core knowledge base and skillsets based on contemporary student knowledge, retention capacity and ability to connect learning to application can be customized successfully. Ultimately, scaffolding of content, assignments, and skillsets was key to optimizing the student learning experience and increasing student performance. As a work in progress, the teaching methods and modalities listed here are still under observation and will likely require tweaking based on class dynamics and program objectives going forward.

Acknowledgements

The author would like to thank the Embry-Riddle Department of Applied Aviation Sciences, College of Aviation, for its support to present this work at SSEA 2022.

Appendix

Appendix A Example Teaching Strategies

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Appendix A Example Teaching Strategies

Ex. Skillset Requirements	Ex. Learning Challenges	Ex. Learning Strategies
Critical Thinking	Knowledge identification, comparison; distinguishing facts, values, positions, statements etc.; applying rational thought analysis (e.g. if we accept x, then what?); framing intelligent questions	• Attention to detail exercises (e.g. issue spotting, rule spotting) • Drafting questions/reflections • Evaluating written sources (popular news posts, blogposts, scholarly articles • Evaluative assessment questions • Scenario based questions • Case study analysis
Active Reading	Reading comprehension, speed reading,	• Note taking/ reading guides • Chapter summaries/ outlines • Reading quizzes • In-class pop quizzes • Cumulative review quizzes
Analytical Writing	Substantive reading, reflection, analytical writing skills (e.g. IRAC, CRAC, FRAC)	Drafting assignments • Topic explanations • Abstract proposals • Full-sentence outlines • Annotated bibliographies • Policy briefs/ industry briefs • Analytical research papers
Research skills	Critical thinking, reading comprehension, evaluating sources, library and digital resource skills	• Digital research skill trainings • Library research trainings (e.g. video modules/certification, in person training) • Subject Matter research guides/ How To Research Guides • Substantive website review (e.g. UNOOSA website) • Research tasks (e.g. research quizzes, summaries) • Annotated bibliographies
Effective Communication	Clear, effective, collaborative communication, distinguishing audience, appropriate communication style, communication modalities (e.g. instrument form, function, persuasiveness)	• Class communication policy • Basics on communication etiquette (with example digital communications templates) • Peer review (written, verbal) • Guided course surveys, reflections, evaluations • Posters presentations • Papers presentations • Short video summaries

DOI: 10.5821/conference-9788419184405.058

Hypatia I: a multi-generational and multi-disciplinary crew of female analog astronauts dedicated to space research, scientific outreach, and promotion of female role models in space careers

Arias Helena, Badenas-Agustí Mariona, Conejo-González Carla, Ribas Laia, Farrés-Basiana Ariadna, Jar Núria, Sabaté Neus, Cufí-Prat Cesca, Bach Anna.

Abstract

The low representation of women (~33%) in Science, Technology, Engineering and Mathematics (STEM) careers is extremely concerning and cultivates male-dominant cultures across a variety of academic and professional disciplines. In Spain, only 39% of national projects are led by women, thus evidencing the so-called "leaking pipeline", that is, the tendency of women and other underrepresented groups to eventually abandon STEM-related fields. This social disequilibrium is particularly strong in the international space sector, where women represent less than ~20% of the workforce. The Hypatia I mission —a multi-generational and multi-disciplinary crew of 9 female scientists— seeks to help address this problem. In April 2023, the Hypatia I crew will participate in a two-week Martian analog mission at the Mars Desert Research Station (Utah, United States) with the goal of (i) performing high-quality space-related research in a simulation environment, (ii) conducting outreach and science communication activities, and most importantly, (iii) promoting female role models in STEM-related fields and inspiring future generations of scientists, particularly young girls interested in space careers.

Keywords

Female, Space exploration, Space outreach, Mars, Analog mission

1. Introduction

1.1. The role of women in science

Women's under-representation in Science, Technology, Engineering and Mathematics (STEM) careers is a longstanding issue, which slowly improves but remains an ongoing challenge.

Despite progress towards achieving close to gender parity in the overall pool of Ph.D. graduate in Europe since 2010, women graduates are still under-represented in the STEM fields of Physical Sciences (38.4%), Mathematics & Statistics (32.5%), ICT (20.8%), Engineering (27%), among others. Moreover, a greater proportion of men are employed as scientists and engineers compared to women within the total labor force (4.4% and 3.1% respectively). These statistics have barely changed since 2017, and while the average growth rate of women researchers has been 3.9% since 2010 –thus showing some positive changes over time– women still represent around one-third (32.8%) of the research workforce in Europe [1].

In Spain, 42.7% of the research community who published at the Web of Science (WOS) between 2014 and 2018 were women. This represents 47.7% of the Spanish scientific production during this period [2]. However, only 20% of the Spanish scientific production had a woman as a principal investigator, and only 39% of national projects are led by women [3], thus evidencing the so-called "leaking pipeline", that is, the tendency of women and other underrepresented groups to eventually abandon STEM-related careers.

Statistics show that these numbers decrease particularly when it comes to the space field and the aerospace industry, where the percentages are roughly the same proportion as 30 years ago [4]. In this sector, less than ~20% of the workforce are women, and if we look at the privileged group of people who have been in space since 1961, when Yuri Gagarin became the first astronaut, only 11% have been women —mostly white— and only 7% of women have been able to take space walks [5].

1.2. Mars Exploration

The proximity of Mars to Earth, coupled with its prospects for future human settlements, make this planet extremely interesting for the field of space exploration. As of today, more than 49 international missions have conducted research on this planet, 13 of which are still operational. There are also 7 missions in development and 16 proposals to be fulfilled before 2030 [6]. Despite this interest, the complexity of sending astronauts to Mars, together with the risks they involve, make it challenging to set a date for the first human mission to the Red Planet [7]. As a result, Martian analog missions have become important to develop technologies, test safety and emergency protocols, and evaluate personal needs for a future crewed mission to Mars.

1.3. The Mars Desert Research Station

Located in the Utah desert (USA), the Mars Desert Research Station (MDRS) is a space analog facility designed to simulate a research facility on the surface of the Red Planet. Since it started to host analog operations in 2001, it has welcomed more than a thousand participants, all of them supervised by a Mission Support center composed of international volunteers with a shared passion for Mars [8].

The MDRS typically invites crews for two-week rotations –a time of confinement and isolation during which the selected crew members attempt to design and create useful technologies and scientific experiments for future crewed missions to Mars. The desert landscape reminds us of the Martian environment, thus making the station one of the most suitable places for Martian analog missions.

The MDRS station contains six separated modules and each of them covers different mission requirements. These include a habitat (Hab), two observatories (the Robotic Observatory and the Musk Observatory), a GreenHab, a Science Dome and a Repair and Maintenance Module (RAMM). All these buildings are communicated with tunnels to let the scientists remain in the simulation as they move between the various MDRS infrastructures.

Figure 1. The Mars Desert Research Station is a facility set in the Utah desert and contains six modules. From left to right: the Science Dome, the Musk Observatory and the Hab. Source: The Mars Society.

2. Hypatia I Crew

Hypatia I is a multi-disciplinary, intergenerational, and all-female crew from Catalonia, Spain, selected to participate in an analog mission at the MDRS in April 2023 [9]. Our crew is named after an extraordinary woman from the Mediterranean who lived during the Byzantine Empire and devoted her life to the study of mathematics, astronomy, philosophy, and the arts despite the religious bigotry of her time [10]. In the spirit of Hypatia, a role model for many women today and a symbol of the connection between the sciences and the arts, our crew embodies the belief that future human settlements on Mars will need people with a variety of interests across all ages and disciplines.

The crew, composed of seven primary and two back-up members, will conduct high-quality space-related research into astronomy, space biology, and engineering during its two-week Mars analog simulation at the MDRS. The members of Hypatia I are presented below:

2.1. Primary crew members

- The Crew Commander and Astronomer is Mariona Badenas Agustí, a Ph.D. candidate in Planetary Sciences at the Massachusetts Institute of Technology (MIT). She graduated in Astrophysics from Yale University and earned a master's degree in Astrophysics, Cosmology, and High Energy Physics from the Autonomous University of Barcelona and the Institute for Space Studies of Catalonia.
- The Crew Executive Officer and Biologist is Carla Conejo González, Head of Science Programs at the Fundació Catalunya La Pedrera. She earned a degree in Human Biology by the Pompeu Fabra University, a master's degree in Pharmaceutical and Biotechnological Industry by the same university, and a postgraduate's degree in Science Communication by the University of Vic.
- The Crew Scientist and Health and Safety Officer is Dr. Arianda Farrés, Ph.D. in Applied Mathematics from Universitat of Barcelona and a member of the Flight Dynamics team at NASA Goddard Space Flight Center, where she specializes on the impact solar radiation pressure has on Liberation point orbits and on optimization of station-keeping maneuvers.
- The GreenHab Officer is Dr. Laia Ribas, senior researcher at the Institute of Marine Sciences of the Spanish National Research Council (CSIC). Before earning her Ph.D. in Biological sciences from the Universitat Autonoma de Barcelona, she worked as a postdoc at the Imperial College of London, United Kingdom. Dr. Ribas is also a member of SONET and participated in the Nüwa project to design a city for 1 million people on Mars.
- The Crew Journalist is Nuria Jar, a freelance journalist specialized in science and health. She earned a master's degree in Scientific, Medical and Environmental Communication and has extensive experience working for some of the most important Spanish media outlets and the international community of science journalists.
- The Crew Engineer 1 is Neus Sabaté, an ICREA Professor at the Institute of Microelectronics of Barcelona and the co-founder of Fuelium, a spin-off company that works on paper-based batteries for single use portable devices. She leads the Self-Powered Engineered Devices Group (SPEED), developing sustainable diagnostic devices that optimize the amount of electronic components and extract the energy required to perform the test from the sample under analysis.
- The Crew Engineer 2 is Cesca Cufí-Prat, an aerospace engineer at Airbus Defence and Space. specialized in attitude and orbital control systems. She graduated in Aerospace Engineering at Universitat Politècnica de Catalunya and earned a master's degree in Aerospace Engineering

DOI: 10.5821/conference-9788419184405.059

with a specialization in Space Systems at Institute Supérieur de l'Aeronautique et de l'Espace.

2.2. Back-up members

- The Back-up Crew Scientist and Artist in Residence Anna Bach, who graduated in Mathematics and Computer Science from Universitat de Barcelona. She currently works as a Product Analyst at the American multinational Scopely, a video game company with its European headquarters in Barcelona. Anna also draws comics trips on a regular basis that she posts on her Annet Planet Instagram page (@annetplanetcomics).
- The Back-up Crew Engineer Helena Arias, a double-degree student of Mechanical/Electronics Engineering and Physics at the Universitat Politècnica de Catalunya and the Universidad Nacional de Estudios a Distancia. She has participated in student research programs at the Instituto de Astrofísica de Canarias and the Weizmann Institute of Science, and she currently works at the Department of Physics of the UPC while developing her own start-up Light Pills.

Figure 2. Hypatia I Crew. From left to right: Mariona Badenas Agustí, Carla Conejo González, Ariadna Farrés Basina (first row); Laia Ribas, Nuria Jar, Neus Sabaté (second row); Cesca Cufí-Prat, Anna Bach, Helena Arias Casals (third row).

3. Hypatia I Projects

The main goals of Hypatia I are to (i) perform space-related research at the MDRS, (ii) communicate science through outreach activities in order promote STEM vocations, and (iii) share new, contemporary female role models, especially among young girls.

3.1. Current projects

To promote scientific and technical vocations among young students, the Hypatia I crew members have already given numerous outreach talks in a variety of primary and secondary schools. As an example of its educational impact, Hypatia I was featured at Info K, a newscast broadcasted in the channel for children of the Catalan TV (Super3, TV3) in November 2021: https://www.ccma.cat/video/embed/super3/6132389/

They have also participated in a variety of public events, including the SONET Meeting organized by the SONET Project; the DonaTIC Awards, and the NewSpace Community Presentation organized by the Catalan Government; the WIA-E Barcelona #Women4Space organized by the Women in Aerospace Europe; and the #100tífiques Meeting organized by the Barcelona Institute of Science and Technology and the Catalan Foundation for Research and Innovation.

In addition, the Hypatia I crew is leading and developing an educational course for Primary students (6 to 12 years-old) on how to become astronauts. The course will guide children to discover the basics of space-related research and covers all the science fields that Hypatia I crew will tackle during the mission at the MDRS (see section below): astronomy, engineering, space medicine, biology, and science outreach and communication. The course has been designed with the collaboration of Marina Domènech López and Mireia Kun Masvidal, referent professionals specialized in science education in Primary and Secondary level respectively. Both of them are part of Hypatia I Orbitals —women professionals that "orbit" the crew to offer specialized aid in different aspects of the initiative. The "Astronauts Course" is being deployed in collaboration with SOM-Abacus, a Catalan company.

3.2. Future projects: MDRS Projects

3.2.1. Astronomy

The astronomy projects will be mainly conducted by the Crew Astronomer. On the one hand, she will create color-magnitude diagrams of stellar clusters, groups of stars with similar compositions [11]. On the other hand, she will search for new asteroids and minor objects in space to contribute to the diverse international Space Situational Awareness projects [12]. She will also perform astrophotography of deep-sky-objects in order to share them in outreach activities.

3.2.2. Space Biology

Research into circadian rhythms in space will be carried out by the Crew Biologist. She will study the effects of the changes that astronauts have to make on their daily routines such as the change of workload and the longer schedules (a sol has 24 minutes more than an Earth day) [13]. The GreenHab Officer, will study the aquaculture on Mars with the aim of finding out the effects of environmental factors on the food productivity. To carry out her research, she will work with zebrafish. Cellular intelligence will also be studied at the MDRS by one of the Crew Engineers, who will study the influence of ultraviolet, visible and infrared radiation on the behavior and sporulation of the *Physarum Polycephalum.*

3.2.3. Engineering

Three projects will be carried out in the field of engineering during the MDRS mission. The Crew Scientist will study the different possibilities of Martian navigation: firstly, she will find reference stars to create a simple sky-map; secondly, she will research the creation of a small GPS network constellation made of CubeSats. The Crew Engineers will both design and build a suitable housing for the Physarum Polycephalum and study the possibility of creating sustainable organic batteries from the rough and abundant materials present in the Martian desert surface.

3.2.4. Outreach and communication

Daily reports and photos will be delivered by the Crew Journalist. She will also work on a narrative podcast called The sounds of Mars, where she will explain the daily challenges of the crew during the mission and the state of the research done at the MDRS. Articles and reports will also be sent to the media outlets. In addition, the Crew Journalist will write a journal in order to compile material to write a long-form story that could be published as a book.

The Crew Executive Officer will also work on a Mars on Earth alternative tourism project. The public have lately shown interest in visiting the MDRS as it is an attractive project for people that are interested in space-related research. That is why she will provide information to create awareness of the wonders of this remote place, the purpose of the simulations, the projects of the crew and the experience during the exploration.

Finally, the Crew Astronomer and Crew Scientist will share their passion for Mars and create outreach activities to learn about observational astronomy as well as navigation in remote places.

4. Hypatia Association: Hypatia I and beyond

One of the objectives of Hypatia I is to inspire girls to pursue space-related research and become role models for future generations. On February 11th 2022, the International Day of Women and Girls in Science, the Hypatia Association was founded. The goals of the newly created organization are to keep the Hypatia's project values alive and to support future crews of women to travel to the MDRS to conduct Mars-related research. We expect Hypatia I to be just the first of many crews.

5. Conclusions

To date, the low percentage of women in STEM —especially in the aerospace sector— is a concerning problem for society as a whole. To help overcome it, the Hypatia Association and its first crew will attempt to reduce gender inequalities and visibilize the contributions of female scientists by offering a chance to underrepresented communities to travel to the MDRS, pursue space-related research, and share their work with the general public. Hypatia I will be the first crew to achieve this goal in April 2023.

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A multi-project student space association

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Abstract

The aerospace sector has always been a challenge. The complex nature of the field requires for talented, skilful engineers. And while the university does great on the development of the theoretical background, it barely gets into the practical application. This is why embracing educational activities is critical to help students develop their technical and teamwork skills in the professional sector.

UPC Space Program is an engineering student association based in the Terrassa campus of the Polytechnical University of Catalonia (Spain), and formed by 5 missions and 80 members. Each mission targets a field of interest in the space sector: rocketry, UAVs for space exploration, High Altitude Balloons, rovers and CubeSats. The sharing of the common spaces by such a number of people who are working on so many and diverse projects creates a vibrant and creative environment that incites learning.

Our work is aligned with the current activities in the space sector. As the exploration of the terrestrial bodies of the Solar System highly benefits from the use of rovers, our Grass mission is focused on the development of planetary exploration rovers. After achieving 10th place in the European Rover Challenge 2021, the objective is to further upgrade the vehicle for the next edition. But currently, a new exploration focus is appearing as flying vehicles are entering the stage. In this context, our Aldora mission is based around a concept mission to Titan via an autonomous plane capable of deploying scientific probes. Obviously, space exploration is not possible without the presence of space transport vehicles. In this matter, Ares mission is focused on the development of High Power amateur rockets. Currently, Ares is developing a supersonic rocket set to participate in EUROC 2022 competition. But most of the payloads carried by rockets are satellites. In this field, the Horus mission aims to investigate and optimize the manufacture of a CubeSat, along with mission performance, to create a fully operational satellite, currently set to participate in the Europe to Space competition. Finally, there is yet another way to perform space science. Our Zephyros mission works in the development of High Altitude Balloons, also developing a set of experiments to test in near-space conditions. The next objective is to achieve the first student-developed zero pressure balloon in Spain.

Keywords

Multi-project, Student's Association, Rocketry, High Altitude Balloons, CubeSats, UAVs, Rovers

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Acronyms/Abbreviations

ADCS	*Attitude Determination and Control Subsystem*
CAD	*Computer Aided Design*
CFD	*Computational Fluid Dynamics*
FEA	*Finite Element Analysis*
RTG	*Radioisotope Thermoelectric Generator*
STEM	*Science, Technology, Engineering and Mathematics*
UPCSP	*UPC Space Program*
VTOL	*Vertical Take Off and Landing*

1. Introduction

1.1. Introduction and state of the art

The curriculum of engineering degrees tends to have a scarcity of hands-on experience. It is logical, as the class hours are limited and there is a considerable amount of theoretical knowledge that has to be passed on if the students have to become, one day, engineers.

That said, this creates a disconnection between the student and the real world. It is a problem, as students end up mistaking the mathematical models for the real thing when it is not the case.

It is for this reason that getting involved in student projects is one of the best things to do when coursing an engineering degree. It allows the students to take the theoretical teachings to build the real things, learning important lessons like those computations that have to be verified with experimentation or some designs that are very nice in theory may not be the most practical when it comes to building them.

Nowadays, student projects in the space field are widespread among worldwide aerospace engineering universities. Only in Spain there are various rocket teams, cubesat student projects, rover groups... in cities like Madrid, Bilbao and, as is the case for this paper, Terrassa (Barcelona province). Most of them share one thing in common, their association is focused on only one project kind. Space projects in real life, except for private companies, have a different approach. Usually, space agencies develop various space missions.

This approach, up to a certain extent, is followed by UPC Space Program (UPCSP) [1]. UPCSP consists of 5 missions that are each related to a space project. Mission Ares is working on supersonic amateur rockets, Mission Grass is working on rovers for planetary exploration, Mission Zephyros is working on high altitude balloons for scientific research, Mission Horus is working on nanosatellites and Mission Aldora is working on a drone for the exploration of Titan. All this, obviously in the frame of the student and university capabilities.

Having all the missions under one association nurtures a creativity-rich environment. Missions share the spaces when working on the projects, which allows for talking about the different missions, sharing of knowledge, and some members even end up working on various missions at the same time, which would be very difficult to do if it were separate associations.

1.2. Objectives and scope

UPC Space Program, which is part of EUROAVIA Terrassa [2], is an engineering student program formed by more than 80 members from different engineering backgrounds whose objective is to apply the knowledge acquired during their degrees in missions related to the aerospace field. Each mission targets a field of interest in the aerospace sector, as mentioned before. UPCSP does not only focus on the technical part, but also the social and human part. In this aspect, the creation of a multidisciplinary project was conceived to accomplish different objectives.

Firstly, UPCSP serves as a learning and professional launchpad for all students [3]. The main goal of this organisation has always been the capability of giving means to all students to develop their skills and put to practice the knowledge obtained during university. UPCSP provides the perfect tools and conditions to gain experience in an environment where team cooperation and learn-by-doing are the foundation principles of the team's daily basis. Moreover, UPCSP not only gives access to technical knowledge by the participation as an active member in the organisation, but also by performing training sessions open to all students interested.

Secondly, UPCSP aims to enable technological progress in the region of Catalonia, thereby helping to pave the way in the development of disruptive and experimental technologies that will enable easy access to space and its exploration. These activities serve as the perfect foundation to establish the basic knowledge and experience needed to successfully start a career in the space sector, which is sometimes difficult to access. Overall, all these aspects are in consonance with the new and innovative space economy, NewSpace [4], currently being developed.
The early stage of this sector makes difficult a fast development of the infrastructure and technical interest in the field. To tackle this problem, UPCSP is involved in projects where

universities and companies cooperate to create a proper environment that enables the easier development of technology and their industries. In fact, UPCSP aims to help the sector and provide value by performing collaborations with relevant companies. Examples of past collaborations are Everis Aeroespacial, HP, etc.

In addition, UPC Space Program is a key platform that enables social interaction and interpersonal skills. Bringing students together and stimulating teamwork is critical to enable the creation of a working environment that promotes equality, honesty and cooperation. Specifically, UPCSP contributes to promote aerospace activities in the university and society, as well as to encourage early involvement in STEM careers among the female sector (Figure 1).

Figure 1. Some of the female members of the UPC Space Program

Finally, one of the main objectives of the UPC Space Program since its creation has been to promote and increase the interest in aerospace activities among young students. This allows university students to better understand technical processes, as well as to enhance their motivation in developing careers in the sector. To accomplish this, UPCSP empowers its participation in competitions, attendance to public events and university talks, etc. Great examples of successful promotions of the aerospace sector have been the XXIII Congreso Virtual AEAE, Splashdown Festival 2019, SURTAM and XVI Exposició Anual de Modelisme, among others.

2. Methodology

2.1. Technical methods

While the specific approach to the development of the mission projects varies depending on mission and on the particular element being developed, in the general point of view, the missions follow a lifecycle similar to the mission phase scheme used at ESA, albeit simpler and without the rigorous scrutiny that an ESA space mission is put through.

The project begins with an idea or concept, which is debated and analyzed by the mission team. If the mission agrees that it is interesting and doable, it is carried on. This could be related to phase 0 in the ESA mission lifecycle.

In the next phase, simplified designs are made and put through initial computational analysis to define a baseline for the design of the vehicle or payload. This could be related to phase A.

When that is done, the baseline created in the previous phase is materialised in CAD, incorporating the required elements for a functional vehicle, like the internal structure. By means of more elaborated computational analysis like CFD and FEA analysis, the design's correctness is assessed. Then, based on the results the design is modified accordingly (this could be related to phase B). And finally, the design is further improved, adding more elements and complexity, until everything is included (this could be associated with phase C).

While the design is being improved, the vehicle may begin to be built. The time available to develop these is much more limited than in a real mission, and, at the same time, mistakes are not as expensive. The electronics departments may even begin development at the same time that the CAD is being made. As the vehicles are being developed, the built structures are tested for resistance and the electronics are tested to verify their performance. This building and testing phase may be related to phase D in ESA missions.

The next phase is the operation of the vehicles (Figure 2), performing the tasks that they were designed for. This would be Phase E in the lifecycle of ESA missions.

Figure 2. Members of UPC Space Program preparing a rocket launch

DOI: 10.5821/conference-9788419184405.060

There is one final phase, that takes place before the mission team takes on a new project. The old vehicle that will not be used anymore, is generally hung in the walls or ceilings of the UPC Space Program workshops, for all the members to marvel at. Not all missions may follow the same route for disposal though, as some vehicles may be broken or some may even be sent to space in the future. This would be associated with Phase F in the ESA mission scheme.

2.2. Organisation methods

In an association formed by almost a hundred members, taking care of the organisational structure and management of the resources is critical to ensure a correct operation of the entire program. In order to assess these aspects, each one of the 5 missions that conform UPC Space Program counts with its own coordinators and technical departments. Each mission is independent, but a common core is shared between all of them, and that is the UPCSP's directive board. This entity, formed by the general coordinators, mission coordinators, treasury members and secretary, is the responsible for the management of the association. The cooperation among members is crucial to guarantee the progress of the entire program.

In fact, the usage of project management techniques combined with the application of a systems engineering approach is key to develop a strategic plan which ensures the success of such a big multidisciplinary project. Each mission is responsible for defining objectives, studying their viability and ensuring the fulfilment of a yearly calendar comprising all the different stages the mission must accomplish. This schedule management, along with the articulation of specially tailored requirements and scope points, identification of risks and their response plan, economic resources management and cost reduction measurements; allow UPC Space Program to successfully develop and intelligently manage all ongoing projects.

This framework of assuming responsibility roles is an inherent benefit in such a massive project, thereby allowing the coordinators and members to prove their adaptability to new work methodologies and software tools, as well as improving their critical thinking and teamworking abilities. This, without any doubt, is not only a skillset that is really valuable if the student is to enter the professional market, but also useful to broaden their perspective of the space sector and to train possible future actors that will, in time, be part of some of the NewSpace entities that employ them.

3. Activities and accomplishments

3.1. Aldora Mission

The Aldora mission began as a mission focused on developing VTOL aircraft. That project ultimately was discarded as most of the first members finished university and left the mission. Some vertical flight prototypes were built and flew, and other two prototypes intended for VTOL flight were 3D printed with multijet fusion printing, but those two never flew because faults in the novel 3D printing technology caused the weight to be above the permissible values. Some of those original Aldora members ended up founding a start-up of VTOL drone package delivery, which today is very close to entering operation.

After that phase, a mission concept was devised, for a drone to fly on Titan and to be able to study locations that both rovers and aerial vehicles would have a hard time reaching by deploying scientific probes from the aircraft.

The drone in the real mission most likely would have to be given VTOL capability in order to take-off and land on Titan, as landing would be required to charge the batteries from an onboard RTG. During the flights, the aircraft would scout the surface in search for points of interest to deploy probes in order to study the locations. The aircraft itself would also carry instruments in order to perform measurements in the areas where it did actually land.

A big advantage of the concept is the capability that the aircraft would have of studying the hydrocarbon lakes. The probes could be designed to sink when reaching the lakes, thus allowing for the study of the depths of the lakes, and later activate an inflatable device in order to return to the surface and send the data. On another note, cryovolcanic regions would highly benefit from this probe approach to take measurements. By carrying various probes, losing one or various does not mean end of mission and thus riskier activities can be undertaken.

Regarding the actual work being developed by the Aldora mission, its objective is to perform an analogue mission to the Titan concept, but on Earth. Aldora has designed a conventional aircraft (instead of VTOL, for simplicity) with space for storing the probes inside the fuselage. This aircraft is a 3 meter-span drone designed for Earth flight being built with composite materials.

DOI: 10.5821/conference-9788419184405.060

Once built, the aircraft will be equipped with probes also designed by the team and it will perform flights, deploying the probes in points of interest. The probes will take measurements and send them to the aircraft. It is also expected to deploy probes in masses of water and test the sinking and then resurfacing approach that would be performed in the hydrocarbon lakes of Titan.

3.2. *Ares mission*

The Ares mission is the branch of the UPC Space Program dedicated to the development of High Power amateur rockets based on additive manufacturing techniques, ranging from 2-stage subsonic launchers to 1 stage supersonic rockets.

The ultimate goal of Ares mission is to successfully design, build, test and launch a two-stage supersonic amateur rocket, Ares III.

Since its foundation in 2016, 4 rockets have been built and launched, evolving different aspects of the design and construction process in each one. From the Ares I, a two-stage rocket intended to test the electronics and the structure, the mission has evolved into designing the Phobos, a rocket whose aim is to compete in European Rocketry Challenges for universities. Such rocket project is also being presented in SSEA 2022.

3.3. *GRASS*

GRASS is the robotics branch of the UPC Space Program, and it focuses on ground rovers for planetary exploration. Their main goal is to participate in international competitions by designing and building a rover able to perform a series of tasks.

The team is currently participating in the European Rover Challenge (ERC) where the teams and their rovers are tasked with performing a series of trials in a Mars analogue terrain. The trials cover a myriad of functionalities: the capability to traverse rough terrain, the fine motricity of the robotic arm, to probe placement or scientific exploration…

The team's first participation in the ERC in 2021 yielded a 10th position, and the team's vision is to become a habitual participant in the ERC, and participate in additional worldwide competitions across the globe. To accomplish this the team is building a competitive base which can be adapted for the multiple tasks and requirements of such competitions. This project is also being presented in SSEA 2022.

3.4. *Zephyros Mission*

Mission Zephyros is the mission dedicated to high altitude balloons. It began being called Neslab, a mission with the objective of creating an experimentation platform in the stratosphere. Neslab went on to the Global Space Balloon Challenge 2016 and won the prize for the best photograph (Figure 3).

Figure 3. Earth photograph taken by Zephyros

Then, the Astronaut Children project was developed: drawings made by children from the Sant Joan de Déu hospital were carried with the balloon and it was retransmitted live for the children to see.

Then Neslab changed its name to HAB, and made it its objective to standardize and improve the subsystems from the previous missions.

The next and current phase has been named Zephyros. The current main objective is to develop the first amateur zero pressure balloon of Spain. This will give Zephyros a robust platform with the ability to stay airborne for an indefinite amount of time for the development of various experiments. This implies the development of a suite of subsystems such as telemetry, killswitch and valve control.

In parallel, work on such experiments to fly on this balloon or in BEXUS has been performed. Two experiments are being developed:

- An experiment to fly a drone in the stratosphere, in order to study flight in a lower density environment.
- A cloud chamber experiment to detect cosmic rays, where the cosmic ray detections at the surface and in the stratosphere will be compared.

The cloud chamber experiment is being presented also in SSEA 2022.

DOI: 10.5821/conference-9788419184405.060

3.5. Horus mission

We know that space missions are ever-changing, with increasingly sophisticated operations, that is why now, more than ever, satellite missions require innovation and solutions to eschew the famous issue on space debris. In November 2021 we formed a new team of multidisciplinary students to investigate and optimize every process related to the manufacture of a CubeSat.

The goal of this Horus mission is to develop the attitude control system for two 1-unit CubeSats in order to establish laser-based communication between them.

With the aforementioned goal in mind Horus mission engaged with Selene, the first UPC Space Program 1U CubeSat prototype. The ADCS department, which develops the orientation control of the satellite, investigated whether the control was more precise using reaction wheels and magnetorquers regarding its accuracy and energetic efficiency. Another point was to use additive manufacturing so it induces less space debris. The communication subsystem intends to make use of a laser system to establish communication between two satellites and regarding propulsion, Horus has researched on ways to propel the satellite with electrostatic ion thrusters or solar sails.

Overall, the idea has been presented for the Europe to Space challenge, which aims to give university students, from any major, the possibility to work on a real space mission, from its conception to the operations in orbit, in just one year. Our idea was accepted and successfully got to the second phase.

The next step of the mission resides in integrating all the components that have been developed and build the first prototype following the standards that are present in a space-related project.

4. The future of UPC Space Program

What does the future hold for UPC Space Program? It is only anyone's guess how the future will be, but we know where we want to be headed.

First of all, we want to maintain the friendly, collaborative and creative environment that has been accomplished, while at the same time we want to improve certain aspects. For one, the ratio of female to male members is low, as is usually the case in engineering disciplines. We want to increase our outreach efforts to show every girl that engineering is also for her if she wants it to be.

On another note, we want to further increase the quality and level of our projects. This means upgrading the materials and techniques used and entering higher class competitions.

GRASS, for example, hopes in the future to not only go to ERC but also to the University Rover Challenge. Aldora has plans to make its drone autonomous as that would be required for flight in a place where messages from Earth take an hour and a half to reach. Horus is determined to send a satellite to space. Ares will continue to build larger and more powerful rockets to compete in international competitions and Zephyros will keep improving its balloon technology to enable more science to be performed in a near-space environment.

Acknowledgements

We would like to thank all current members of UPC Space Program and all members that at some point have been part of it, especially to all former coordinators and program founders. The success of the project has been possible thanks to their skills, rigorousness and their tireless spirit through all these years.

Obviously, this would not be possible without the help of our sponsors and partners, who provide the needed tools and resources to face the adversities and technical challenges that arise during the development of the projects. Special thanks to EUROAVIA, Universitat Politècnica de Catalunya, Valispace, Altair, HP, Resineco and all other companies involved.

Last but not least, the UPCSP thanks the 4th SSEA22 Scientific Board for enabling young students to present their projects and get in touch with the scientific community.

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Findings from the ESA Education Fly a Rocket Campaign - Sensor Experiments Team

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Abstract

The paper summarises the endeavour of 24 students during a Fly a Rocket campaign in October 2021. The programme is an educational week-long activity aimed at university students with limited hands-on experience. The campaign took place at Andøya Space Center and was possible by the collaboration of ESA Education, Andøya Space, and the Norwegian Space Agency. The participants learnt about the fundamental aspects of a rocket launch campaign, from deciding the scientific case, rocket assembly, safety briefings and countdown procedures. The students came from diverse backgrounds, such as aerospace engineering, electrical engineering, physics, mathematics and astronomy. They were divided into three groups for the campaign: payload, telemetry and sensor experiments. The paper mainly focuses on the findings of the sensor experiments group. It first introduces the launch campaign details and the online course. Then, all the steps that went into the scientific cases, which students had to prepare, are summarised. The cases they decided to work on included a comparison of the trajectory simulation done in OpenRocket and the real-life measurements, cloud detection using optical and humidity sensors, the measurement of the spin of the rocket and the collection of data from the atmosphere that was compared to the international standard atmosphere. This paper aims to share the learning outcomes from this campaign with the wider public and students. The collaboration and responsibilities of the students taught them many important lessons, most notably the importance of diversity and the significance of cross-communication between teams.

Keywords

Andøya Space Center, ESA Education, Fly a Rocket, OpenRocket, Sensor experiments

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Acronyms

DOF	Degrees of freedom
IMU	Inertial measurement unit
ISA	International standard atmosphere

1. Introduction

This paper is the result of ESA's Fly a Rocket campaign 2020-2021, and its main goal is to provide an inside look at the program as well as details on one of the main scientific cases. At the beginning of the paper, the focus will be primarily on the campaign's prerequisites, such as the online course, the launch campaign, and the completed study cases. Moving forward, the emphasis will shift to the paper's main study case, the comparison of real-world sensor data and OpenRocket predictions for the calculated trajectory of the Rocket. The main result would be the OpenRocket simulation's accuracy compared to real-world scenarios.

2. Fly a Rocket

The Fly a Rocket Program is an interactive hands-on program by the ESA Education Office in partnership with Andøya Space Education and the Norwegian Space Agency designed for university students studying STEM subjects. The campaign itself provides an opportunity for the students to get experience with an actual sounding rocket and gain knowledge about rocketry, sensor electronics, balloon meteorological data experiments, and a rocket launch. It also enables students to perform scientific experiments and collaborate in an international environment. Firstly, in the theoretical sense through an online course, and subsequently in practice by flying to Andøya, Norway, an island above the Arctic circle, and working side-by-side with field experts.

2.1. Online Course

One of the prerequisites for attending the launch campaign was to complete an online course provided by Andøya Space Education. The online course covered the basics of rocket propulsion, rocket dynamics and foundations of orbital mechanics. Additionally, it covered the details of the student rocket, which was to be launched during the campaign. The pre-study material also contained a section focusing on atmospheric physics and the northern lights, which are characteristic of Andøya.

The knowledge gained from the pre-study material concluded in a three-part assignment given over a period of six months. The first tested the understanding of basic orbital dynamics by calculating a satellite's trajectory orbiting Earth. In the second part, the students performed increasingly more accurate calculations on the student rocket. It started from handwritten calculations and progressed to a 2D numerical solution written in Python. The last, optional part expanded on the previous solutions aiming to deliver a 3D numerical solution to the rocket's trajectory.

2.2. Launch Campaign

The rocket for the launch campaign was a $2.7\ \mathrm{m}$ sounding rocket called the Mongoose 98, slightly modified for student launch campaigns. The rocket body was made of carbon fibre, except the nose cone, which was made of fibreglass to not interfere with the GPS tracking. The rocket was fitted with a Pro98 engine from Cesaroni, which used solid propellant to raise the rocket to an apogee of about $8\ \mathrm{km}$ and a maximum speed of $\mathrm{Mach}\ 2.2$. To introduce scientific objectives to the campaign, a series of study cases were analysed based on the available sensors on the rocket.

There were seven different sensors mounted on the aluminium avionics plate of the rocket. There was an accelerometer, magnetic field sensor, pressure sensor, GPS, IMU, a temperature array and an optical sensor.

After assembling and testing, the rocket was delivered to the professionals at Andøya Space for final testing and adjusting the centre of mass. Before it was launched, the students participated in the safety briefings and the countdown procedure. Multiple students had specific roles during the countdown. These mainly included telemetry, launchpad operations, science objective monitoring and mission operations. They took part in the go/no go sequence before launch, which gave them a unique experience of launching a sounding rocket. In the end, the rocket was successfully launched on the 14th of October 2021 from Andøya Space Centre, reaching an apogee of $8.6\ \mathrm{km}$.

2.3. Study Cases Overview

One of the critical parts of the launch campaign were the study cases, that aimed at utilizing the pre-determined sensors on the rocket. Students had to come up with reasoning for why these sensors would be interesting for data analysis.

DOI: 10.5821/conference-9788419184405.061

A brainstorming session concluded in four study cases.

The first scientific case compared the weather balloon and rocket temperature and pressure readings with the ISA model [1] up to $20\ \mathrm{km}$.

The second case focused on determining the spin of the rocket using the angular velocity derived from the accelerometer, magnetometer and optical sensor converted into frequency.

The third case focused on cloud detection using optical, temperature and humidity sensors. The aim was to confirm the assumption that once the rocket goes through the clouds, the light intensity lowers, humidity increases, and the temperature gradient will change.

The fourth study case, the principal discussed in this paper, concerned the comparison between the sensor measurements and OpenRocket simulation to determine the rocket's trajectory.

3. Trajectory of the Rocket

3.1. Python Simulation Trajectory

As part of the second assignment, the students were tasked with writing a two-dimensional simulation of the rocket's flight trajectory using Python, treating this as an initial value problem. To achieve this, the equations of the rocket's motion were derived with the following major assumptions and simplifications:

- Constant drag coefficient C_d.
- The rocket is non-rotational.
- The rocket is a point mass.

The rocket's equations of motion are established under these assumptions using Newton's second law (Eq. 1).

$$\vec{T}(t) + \vec{D} + m(t)\vec{g} = m(t)\vec{a} \tag{1}$$

Where $\vec{g}$ is the gravitational acceleration vector, $\vec{a}$ is the rocket's acceleration vector, and m is the rocket's mass. Both $\vec{T}$ and m were functions of time. $\vec{T}$ was assumed to be equal to the average thrust of the rocket's motor during the burn time (up to $6.09\ \mathrm{s}$) and then set to 0, while m was approximated as a linear decrease from wet mass to dry mass of the rocket during the burn. By expanding this equation into two dimensions and applying the drag equation, the final system of equations was obtained (Eq. 2).

$$\begin{bmatrix} T\cos\theta \\ T\sin\theta \end{bmatrix} + \begin{bmatrix} -\frac{1}{2}\rho\left(\frac{dx}{dt}\right)^2 AC_d\cos\theta \\ -\frac{1}{2}\rho\left(\frac{dy}{dt}\right)^2 AC_d\sin\theta \end{bmatrix} + \begin{bmatrix} 0 \\ -mg \end{bmatrix} = \begin{bmatrix} \frac{d^2x}{dt^2} \\ \frac{d^2y}{dt^2} \end{bmatrix} \tag{2}$$

Where θ is the rocket's angle relative to the horizontal, A is the rocket's frontal area, x and y are displacements in the horizontal and vertical directions, and ρ is air density dependent on y as given in Equation 3.

$$\rho(h) = \rho_0 e^{-\frac{y}{H}} \tag{3}$$

Where ρ_0 is the density at sea level, and H is the scale height [1]. The system of equations in Equation 2 was then solved numerically using the Runge-Kutta method. The results of this simulation for $\theta = 75°$ and other initial parameters given in the assignment can be seen in Figure 1.

The rocket simulation can be extended to three dimensions, introducing a 6-DOF system. The dynamics of this system are then fully described by four state vectors, namely the position vector $\vec{X}$, a quaternion $\vec{Q}$ which describes its orientation, the linear momentum $\vec{P}$, and the angular momentum $\vec{H}$. Knowing these vectors at any given point in time allows for determining the state of the rocket at any subsequent point in time. This is accomplished by solving a set of ordinary differential equations describing the dynamics of the rocket, given in Equation 4, using the Runge-Kutta method [2].

$$\begin{gathered} \dot{\vec{X}} = \frac{\vec{P}}{m(t)} \\ \dot{\vec{Q}} = f(\vec{Q}, \vec{H}) \\ \dot{\vec{P}} = \vec{F}(t) \\ \dot{\vec{H}} = \vec{M}(t) \end{gathered} \tag{4}$$

$f(\vec{Q}, \vec{H})$ represents the quaternion derivative [3]. $\vec{F}(t)$ and $\vec{M}(t)$ represent the resultant force and moment acting at the centre of gravity of the rocket as a function of time. $m(t)$ represents the rocket's mass, which changes in time. For this simulation, the following forces and moments were considered for modelling the trajectory of the rocket: axial drag, normal drag, force due to gravity, thrust and the moment due to drag force acting through the centre of pressure.

The standard drag equation is used with a constant drag coefficient obtained from an OpenRocket model for modelling the drag forces. The density is adjusted according to the rocket's altitude based on the ISA. The gravitational force is calculated using a constant gravitational acceleration of $g = 9.81\ \mathrm{m/s^2}$. Thrust is obtained from the thrust curve of the rocket engine, the Cesaroni 15227N2501-P [4]. The normal drag force causes a moment, with the moment arm being the distance between the centre of pressure and gravity. In the modelling of this moment, a shifting centre of gravity due to changing mass is considered.

The complete rocket trajectory is obtained by numerically solving the set of ordinary differential equations given in Equation 4. Doing so renders the trajectories shown in Figure 1.

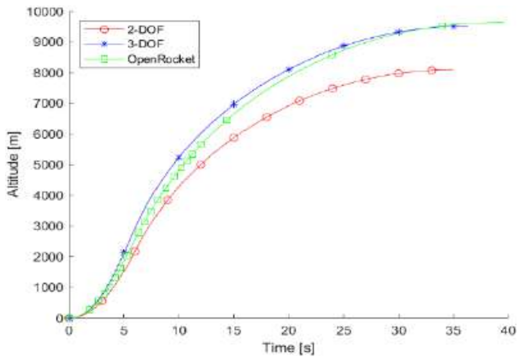

Figure 1. Python and OpenRocket trajectory simulations

The apogee on the 6-DOF case was 17% higher than it was for the two-dimensional case.

3.2. OpenRocket Trajectory

The OpenRocket simulation software was developed as a master's thesis project by Sampo Niskanen in 2009. This open-source program was created to support amateur rocketry. The OpenRocket 6-DOF simulation software has vast educational benefits since it allows anyone from middle school students to even rocketry teams in universities to run calculations, design their rocket, and test it.

The software allows users to define the rocket model and launch conditions to generate the expected behaviour including altitude, roll rate and recovery deployment events. The calculation process is detailed in the software documentation [5]. However, as with any simulation, the software cannot take all effects into account and must use assumptions to achieve the most accurate result. The biggest challenge, as with any aerospace simulation, occurs during the transonic and supersonic parts of the flight. This is due to the effects that shock waves and expansion fans can have on the aerodynamic forces acting on the rocket. Furthermore, atmospheric conditions such as wind in different heights affect the overall trajectory. The assumptions identified as having a major contribution to the data generation can be listed as follows [5]:

- The angle of attack is close to zero.
- The flow around the body is steady and non-rotational.
- The fins are flat plates.
- Pressure drag for supersonic velocities uses certain assumed hypersonic and supersonic conditions.

Ultimately the intention was to analyse the error in the rocket simulation for the transonic speeds and above by comparing it with flight data from the campaign. Transonic flows are difficult to model as high-fidelity computational fluid dynamics analysis is required due to the non-linearity of the governing equations [1].

To model the rocket, the structure given in Figure 2 was adopted. To represent a correct mass distribution, the rocket mass and centre of gravity were overwritten to the measured values of the physical rocket. The main properties used to model the rocket are given in Table 1. Both the centre of gravity and the centre of pressure are measured from the nose tip.

A simulation of its flight was obtained using an average windspeed of $5\ \mathrm{m/s}$ with standard deviation of $1\ \mathrm{m/s}$ and a wind direction of $90°$. For the atmospheric conditions, the ISA was specified. The launch rod was set to a length of $300\ \mathrm{cm}$ at an angle of $16.3°$. The resulting trajectory of this simulation is given in Figure 1.

Table 1. Properties used in OpenRocket model

Properties	Values
Mass with motor [g]	19500
Length [cm]	271
Diameter [cm]	10.3
Center of gravity [cm]	194
Center of pressure [cm]	205

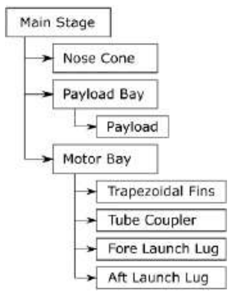

Figure 2. Schematic of OpenRocket components used to model the rocket

3.3. *IMU Data and Qualitative Analysis*

The IMU provides inertial data in 9-DOF. It is composed of three individual sensors, each measuring orthogonally, given in Table 2.

Table 2. IMU sensors

Sensor type	Range
Magnetometer	-16 to 16 Gauss
Accelerometer	-16 to 16 g
Gyroscope (angular velocity)	-2000 to 2000 deg/s

The encoder of the telemetry station transmitted the data from the IMU sensors in 16-bit integers, where the integer value corresponded linearly to the scale of each sensor.

The intention was to integrate this inertial data using a Kalman filter to obtain the rocket's trajectory. However, this method would have certain trade offs:

- The trajectory would most likely be subject to significant drifts as the error would accumulate over time.
- Some of the sensors either saturated (gyroscope) or provided faulty data (magnetometer), and filtering their influences out is very challenging.
- Most open-source IMU orientation filters are not tuned to work with significant accelerations; a substantial amount of work would have to be put into implementing the algorithm.

For future work it is recommended to implement a Kalman filter to obtain the trajectory from IMU.

4. Discussion and Results

This section compares the methods used to determine the rocket's trajectory. It was decided that simulation data from OpenRocket would be used for its higher accuracy than the Python script. The main data sources were the following sensors: GPS, IMU, accelerometer and barometer. The sensor data was compared with OpenRocket data to establish its precision for a rocket of this type empirically. The presented plots focus on the flight up to the point of apogee.

Figure 3 shows the altitude over time for each source of data: OpenRocket, GPS and barometer. All three sources present the same characteristic curve, although they predict different apogees. The barometer follows the OpenRocket curve closely for $M < 2.0$ but under-predicts the apogee, likely due to a lag in pressure equalisation between the interior and exterior of the rocket at supersonic speeds. The GPS apogee, $8627\,\mathrm{m}$, is likely to be the most accurate as it would not have been affected by pressure changes, however its low sampling rate reduces its accuracy during ascent.

Figure 4 shows the local Mach number over time. The derivative of the altitude data obtained from the barometer only gave the vertical velocity, hence the barometer curve differs greatly from the OpenRocket simulation. The accelerometer, on the other hand, follows the OpenRocket curve closely, varying slightly at higher Mach numbers. All three sources predict that the maximum speed was reached at a similar time, approximately $6\,s$ after ignition.

The data obtained from the Python simulations before the campaign explained what the trajectory should look like and what the altitude would be. The more accurate approach of OpenRocket simulation then provided a more detailed approximation.

Figure 5 presents the rocket's acceleration against time and it was expected that the onboard sensors would closely follow the OpenRocket prediction here as both the IMU and the accelerometer directly measure the acceleration. The curve from the accelerometer generally follows the OpenRocket simulation, giving a very similar characteristic shape, although the maximum acceleration differs by about $2\,\mathrm{G}$. This acceleration occurs during launch and therefore the discrepancy is likely caused by OpenRocket omitting the effect of friction between the rocket and the launch rail.

Unfortunately, the IMU data was not usable. Although it follows the same shape, the huge difference in magnitude compared to the other two sources indicates an error with the sensor and/or data retrieval.

Overall, it was found that the barometer provided the most accurate readings for altitude, whilst the accelerometer was the optimal choice for velocity and acceleration. It is expected that the GPS will have provided similar results, however its low sampling rate reduced the accuracy of its derivatives.

DOI: 10.5821/conference-9788419184405.061

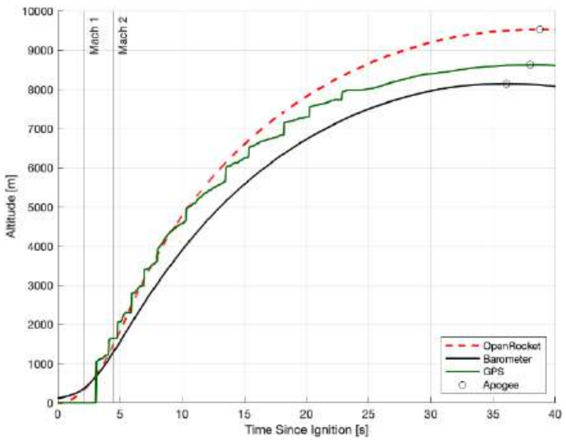

Figure 3. Comparison of Altitude Data

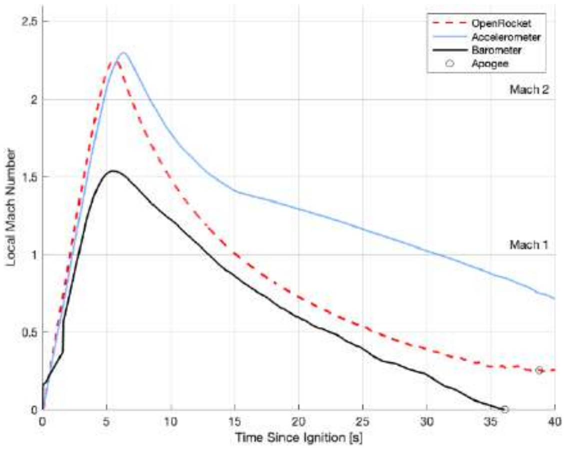

Figure 4. Comparison of Mach Number Data

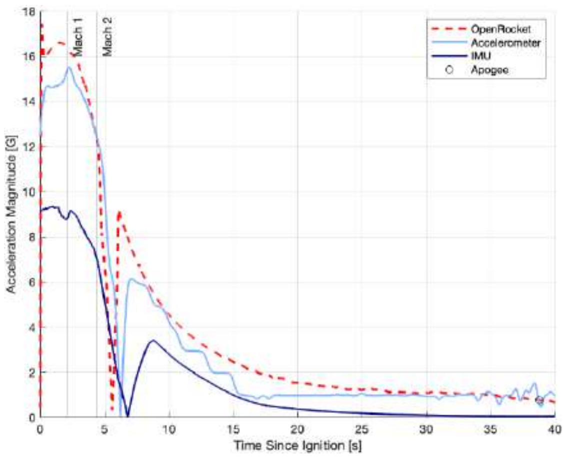

Figure 5. Comparison of Acceleration Data

5. Conclusion

The paper summarised students' work as part of ESA Academy Fly a Rocket Programme and the consequent work on data analysis to determine the accuracy of OpenRocket simulation software for rockets of this type. Full detail of the programme's specifics was given, and simulation software basics were explained, starting from simple Python estimations to the advanced simulations using OpenRocket. Furthermore, the data readings from the other sensors on the rocket were discussed. In the end, the data obtained from the sensors which could be used to predict rocket trajectory was compared in detail with OpenRocket. The OpenRocket was concluded to offer good precision for low Mach number speeds and slowly decreasing precision at higher Mach numbers. However, the rocket trajectory estimation precision up to $\mathrm{Mach}\ 2.5$ is still very relevant to amateur rocketry as it provides a good idea about the rocket's behaviour.

Acknowledgements

The authors would like to thank the Fly A Rocket! programme organisers from ESA Academy and Andøya Space Education for their assistance and support.

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Lessons-learned from Teaching Satellite Operations in a Novel Hands-on Student Project Utilizing In-Orbit Spacecraft During the COVID-19 Pandemic

Tony Erdmann[1], *Mara Krachten*[2]

Abstract

The Chair of Space Technology at TU Berlin continuously develops new satellite technology and software that is verified and used in various missions in orbit. 27 satellites were launched as of 2022. Many of these satellites by far outreach their design lifetime and work until today. At the same time, an increasing number of satellites not only in the academic domain is demanding for qualified operators. Hence, some of the satellites at TU Berlin are not fully operated anymore. To enable an efficient and sustainable use of those satellites, a novel hands-on student-driven project was implemented in order to utilize these aged but functional satellites to train a new generation of satellite operators. In this lecture course, students with various backgrounds are introduced to the basics of satellite operations by student tutors. Using a laboratory model of a CubeSat as a hardware-in-the-loop operations simulation, participants can collect first experiences in the university's own Mission Control Center (MCC). Besides theoretical and practical foundations of satellite operations they gain skills in managing and coordinating satellite missions. After finishing the basic course in a theoretical and practical operations test, students qualify to participate in the advanced project giving them the opportunity to work with and operate the available satellites in orbit under supervision. Each semester, several interdisciplinary teams conduct experiments such as Earth Observation scenarios or work on related tasks like the improvement of the operations software or Human Factors of satellite operations.

The pandemic has posed new challenges to this innovative educational concept, but was also a motivation to find alternative ways to teach satellite operations. The setup of simulated operations in the MCC was transformed into a combined setup of remote access and video conference. In this way, students are enabled to practice satellite operations from home. Theoretical lectures are prepared as screencasts. Further, the advanced project work was transferred to a remote manner. Students planned satellite scenarios from home, which subsequently were conducted by the student tutors, who provided the acquired telemetry data to the participants for analysis.

Among the results of the project are several images with the focus on environmental monitoring of Earth, a software update for a satellite and the continuous analysis and documentation of degradation of components that have been in orbit for many years. These achievements do not only provide exciting hands-on classes and new skills to the students but often even contribute to the institution's research.

Keywords

Mitigating COVID-19, Satellite Operations, Space Education

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Acronyms/Abbreviations

ADCS	*Attitude Determination and Control System*
BEESAT	*Berlin Experimental and Educational Satellite*
COVID-19	*Corona Virus Disease 2019*
EGSE	*Electronical Ground Support Equipment*
EQM	*Engineering and Qualification Mode*
GNSS	*Global Navigation Satellite System*
MCC	*Mission Control Center*
PL	*Project Laboratory "SatOps"*
STK	*Systems Took Kit by Analytical Graphics Inc.*
TTC	*Time-tagged Telecommand*
TU Berlin	*Technische Universität Berlin*
U	*(CubeSat) Unit*

1. Introduction

The thriving program for satellite missions at Technische Universität Berlin has allowed for unique educational methods. In 2019 a novel hands-on project course in satellite operations was introduced, with the aim to train operators and exploit the capacities that 19 operable satellites offer in 2022. The students are taught the basics of satellite operation and can then integrate their knowledge in group projects executed on in-orbit satellites. Around a hundred students have participated in the "SatOps" project laboratory (PL) as of today. Among these are not only aerospace engineering undergraduates but students from various fields like computer science, physics and human factors. The training is performed on a unique architecture using a lab model of a CubeSat. Even though the COVID-19 Pandemic posed challenges to the program, the tutors managed to transpose the approach to a remote course.

2. Satellite Program at TU Berlin

Until today 27 small satellites have been developed, launched and operated successfully by TU Berlin. The number is continuously increasing, as new satellite missions are devised with help of the expertise that was synthesized in the last 30 years. Among the satellites in orbit are various CubeSats of 1U and even smaller, but also bigger nanosatellites, that carry a broader range of technologies. The CubeSat series BEESAT holds 5 satellites of the 1U-class of which 4 are still operable although they have already passed their conceptualized mission phase by far. These are available to use and were therefore integrated in the course concept of SatOps to guarantee a sustainable use of aged satellites and introduce students to satellite operations. They offer possibilities for Earth Observation with cameras sensitive in the visual spectrum, attitude control and GNSS tracking experiments. And the future offers a prospect for further satellites, like the nanosatellite TechnoSat, to be integrated into the course's fleet. However, the growth of TU Berlin's satellite program does not only allow for this unique course concept but further demands for skilled operators. Therefore, the PL offers a symbiotic relationship, providing operators and further personnel that have already gained experience in handling small satellites.

3. The SatOps Project Laboratory

In the beginning of the course the students are provided with general knowledge about orbit mechanics and satellite technology, which also allows non-engineering students an easy entry into the matter. The students are introduced to satellite operations at TU Berlin, learning about the ground station setup, the mission control center (MCC) and the infrastructure that enables simulated operations. Especially, they get to know the system design and subsystems of the BEESAT bus. Weekly sessions of operation training using an engineering and qualification model (EQM) allows the students to get comfortable with the university's operations software and to learn their first procedures. After about two months they take a practical exam in order to qualify them for operating the flight models under supervision of the tutors during the project phase of the course. These projects enable the students to collect practical experiences on in-orbit satellites and further expand their comprehension of space systems.

3.1. Simulated Satellite Operations

As mentioned before, an EQM of one of the available CubeSats, namely BEESAT-9, is used in a hardware-in-the-loop setup to simulate the actual satellite operations. The EQM is situated in an integration laboratory and connected to an EGSE server which emulates a ground station. This simulated ground station can be remotely accessed from the facility's network and especially from the MCC. Here, the weekly practical sessions in the scope of the PL's basic course in satellite operations take place. During the first session the students are introduced to additional software like the open-source

DOI: 10.5821/conference-9788419184405.062

prediction software gpredict which is essential for every day satellite operations. Shortly after they get to know TU Berlin's in-house software solution for satellite operations: The program TC-Control is used for commanding, the TM-Viewer for acquiring and visualization of live telemetry. This setup also represents the basic call and response structure of BEESAT's communication link. During regular operations the satellite answers with telemetry on every single sent telecommand. Students have to internalize this concept during the first hands-on session.

In the following session they are introduced to basic and advanced procedures with increasing complexity. At first, they learn how to acquire and interpret live telemetry to evaluate the satellite`s health which is necessary during every satellite contact. After that, they are trained in basic procedures for regular operations like downloading offline telemetry from the satellite`s memory or uploading simple command lists. In case of anomalous operations they learn how to set the satellite back to active after a reset occurred. In preparation for the following project phase they get to know how to properly compose and upload time-tagged telecommand (TTC) lists which represent experiment setups in satellite operations. In the final integrated session they are tasked to prepare an image capture. Therefore they are also introduced to the simulation software STK to predict required accesses and attitudes for a given area of interest. Finally a TTC list is composed which also requires the system knowledge of how to operate the camera payload and which ADCS mode to choose to point the satellite to the target.

The hands-on training phase ends with an integrated practical and theoretical test. In the practical parts students are challenged to perform a randomly selected known procedure on the EQM embedded in a simulated satellite contact thus requiring time pressure. In the theoretical part they are questioned related to basics of satellite technology and system knowledge of the BEESAT bus which is critical for its operations.

In general this simulated setup provides advantages for the operations training. Students can be trained on the actual in-orbit hardware as the EQM is identical in construction to the flight model. It is always available and not restricted to contact times. As a wired connection to the EQM is established no frequencies are blocked and no radio license is required during the training. BEESAT-9 is the most advanced 1U-BEESAT, however the operations procedures have slightly changed in the development process. Hence, students are simultaneously qualified for the operations of multiple satellite models.

3.2. In-orbit Project Work

After the completion of the EQM training, small groups of three to five students can choose between available project topics or even devise their own project ideas. In this way, many successful projects could be conducted in the last two years. Among them are many image captures that aim to portray relevant issues within the capacities of the CubeSats. A focus is laid on research on sustainable use cases of the available Earth Observation payloads. Furthermore, the students have carried out many experiments to review the satellites degradation during the years. Software engineering students participating in the PL have recently started to develop, upload and test a software update in order to guarantee a maximal exploitation of the satellites capacities. Also the operation itself is critically analyzed by students, who have researched possibilities to enhance the link to the satellite or analyzed the workflow of satellite operations and coordination with operators. During the COVID-19 pandemic the changes for satellite operations in the whole institute were reviewed, to analyze the additional liabilities for the operators. These projects, however, do not only promote the optimization of satellite operations in the PL and beyond, but further cause remarkable progress in students' skills.

4. Adoptions to the Project Laboratory due to the Pandemic

The COVID-19 pandemic poses great challenges on space education in general [1]. Especially this novel course concept which focusses on hands-on training and experiences was highly affected. Although the first intake of the course started in presence and the whole training phase could be performed in the MCC, already the first project phase had to be aborted due to the first lockdown in Germany in 2020. After a short orientation break the project work was quickly adopted to a remote manner and continued. Daily project meetings were realized as voice or video online meetings. Students prepared experiments and TTC lists from home which afterwards were implemented and uploaded by the tutor who still had access to the operations infrastructure. After execution the gathered telemetry or payload date was downloaded and provided to the students for

DOI: 10.5821/conference-9788419184405.062

analyses. This general workflow for the in-obit activities is repeated in the semesters in which an access to the MCC could not be granted to students due to the current pandemic situation. Despite these adverse circumstances notable results could be gathered during these phases.

In the following semesters the remote transformation of the basic training course followed up on the remote project work. At first the required theoretical input, intentionally taught in regular presence lectures, was prepared as screencasts. A series of 10 30-60 min long video lectures was composed. During the semesters under the ongoing impact of the pandemic, the videos are published weekly via TU Berlin`s e-learning platform. A weekly remote Q&A session with the tutors supplements the asynchronous self-study of the students. Further, in preparation of the hands-on training, tutorial videos are captured, showing and commenting on the use of the different operations software and various procedures. Many of these videos have already undergone iteration during the following pandemic semesters.

The biggest technical and organizational challenge is the realization of practical operations training in a remote manner. However, a complex setup of screen sharing and remote access was conceived to allow students to practice satellite operations from home. The setup is visualized in figure 2 attached to this paper. The general software setup for simulated operations runs on a workstation in the MCC supervised by a tutor. The workstation also hosts the exercise video conference and the screen is shared for the participating students to follow the ongoing training. The students are granted remote access to the workstation with a respective software one by one. Each one is challenged with a subtask or a whole procedure of the current week. The whole exercise sessions are captured and published to the students afterwards, as time capacities are not sufficient for everyone to train everything.

Despite the limited remote capacities and minor technical problems like disconnections and audio disturbances it has become apparent that hands-on training can be successful even in a remote manner and learning goals are reached. Most of the students pass the final operations test even if they are in the MCC for the first time and previous training has been solely performed remotely. Partly due to the pandemic situation and resulting rules it was even required to hold the final exams online. Also those batches convinced the examination board to a large extent and were cleared for the following project phases.

5. Selected Flight and Project Results

During the 5 conducted semesters many project results have accumulated. Even though the examinations primarily serve the development of the students, they often manage to gather interesting conclusions. Hence, some of the results will be outlined in the following.

In a semester during the pandemic, a group of human factors students reviewed the changes in the workflow during the pandemic at the Chair of Space Technology. The group found that the home office meant increased stress due to disturbances at home, difficulties to separate private from work life and increased effort for the coordination of satellite operations.

As mentioned before, many groups have managed to take images with BEESAT-2, -4 and -9, trying to capture interesting phenomena on Earth from space. Many of the subjects of interest are chosen to address sustainability by portraying environmental destruction and manifestations of global warming. Thereby, students learn to understand the capacities of the available CubeSats' cameras, as some phenomena are easily visible, while others cannot be detected on the images at all. A successful example from 2021 is imagery from Lake Chad, which is diminishing due to "overuse and climate change effects[1]. Figure 1 shows a stitch of three images captured during a pass by BEESAT-9 over Lake Chad. The image capture was planned, simulated, prepared and executed by students.

In 2021 the tutors of the PL further engaged the PL graduates to found the student satellite operation group "StudOps". With an extended training, its members are now allowed to practice self-sufficient satellite operation within the scope of regulatory possibilities. The members that completed this training further support the training of new members and therefore support the maintenance of the group. The group allows students to continue their training and practice beyond the PL and assists the course with training and operational exercises. The members currently perform the nominal operations of BEESAT-9. They regularly record GNSS data, which is meant to be analyzed in terms of long-term degradation and develop their own project ideas like capturing the volcano eruption at La Palma island in 2021.

DOI: 10.5821/conference-9788419184405.062

Figure 1. Stitch of 3 Images Captured by BEESAT-9 over Lake Chad on 5th March 2021

6. Results and Discussion

Overall the integration of the course concept into a remote setup turned out to be successful. However, the new course configuration comes with some tradeoffs. Especially the group experience and the hands-on character during the project phase in the MCC could not be served as well. Nevertheless, the project results show that despite the challenges the PL was able to successfully train new operators. Furthermore, the advantage of EQM training in a video conference became clear, as all students could observe the operation simultaneously and manifest their knowledge observing others' training.

7. Conclusions

It has been shown that a novel course concept for hands-on satellite operations training could be adapted to a remote manner. Impacts of the COVID-19 pandemic were mitigated by finding innovative ways to remotely train students at home. Not only training results are generated but also further research results as students are taught to operate and exploit available satellites in orbit. A comparison between the initial course concept, its implementation during the pandemic and finally its realization after the pandemic might be the scope of future work.

Acknowledgements

The authors thank all former BEESAT teams for the ongoing support and all ops teams of TU Berlin for the good cooperation.

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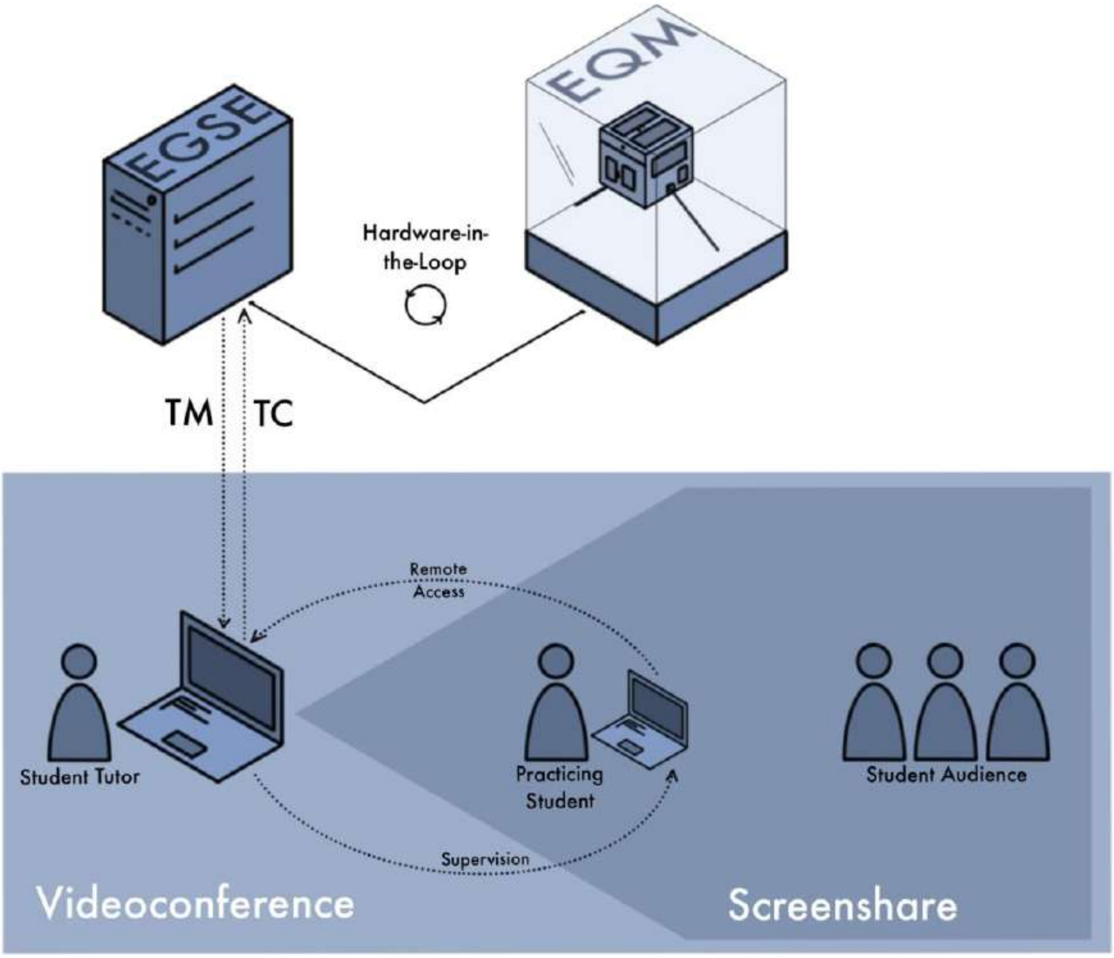

Figure 2. Remote Setup for Students Practicing Satellite Operations from Home

A selection of lessons learned from phase C/D of CubeSat projects of the Fly Your Satellite! programme

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Abstract

Fly Your Satellite!" (FYS) is a recurring programme part of ESA Academy's portfolio of "hands-on" activities. The programme was established to support University student teams in the development of their own CubeSat missions and aims at transferring knowledge and experience from ESA specialists to students. Selected teams are guided through project reviews and supervised through design consolidation and verification activities, conducted according to ESA professional practice and standards, tailored to fit the scope of university CubeSat projects.

As part of the educational goal of the programme, a systematic effort of capturing, discussing and contextualising difficulties, mistakes, and anomalies in general, is carried out. From this effort, the participating students benefit from a unique framework where lessons learned from one project can be transferred to other ones. This exercise is blended with the "regular" transfer of knowledge from the ESA professionals that support the programme and occurs both concurrently (lessons learned from current cycles) and from previous projects (lessons learned from previous cycles).

This paper reports a revised and updated collection of lessons learned during phase C/D of the FYS CubeSat projects, in particular the projects now participating in the 2nd cycle (FYS2). At the same time potential changes and mitigating approaches are discussed.

Particular focus is given to lessons learned from issues which arose in hardware development activities, as well as from planning and execution of system-level assembly, integration, and verification (AIV) activities.

This approach is taken since first-time developers tend to underestimate the number of issues arising when their design is translated from documentation and models into real hardware. In general, it has been observed that many of these issues typically arise from lack of (space) project management experience of the student teams, or from the lack of resources which prevent the application of standard/established methodologies to small satellite/educational projects.

Keywords

Assembly, Integration, Testing, Verification, CubeSats, Education, Phase D, Phase C,

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Abbreviations

AOCS	*Attitude & Orbit Control System*
CDR	*Critical Design Review*
COTS	*Commercial Off-the-Shelf*
ESA	*European Space Agency*
FAR	*Flight Acceptance Review*
FYS	*Fly Your Satellite!*
GEVS	*General Environmental Verification Standard*
LEO	*Low Earth Orbit*
LTAN	*Local Time of Ascending Node*
PFM	*Proto-Flight Model*
RF	*Radio-Frequency*
TVAC	*Thermal-Vacuum*

1. Introduction to Fly Your Satellite! 2

The second edition of the Fly Your Satellite! (FYS) programme started in 2017 with the selection of six teams: ³Cat4, CELESTA, EIRSAT-1, ISTsat-1, LEDSAT, and UoS³ .

The teams were supported through Phases C to E of typical satellite missions.

Phase C, known in FYS as "Design Your Satellite", focused on the consolidation of the CubeSat design and was concluded with a Critical Design Review (CDR).

Phase D1, "Build Your Satellite", focused on the production of in-house units and qualification of their engineering models. Different model philosophies and flatsats and "stacksats" were used to carry out various tests. Following subsystem development and qualification, the CubeSat is assembled and a Full-Functional and a Mission Test is performed.

Phase D2 "Test Your Satellite", includes environmental tests. Before being offered a launch opportunity, teams pass ESA's Flight Acceptance Review (FAR) demonstrating that the full system has been successfully verified, and that the legal and regulatory obligations are fulfilled.

At the time of writing, of the six selected teams, one has launched (LEDSAT, Aug. '21), and two have Flight Models Assembled (ISTSAT-1 and ³Cat4) and one (EIRSAT-1) has completed Engineering Model qualification.

2. Introduction to Lessons Learned

Building upon FYS first edition, which was primarily focused on testing CubeSats at an advanced stage of development, the second edition of the programme has supported teams from the detailed design stage, enabling the identification of fundamental issues earlier when may then be addressed with reduced impact to the project cost or schedule.

This paper focuses on common problems identified in the second edition of FYS during the design, development and testing phases. These elements have informed the definition of subsequent programme cycles and have prompted the preparation of guidelines and webinars to help students in their work.

Team specific technical or managerial issues will not be discussed in this paper.

3. Systems Engineering Lessons Learned

3.1. Orbit compatibility analysis

Student teams often baseline their mission analysis to a specific orbit simplifying simulations and analysis. When launch opportunities present themselves, this can be a limiting factor as compatibility to different orbits is uncertain. This is compounded by the knowledge gap created when team members leave the project or if the project resources are dedicated to other critical issues closer to launch.

Mission analysis should reflect the full compatibility or flexibility to different orbital altitudes, LTANs and inclinations. This includes eclipse, power generation and energy budget, thermal analysis, AOCS simulations, Earth coverage, payload performance, ground station contact, link budget, orbital lifetime (in compliance with Space Debris Mitigation Rules), radiation, etc.

3.2. System Budgets

The preparation and maintenance of system budgets is a standard systems engineering tool used by most teams in the definition and detailed design of their system. However, students struggled to prepare detailed system budgets, resulting in undetected issues at the design stage. Points of attention were the misapplication of margin policies and the derivation of unnecessary requirements from the subsystem budgets.

Teams were thus requested to prepare budgets (power, data, link, pointing, etc.) for each CubeSat operational mode, to consider duty cycles, and to apply different margins depending on the maturity of the subsystem.

Having margin in the system budgets is beneficial to cope with changes in the design, remaining flexible to several orbits and to mitigate discrepancies between "as-designed" or datasheet values, and the "as-built" or "as-measured" characteristics and performances.

DOI: 10.5821/conference-9788419184405.063

3.3. Requirement's definition

Defining good requirements for the mission is always a daunting task for students on a CubeSat mission, as this might be the first time, they convey the needs of the mission into a formal specification. Some patterns have been observed when students have prepared their technical requirements, such as reliance on external advisors' or project stakeholder's knowledge or derivation of requirements from COTS (Commercial Off-the-Shelf) datasheets. It is also typical that requirements are poorly formatted resulting into tricky situations when preparing the verification plan or if a specific COTS product is replaced.

The FYS programme tries to mitigate this issue by performing requirements reviews and explaining the importance of requirements as means of system design and verification. Teams are invited to conduct requirements workshops and to often revisit their technical specifications.

3.4. Operational Modes

The importance of a well-structured operational mode philosophy is found to be regularly underestimated or overcomplicated by CubeSat teams. A clear definition of all operational modes, their boundary conditions and the transition logic should be clearly defined at the design stage, to facilitate the identification of possible risks and flaws (e.g., loops).

The number of modes should be limited to avoid unnecessary complexity, and the difference between each mode should be evident: a parameter change, or subsystem status change should not necessarily be regarded as a different mode. Additionally, all possible modes and mode transitions should be tested, under mission conditions, in simulated scenarios and during environmental testing. This will limit any unexpected transitions and will aid in the characterisation of the performance of each mode and transition (e.g., temperature dependability of voltage-driven transitions).

3.5. Flexibility to launch requirements

CubeSats are most often launched as piggyback or secondary payloads and may be subject to late launch configurations changes. Teams should prepare to accept any change in requirements from the launch authority or the main passenger, including changes in the environmental levels, for example due to a configuration change.

A general recommendation for teams is to design according to the most demanding environment possible e.g., GEVS (General Environmental Verification Standard) [1] to envelope all the possible cases.

Additional needs from developers such as late access for battery charge or to replace short shelf-life items on-board are typically not included in the launch service, and reduce the possible launch vectors.

Furthermore, when considering a deployment from the ISS, teams need to be aware of the additional requirements imposed by the human spaceflight safety requirements, such as the safety certification of batteries which may affect budget and schedule

4. AIV Lessons Learned

4.1. "This is our flight model but not the model that will fly"

Many CubeSat teams adopt the proto-flight model (PFM) philosophy for its simplicity and theoretically lower cost.

For COTS subsystems, a single unit is procured in line with the reduced cost budget. In some cases, these units are either expensive or subject to long-lead times, creating risk. In these cases, additional protection and handling measures shall be taken to prevent unintentional damage during development and testing work.

For in-house developments, it was observed that soon after the (first) proto-flight unit was manufactured, a need for design iterations was identified due to insufficient performance or mistakes. In fact, development and engineering models were often not included in the AIV planning, with a belief that the first build would be correct. Therefore, it is recommended to plan from the beginning the use of prototypes, development, engineering and/or qualification models. This approach also allows early prototyping, testing and interface verification activities as a de-risking activity. Furthermore, it can sometimes be simpler to verify functionalities and performances by testing development or engineering models than by analysis.

4.2. Design for testing

As part of the FYS programme, teams are required to conduct the following tests at CubeSat level: Full Functional, Mission, Vibration and Thermal Vacuum-Thermal Cycling Tests. For these campaigns to be successful, the following considerations shall be made early in the design stage:

- Access to internal buses is possible via the umbilical connector with sufficient parameters to observe all the components and elements of the system including lines to charge the batteries.

- In TVAC (Thermal-Vacuum) it should be possible to switch on/off the CubeSat; how this affects the deployment switches logic should be considered.
- Internal thermocouples are needed during TVAC testing. Their installation, compatibility with the facility and routing and post-test passivation should be ensured.
- Effects of activating the transceiver inside the TVAC chamber. Routing of a coax cable through the flange may be needed.
- If possible, solar panels should have probe-points to conduct electro-luminescence tests after environmental testing. This allows the detection of cracks in solar cells not visible with the eye.

4.3. Preparation for testing

The preparatory work required to conduct testing activities is often underestimated by students. Prior to testing teams must:

- ready the item under test (procurement, manufacturing, and inspections),
- develop the firmware and software,
- develop and manufacture the Ground Support Equipment (mechanical and electrical),
- develop and validate the testbed,
- prepare written procedures.

Being aware of this asymmetry in the duration of preparatory activities vs. the actual test, already helps students to prepare more realistic schedules. For tests at external facilities, it is recommended that teams conduct a dry run before travelling to check that they have available all the tools and resources and as a sanity check for the test procedures.

4.4. Interfaces Verification

Frequent verification of the interfaces between different units or subsystems of the CubeSat is recommended. This includes:

- Mechanical fit-checks of parts.
- Incoming inspections and verification of conformance to purchase order or datasheet.
- Dimensions measurement. Especially for external units such as solar panels,
- Early mechanical interference check and with the primary structure and side panels, e.g. using detailed CAD.
- Harnessing design and fit-checks. Mistakes in cable lengths and connector angles have been found after manufacturing.
- Verification of electrical and data interfaces: correct commanding of power and data lines shall be part of the early functional verification activities.

4.5. Software, GSE, Operations and Ground Station

Software, GSE (Ground Support Equipment), Ground Station and Operations are activities typically overlooked during the design phase but are soon in the spotlight in phase D when hardware verification becomes the priority.

Hastily developed software and GSE is likely to result in anomalies during testing, or even later when the CubeSat is in-orbit. To prevent this, teams should assign a taskforce for this early in the project so that the development of software and GSE does not end up on the critical path.

Due to the relatively small size of university CubeSat teams, it may be advantageous to blend elements of software development with operations planning, thus facilitating the implementation of the operational needs and the automation of certain functions. A lean implementation of software may result into simplified and more robust operations: from data generation to on-board storage, RF encoding/ decoding, on-ground storage and data visualization, and back to spacecraft commanding.

4.6. Full Functional testing

The Full Functional test is requirement oriented and demonstrates the integrity of all functions, in all operational modes, redundancy paths and all foreseen transitions. The difficulty for teams has been preparing this test starting from slim and non-exhaustive sets of requirements. The AIV students have had to work hand-in-hand with the systems engineers to develop a comprehensive test procedure starting from the verification of basic and critical functions, modes transition, functional diagrams, software design, etc. Some teams have reported about the benefits of automating parts of the tests, e.g., repeatability.

4.7. Mission testing

The idea of a mission test is to "test as you fly", following the expected operational plan after deployment in orbit. Defining the mission test procedures should therefore be done in parallel with the operations planning ensuring all necessary telecommands and sequences are verified and validated. Contingency operations should also be tested *in* the mission test, but even experienced student teams might find producing procedures for unpredicted issues in orbit difficult. Failure Detection, Identification, and Recovery should be verified, including testing of watchdog timers.

The temperature and pressure conditions between LEO (Low Earth Orbit) and the lab can cause unpredicted scenarios. While a full mission test may be difficult to carry out during TVAC testing a reduced mission test is still recommended to be carried out during TVAC.

4.8. End-to-End testing

End-to-End tests are recognised a useful tool to verify the full chain of command and downlink, demonstrating, prior to launch, correct functionality of the RF link between the ground segment and the space segment. Because the Ground Segment antennas are located outdoors and the CubeSat shall be kept inside the cleanroom, different test set-ups have been implemented:

- In-lab testing over short distances using attenuators to simulate the loss of signal expected in orbit.
- Long range, requiring specialised approached to keep the CubeSat in a clean environment during the test. Long distances tests also require direct line of sight, which requires careful planning.

4.9. Vibration testing

Vibration test is one of the essential environmental tests, verifying the CubeSat can withstand the mechanical environment levels seen during launch. During the system level test any fasteners may experience loosening if not properly tightened, leading to loose material moving freely within or outside the CubeSat. Use of the correct specified torque levels for each fastener is essential with “hand-tightened” not being sufficient. Secondary locking e.g., thread-locker, acknowledging difficulty in removal if needed.

Large shifts on resonance search (both in frequency and amplitude) are often results of parts dislodging or loosening during the test. Some systems may however experience a natural shift e.g., non-clamping deployers, and may settle during the vibration test. This may result in the test success criteria being violated, despite that the origin of the failure is not directly related to the CubeSat. Nevertheless, any shifts in frequency and amplitude should be investigated further to determine the origin.

4.10. Thermal Vacuum Cycling testing

TVAC tests are arguably one of the most representative test environments that the CubeSat will see before flying. Some teams opted to conduct subsystem thermal qualification as a de-risking strategy for in-house developments. Many anomalies were encountered due to individual components having different performance at temperatures other than laboratory conditions. In addition, the thermal cycles amplify any microcracks caused during vibration testing.

A bake-out at the maximum temperature allowable by the most sensitive component shall be foreseen during TVAC. Preferably, bake-out should be done at subsystem level prior to the system integration, enhancing the outgassing process by going to higher temperatures, and mitigating the risk of contamination to other components and/or the thermal vacuum chamber.

4.11. Shock testing

CubeSats rarely perform shock qualification as shock levels seen at the CubeSat-deployer interface fall typically below a certain threshold [2] and many COTs subsystem are already qualified. However, identifying any shock sensitive items [1] during the design phase to highlight potential risks is *still* highly recommended. While individual units may be shock tested if needed, PFM and FM system level shock testing is not advised.

5. Legal and regulatory Lessons Learned

5.1. Frequency Notification, Mission Authorisation

The administrative work related to the authorisation of a mission and the frequency coordination is often underestimated and delaying addressing them risks being non-compliant to the applicable laws at the time of the launch. Starting the process early was shown to be advantageous for FYS teams.

The use of radio frequency bands is strictly regulated and requires careful planning and coordination. While often wrongly assumed in the past, this also applies to radio-amateur frequencies [3].

National and international law applies and imposes requirements on satellite developers and operators. When a CubeSat is the first space object to be launched by a country, it is vital that team identifies, informs and collaborates with national authorities to identify or sometimes establish the processes to follow.

Some national laws also have insurance requirements for satellite owners/ operators, this must also be understood and addressed.

5.2. Space debris mitigation

International law and guidelines are applicable to CubeSats [4], and following the ESA guidelines is mandatory for participation in FYS. In addition to limiting the orbital lifetime to less than 25 years, space debris mitigations means no parts should intentionally detach from the spacecraft. Other requirements should be

DOI: 10.5821/conference-9788419184405.063

considered early in the design, such as the avoidance of fragmentation in case of battery explosion, passivation at end of operational lifetime, and limiting re-entry casualty risk.

6. Project Management Lessons Learned

6.1. Rolling schedules

An optimistic schedule is a common problem, even when margins are considered. Underestimation of development time of in-house hardware and/or software is often seen along with issues during tests. This can impact the schedule of the mission and can also affect the morale of the team. While unforeseen issues are, by nature, difficult to predict, anticipation of these in the schedule in the shape of correct margins is highly encouraged to the student teams.

6.2. Working with COTS

One of the benefits of procuring a COTS subsystem or unit is often the environmental qualification of the item has already been conducted. COTS products can also benefit student teams that might not have the necessary skills or facilities to develop in-house units. While in-house development provides a good educational opportunity, teams may perform a trade-off between the cost of the COTS product vs. development time and skills needed of an in-house product.

Using COTS products does have drawbacks, such as long lead times, especially with the current supply issues of semi-conductors. Moreover, while certain COTS have some degree of flight heritage, this does not mean that the product is flawless. The term flight heritage should be understood with caution as it may provide confidence in a products ability to “work out the box”. While it might have functioned as expected on a previous mission, the same result it not guaranteed for the next. Quality issues may still be present in COTS and inspections of all incoming products is highly recommended.

6.3. Team organisation

With a high rate of student turnover, teams can secure continuity in the project by involving a core team of PhD and Master students, who can support the handovers between students.

Good documentation is also key to a good handover. Sufficient documentation of the design and its justification prevents new students from reverse-engineering designs and facilitates their integration in the team. The predefined FYS data packages have shown to be a good starting point for the teams as they offer clear guidelines on the content and structure.

Involving University employees is also beneficial with crucial tasks such as securing funding, facilities, contacting authorities to deal with regulatory issues and liaising with the university administration.

A limitation that almost all teams suffer at some stage is not having coverage of all relevant areas of the space domain, hindering the development for certain subsystems and delaying the overall progress.

7. Conclusions

The second cycle of Fly Your Satellite! 2 has supported student CubeSat teams through the design, assembly, testing, and even launch of their CubeSats. During this process several lessons have been learned in different domains, but in particular throughout the Assembly, Integration and Testing Phase, primarily in the topics of system engineering, AIV, legal and regulatory issues and project management.

These lessons learned as used to inform further developments of ESA’s CubeSat programmes, and, crucially have demonstrated the participating CubeSat teams the importance of carefully planned and executed verification campaigns, planning and multi-disciplinary system design.

Acknowledgements

The authors would like to thank all ESA specialists supporting the programme for their evaluation, guidance and valuable feedback. Thanks also to all team members of the CubeSat teams that participated in the second edition of Fly Your Satellite!, 3Cat4 (Spain), CELESTA (France), EIRSAT-1 (Ireland), ISTsat-1 (Portugal), LEDSAT (Italy), and UoS3 (United Kingdom).

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The Space Station Design Workshop goes digital - opportunities and challenges during pandemic-times

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Abstract

The Stuttgart Space Station Design Workshop, aimed at university students and young professionals, focuses on the conceptual design of a space station in an interdisciplinary and international environment within a limited timeframe. It lasts about one week and has been carried out by the Institute of Space Systems – University of Stuttgart for over 20 years. The goal of the workshop, besides its educational purpose, is to obtain creative solutions from the future generation of space experts. For the participants, the SSDW offers a unique opportunity for learning by doing and to get involved in a space project. Participants do not only need to apply their knowledge obtained during their university courses but also to put in practice and improve soft skills. The workshop starts with some lectures in relevant fields such as Project Management, Systems Engineering, as well as the different subsystems, for example Life Support. The participants are then divided into two teams. To monitor the teams' progress several milestones and reviews are planned during the week. Several tools, guides, recipes and experts are available during the workshop. Within the team, each member has a specific role, which is defined before the workshop starts, allowing preparation. The mission statement of the workshop changes every year, adapting to the current plans on human spaceflight exploration. The results of the last editions have been presented at international renowned conferences. In 2020, due to the current COVID-19 situation the workshop was cancelled. In 2021, with increasing vaccination rates in Europe, the situation had improved. However, carrying out such an international in-person workshop was still not an option. For that, the core team decided to carry out for the first time the SSDW in a digital form. Adapting the existing workshop to a digital form presented many challenges but at the same time offered many opportunities. This version has allowed to join participants and staff, that would not have been able to attend in-person, and has also opened new possibilities of communication, using currently existing tools. This paper first introduces the main characteristics of the workshop before it presents a comparison between the 2019 edition, which took place in-person, and the 2021 edition, the first digital SSDW. It summarizes the activities that took place during the one-week workshop, the tools used, and the feedback provided by the participants and staff.

Keywords

Concurrent Design, Digital vs In-person Workshop, Space Station Design

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Acronyms/Abbreviations

IRS	*Institute of Space Systems*
SSDW	*Space Station Design Workshop*

1. Introduction

In recent years, digitalization has been advancing in many areas. Besides the digitalization and automation of monotonous office tasks new formats of knowledge transfer are also emerging. One reason is that the digital infrastructure is being expanded and more and more tools are available for digital teaching. This has a number of advantages. Based on sufficient internet access, students can for example attend lectures from any location or watch them on a time-delayed basis. This can strengthen national and international cooperation, as the respective availabilities increase when the times for transfers are eliminated. In addition, possible limitations of lecture halls due to the available seating capacity are eliminated, and the implementation of events can be guaranteed even in spite of pandemic restrictions. In light of general digitalization and the pandemic situation, a digital format was added to the already established Space Station Design Workshop (SSDW) format, described in more detail in [1]. As with previous workshops, which were held in-person, beginning in 1996, the SSDW is intended to retain its essential characteristics. Thus, the SSDW is aimed at university students and young professionals, who will be divided into two teams. Under the supervision of experts from academia and industry, these teams are to design an initial concept for a space station within a few days in an interdisciplinary, international and intercultural environment. The goal of the workshop is to obtain creative solutions from the unbiased, future generation of space experts. For the participants, the SSDW not only provides a unique opportunity to apply their theoretical knowledge acquired in university courses to a space project, but also improves their soft skills in teamwork. The workshop's task changes each year, adapting to current plans for human spaceflight exploration. The results of previous editions have been published in congresses [2-5].

2. Digital vs In-Person Workshop

The transformation of such a workshop poses some challenges to various sub-aspects, which are described and compared in detail based on the last face-to-face workshop (2019) and the first digital edition (2021). In addition to the organizational preparation and follow-up of the workshop, the two formats will also be evaluated from the participant's point of view.

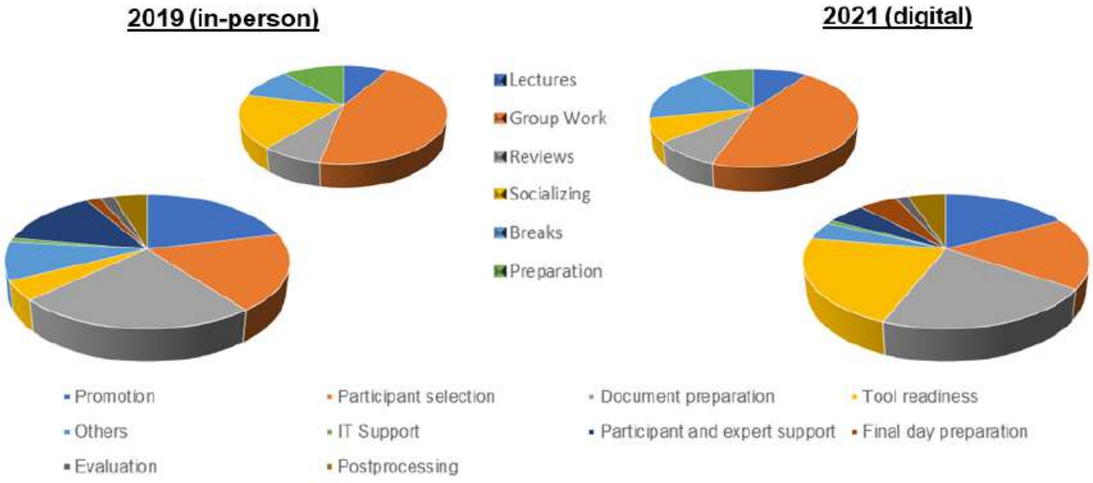
2.1. Preparations

Promotion:
The SSDW is characterized by its high professional standard based on many years of experience as well as the integration of expert knowledge, which is why it has continuously gained in popularity. The enthusiasm of the annual alumni supports the high visibility by their verbal promotion. Additionally, the posters on site and a successful web presence, both on the SSDW website [6] and in social media increases the level of awareness and consequently the application rate. Due to the prevalence of digital teaching in 2021 and the resulting low number of students on campus, posters were not used for promotion in 2021.

Participant selection:
The participants of the SSDW are selected from a three-digit number of applicants. Since the number of participants can be handled more flexible in a digital format, 50 instead of the usual 40 participants were accepted to participate in 2021. For example, additional positions in team management as well as visualization were established to accommodate the expected difficulties in the communication between participants in the digital format.

Document preparation:
To prepare the participants in the best possible way for their tasks in the team during the workshop, so-called *work packages* are created for each position. These contain various tasks with which the participant must familiarize himself with the topics. To enable the participants to get started as quickly as possible, additional help is distributed at the beginning of the workshop. The preparation of the respective documents was the same for both workshops.

Tool readiness:
Figure 1 summarizes the tools used during 2019 and/or 2021. The main difference is the integration of additional tools for the digital version of the workshop. With *Gather* [7], a virtual 2D world was created simulating the main rooms of the in-person workshop. *WebEx* [8] was used as a back-up and during the



Tools	Pre-Work		Workshop-Week-Organization		Workshop-Week – Teaching		Post-Processing	
	2019	2021	2019	2021	2019	2021	2019	2021
Gather		✓✓		✓		✓✓		
MS Office	✓✓	✓✓	✓✓	✓✓	✓✓		✓✓	✓✓
Slack		✓✓		✓✓		✓✓		✓
Webex		✓✓		✓✓		✓✓		✓✓
ASTOS	✓	✓			✓✓	✓✓		
Valispace	✓	✓			✓✓	✓✓		
LSS-Tool					✓✓	✓✓		
EDL-Tool					✓✓	✓✓		
Documentation-Tool					✓✓	✓✓		
Visualization-Tools					✓✓	✓✓		
Video / Image-Editing-Tool	✓	✓✓		✓✓	✓✓	✓✓		✓✓
Cost/Risk-Tool					✓✓	✓✓		
Kahoot				✓✓		✓✓		✓
Evaluation-Tool							✓✓	✓✓

Figure 1: Comparison of the in-person and digital SSDW format with respect to time management and tools

preparation. In addition, *Slack* [9] was introduced as a written communication tool. These programs were completed with *Kahoot* [10] as quiz tool.

Others:
In addition to the planning and coordination with the invited SSDW experts, additional aspects must be considered, especially for the in-person workshop. For example, accommodation for the participants must be arranged as early as possible. Furthermore, catering must be organized for the workshop days. In the digital version of the workshop, special focus was put on designing and sending the SSDW T-shirts to the participants early on and involving them in a puzzle quiz as team challenge to get them connected before the workshop and initialize the creation of a team spirit.

2.2. *Workshop execution*

The workshop week was divided into the work of the organization team and the time allocation for the participants.

2.2.1. *Organizational Framework*

IT support:
Technical issues can occur in any project involving different digital tools. Therefore, it is important to recognize possible problems at an early stage in order to avoid them if possible or to be able to solve them quickly. While the Institute of Space Systems (IRS) provides usually the IT infrastructure during the in-person workshop, the digital format required the participants' to use their own hardware, which could not be tested in advance. Due to the reliable preparation work of all participants, there were no significant issues in both years.

Participant and expert support:
With regard to the supervision of the participants, care must be taken to ensure that they are provided with sufficient catering during their group phases, which was not required during the digital workshop. Furthermore, it must be ensured that the schedule is followed,

DOI: 10.5821/conference-9788419184405.064

i.e. that the deadlines specified in the weekly schedule, e.g. for submissions, are met, but also that socializing events take place on time. It also makes sense to observe the internal organization of the teams, whereby it was difficult to capture the team dynamics.

Final day preparation:
On the last day of the workshop, a final presentation takes place, which is broadcasted live via web in order to enable the presentation of the results to a broad audience. The presentations will be followed by a closing event at which the winner of this year's SSDW will be announced. While the certificates are handed over personally at the in-person workshop, and the team spirit is more evident, a digital version poses new challenges. Through the digital footages, gathered during the workshop week, however, it was possible the create a euphoric community atmosphere by editing special highlights of the workshop week into a final closing video. Thanks to the personal avatars used in *Gather*, traditional events like a team picture could also be realized.

2.2.2. Educational / Teaching Framework

Time Management:
Figure 1 shows what proportion of the workshop's time is taken up by the respective categories. It can be seen that approximately 50 percent of the time is allocated to group work. The lectures and reviews receive a similarly large share in both years. Nevertheless, the ratio between socializing and the breaks has changed significantly, which can be explained, by the fact that the evening program in the in-person workshop served socializing purposes and had to be dropped in 2021. In addition, the breaks in the online event were extended, which provided the participants for example with enough time to prepare their meal.

Lectures:
Expert presentations on various aspects, such as project management or space station subsystems, serve to provide each participant with certain basic knowledge from the current state of research in all fields. This is also intended to raise awareness of any concerns other team members may have based on their individual academic background. While the experts have always been on site or reachable by phone in the past workshops, this time they were mainly connected digitally. Thanks to the virtual representation of a lecture hall (see Fig. 2), the participants fell into typical patterns of an in-person event. For example, a crowd was formed in front of the microphone, as seen in Fig. 2, from which questions could be posed to the lecturer.

Figure 2: Virtual lecture hall

Group work:
As in the in-person workshop, both groups were given their own team rooms. Since one can move freely with one's avatar in the virtual world, the expected problem of communication difficulties between persons was significantly mitigated. Often subgroups met in the prepared compartments with whiteboards to participate in brainstorming sessions or discussions regarding implemented values. Furthermore, participants could go to the expert room to get their advice. If they were not present, they could be contacted via the messenger tool (Slack). This tool was also used for general advice from the organization, but also within different groups, so that the working meetings of individual subgroups did not have to be disturbed.

Reviews:
A side room in the respective team room was used as a presentation forum for the reviews. After the presentation of the team's current status, the experts posed follow-up questions to understand the depth of detail of the ideas or to provide new inputs. Afterwards, there was also an opportunity for students to raise specific questions to the experts. These reviews were mostly similar in 2019 and 2021 apart from an

DOI: 10.5821/conference-9788419184405.064

additional review during the digital workshop. The reviews also served as practice for their public final presentation of the results. Based on this final presentation and the project report of each team, an evaluation committee decides which team wins the current edition of the SSDW. Figure 3 shows the winning concept from 2021.

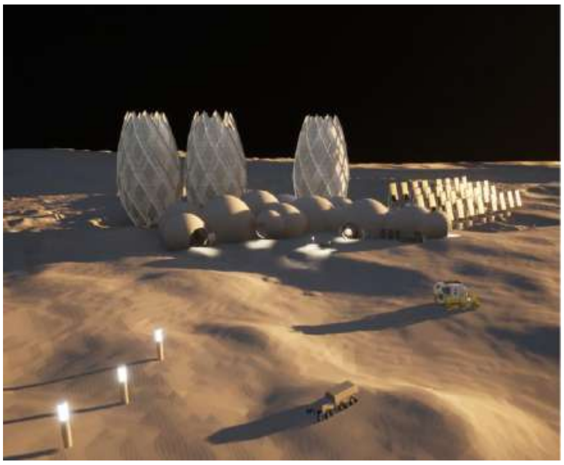


Figure 3: Winning concept 2021

Social Events:
Together with the adjustments to group work, the necessary changes for adequate digital socializing represent the greatest challenges. For example, the team spirit should also be created during SSDW 2021, although personal contact between participants was unfortunately not possible. Since evening activities such as a joint dinner at a typical local restaurant or a tour to the local planetarium were not possible, these were substituted, for example, by video contributions by the organization team produced especially for the SSDW. In addition to a video tour through the planetarium, participants were also able to attend on a virtual tour through Stuttgart and have a look at various working groups at the IRS. While the 2019 participants built and launched water rockets in small groups, the 2021 students participated in a treasure hunt through the virtual map. To break up the intense group work after a few hours of work a social event was integrated. Hereby the panel discussion of the in-person workshop was substituted by a *PowerPoint* karaoke (Fig. 4) in the digital format. The euphoria of the participants was clearly visible from the emojis shared. A new addition to the digital version is a short quiz after each lecture block to keep the attention and to review what has just been learned.

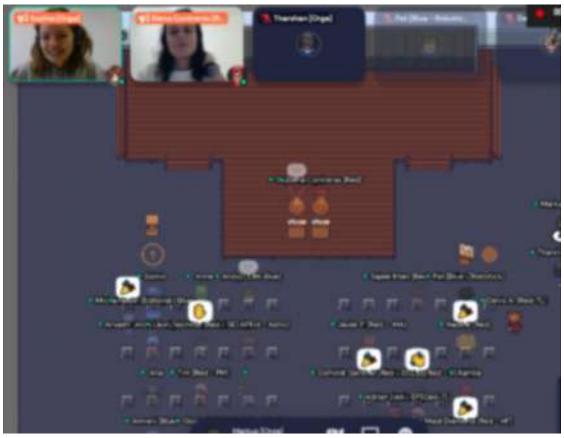


Figure 4: PowerPoint karaoke in Gather

Breaks:
While the breaks in the in-person workshop offered another opportunity for networking, these were used in a variety of ways in the digital version enabling a flexible networking process.

2.3. Post-Processing

Evaluation:
In order to further optimize the workshop, an evaluation was carried out among the participants and experts. The highly positive feedback from the last evaluations was also reflected in the efficient verbal promotion mentioned at the beginning. The choice of additional tools for digital implementation was particularly emphasized in the last evaluation. Despite the successful coverage of many aspects through the integration of digital tools, both experts and participants favored an in-person workshop, since the evening socializing events could not be fully implemented digitally.

Further Work:
In addition to the usual final documents which need to be sent to various institutions, this digital edition was followed up by sending out the certificates of participation by mail. In order to enable further international networking of the participants with the SSDW team, they are integrated into the SSDW alumni network.

3. Results and Discussion

The results delivered by both teams at the end of the digital SSDW are equal to those of the in-person workshop, which is why the implementation of the first digital workshop must be considered as a success. In both workshops, thanks to the many socializing

DOI: 10.5821/conference-9788419184405.064

events, a team spirit was created, which led to final results of the workshop serving as a basis for further work in both editions [11]. The preparation of this new concept was more challenging than the organization of previous years, as new tools had to be tested and implemented. The workload during the workshop week was similar, as essential aspects such as the provision of catering were not required, but balanced by additional digital aspects as the video editing.

4. Conclusions

With the successful implementation of the SSDW 2021, a digital version of the already established SSDW in-person format was created. The concept established in this way is decoupled from the previous constraints and is now available as a location-independent version, enabling a more flexible response to unforeseeable global impairments in the future. A hybrid edition of the SSDW might be able to combine the positive aspects of both workshop formats and might be an additional concept considered worth testing.

Acknowledgements

The authors would like to thank everyone that made the first digital workshop edition possible. Without such great staff and experts and their ideas and knowledge shared before and during the workshop it would have not been such a successful experience. As the workshop always needs to be funded, the authors gratefully appreciate the supporters assistance, namely the DAAD, TESAT, Airbus, Price Systems, Astos, Valispace, HE Space, the Institute of Space Systems, the University of Stuttgart and many more!

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From educational programmes to professional projects: finding flight opportunities

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Abstract

Nowadays, lots of opportunities are offered to students to fly their own experiment on board of rockets or balloons. Thanks to those opportunities, young scientists have a chance to experience hands-on project and even to find a vocation: pursuing experimentations on-board of flight missions. However, it can appear, for these young professionals, that flying on board sounding rockets or stratospheric balloons is hard to access or to afford. Yet the opportunities exist and are waiting for them!

Space educational programmes enable students to learn, in a short period of time, all phases of a scientific project; a unique chance to experience a full project cycle from objectives' definition to the publication of the results. Thus, students define mission requirements, design, manufacture, test and finally launch their own experiment! On REXUS/BEXUS [1] for example, students experience an end-to-end project with all disciplines required by a Space project (science, mechanics, electronics, software, system engineering, management, finances, outreach). The concretisation of all efforts occurs during the launch campaign, organised at SSC Esrange (Sweden). The campaign is always an intense period for the participants: high level of concentration, pressure, stress but a massive work that pays off during the flight and after. Usually, this key event enables ideas and improvements to pop up; a prolific event to define the next step of an experiment, maybe on a future mission!

Many students start their professional career after the campaign. Despite new ideas and the drive to pursue, a common idea of these young professionals is that it is hard to access to flight opportunities on sounding rockets or stratospheric balloons while not being a student anymore: too expensive to finance a campaign? too complex to organise? who to contact? Many questions that it is time to answer. Yes, it is possible! At SSC, we enable access to stratospheric balloons, sounding rockets and drop tests on a cost-efficient entrance level or fully funded through national and international programmes. One of these examples is the EOSTRE mission [2] (Experiment on Outliving Microorganisms under Stratospheric Environment), developed by FH Aachen University of Applied Sciences (Germany) in collaboration with the University of Oulu (Finland); a former BEXUS team that developed its own balloon mission, launched successfully from Esrange in March 2020. Several former students from REXUS/BEXUS have joined professional opportunities, such as the HEMERA [3] programme, with the experiments GRASS from INAF (Istituto Nazionale di Astrofisica) and STRAINS (Sapienza University, Rome) and launched it from Esrange in September 2021. Today, SSC is also offering ride share opportunities on sounding rockets with the programme SubOrbital Express [4]; first successful launch was in June 2019 on board MASER 14 (S1X-1). Opportunities are still open for the next missions in fall 2022 (S1X-3) and in 2023 (S1X-4).

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DOI: 10.5821/conference-9788419184405.065

Keywords
Students, professionals, new flight opportunities, sounding rockets, stratospheric balloons

Acronyms/Abbreviations

AO *Periodic Announcement of Opportunity*

BEXUS *Balloon EXperiment for University Students*

CORA *Continuously Open Research Announcement*

DLR *Deutsche Zentrum für Luft und Raumfahrt*

ESA *European Space Agency*

ESC *Esrange Space Center*

GSTP *General Support Technology Programme*

REXUS *Rocket EXperiment for University Students*

S1X *Suborbital Express*

SciSpacE *Science in Space Environment*

SNSA *Swedish National Space Agency*

SSEA *Symposium on Space Educational Activities*

SSC *Swedish Space Corporation*

1. Introduction

Sounding rockets and stratospheric balloons enable to carry on a wide spectrum of scientific experiments such as atmospheric research, astronomy, astrophysics, biology, material science, physics and of course microgravity research. In addition, both vehicles could be used for technology demonstration. However, as young professional, having your experiment accommodated on such missions seem complex. In this paper, you will find a synthetic description of the existing opportunities in Europe, advises on how to finance your project and contact points to not miss any opportunities.

2. Sounding rocket & Stratospheric balloon missions: the opportunities

2.1. Institutional missions: answering a call for proposals

2.1.1. National missions

To find a mission, the first step is to look at opportunities offered by the national space agencies. For example, in Sweden, the Swedish National Space Agency (SNSA) opens regularly calls for applications; the national programme enables a wide diversity of research such as astronomy, astrophysics, astrobiology, atmospheric sciences, Earth observation, fundamental physics, life and physical sciences, space physics and technology demonstration. A particularity of this programme: all missions are launched from Esrange Space Center (ESC). The national programme enabled missions such as SPIDER (Small Payload for Investigation of Disturbances in Electrojet by Rockets) and SPIDER 2 studying the Farley-Buneman instability in the auroral electrojet; rockets launched respectively in 2016 and in 2020). More recently, a group of scientists have been selected by SNSA: the BROR mission (Barium Release Optical and Radio rocket experiment) will study the dynamics of the ionosphere's electric and magnetic fields. This mission, initiated by IRF (Institutet för Rymdfysik, Institute for Space Physics) in cooperation with EISCAT (European Incoherent Scatter Scientific Association) and SSC (Swedish Space Corporation), will be launched in 2023. The national programme also enables stratospheric balloons missions like PoGO (balloon-borne telescope studying polarisation of gamma-rays from pulsars) [6]. The balloon flew successfully in 2013 during 12 days around the North Pole, from Sweden to Canada. After this successful mission, another collaboration with SSC was initiated by KTH (Kungliga Tekniska Högskolan, Royal Institute of Technology Stockholm) in collaboration with Swedish and Japanese scientific teams, still under the umbrella of the national programme: the PoGO+ mission.

To reach such national mission, scientists are strongly advised to subscribe to the SNSA newsletter [5] to not miss any opportunity! Calls are open regularly and proposals are evaluated by a panel of experts.

2.1.2. International missions

In Europe, scientists should look for calls for announcement from the European Commission and the European Space Agency (ESA).

The European Commission established a programme called Horizon Europe (formerly

Horizon 2020). This programme opened regularly calls for proposals. Unlike the Swedish national programme, Horizon Europe is divided in topics. Thus, an important attention should be brought by the group of scientists to find an appropriate topic for which their experiment can fit in. This is a critical aspect of any proposal to increase the chances of being selected [7].

An example of a mission that was funded by this programme is ESBO (European Stratospheric Balloon Observatory) [8]; a dedicated mission led by a consortium of 5 partners: Institute of Space Systems at University of Stuttgart, Institute for Astronomy and Astrophysics at the University of Tübingen, Max Planck Institute for extra-terrestrial Physics, Institute of Astrophysics of Andalucía and SSC. ESBO was initiated by scientific institutes experts in astronomy, to enable astronomy observation from the stratosphere. The ESBO partners submitted a proposal to the Astronomy call of the Horizon 2020 and was selected. After a successful project, ESBO partners submitted another proposal to Horizon 2020 to pursue the development. It was then another success for the group of researchers that got the funding for a full development of the telescope, the detector, the image stabilisation system and the development of the spin stabilised gondola.

Second main call for international missions is SciSpacE (Science in Space Environment) programme by ESA [9]. SciSpacE offers opportunities on several ground-based platforms such as in Antarctica station, drop tower, parabolic flight and sounding rockets. It is opened to researchers studying human research, biology, astrobiology, planetary sciences and physical sciences. When selected, experiments are accommodated on TEXUS (Technology Experiments in Zero Gravity) (for DLR (Deutsches Zentrum für Luft und Raumfahrt, German Space Agency) and ESA microgravity research programmes) or on the Swedish rocket SubORbital Express / MASER (MAterials Science Experiment Rocket) as well as on TEXUS. Both TEXUS and MASER could carry up to 230kg of experiments to an altitude of 260 km, providing 6 minutes of microgravity. ESA is procuring the flight opportunity and the execution of the launch campaign. As an example of former flights: TEXUS 56 [10] was launched in 2019 embedding experiments from McGill University PERWAVES, Université Libre de Bruxelles, Braunschweig ICAPS, University of Freiburg InSituKris, E4T from Airbus & OHB and AEGIS from Sint Pieters College in Belgium.

Lastly, other calls initiated by consortium of major space actors can be reached. Such as HEMERA, funded by CNES (Centre National d'Etudes Spatiales), SNSA, DLR, ASI (Agenzia Spaziale Italiana), CSA (Canadian Space Agency), ASC (Andøya Space Center), SSC and Airstar. HEMERA [3] was funded by Horizon 2020 to enable scientists to launch experiments on stratospheric balloons making accessible a wide range of mission profiles to fit the largest user community. Two calls for proposals were opened in 2018 and 2019. The next launch campaign is scheduled for September 2022.

2.2. Commercial missions: booking a flight ticket

New opportunities emerged recently: commercial missions for sounding rockets launches. Announcement of flight opportunities are published on the SubOrbital Express website [4] regularly and experimenters can simply book a flight ticket! The first mission was launched in 2019 from ESC on SubOrbital Express 1 / MASER 14 rocket. Currently two missions are under preparation: one is scheduled for a launch in October 2022 and the next one in autumn 2023 (still open for payloads).

SubOrbital Express enables dedicated and rideshare missions (like MASER 14). Each experiment could have a dedicated rocket module or could share the module with other experiment(s). Mass, volume, power supply, communication service and any special requests from the experimenters are discussed with SSC to provide the most suitable solution for the scientists. Price of the flight ticket mainly depends on those parameters.

2.3. Open missions: initiating your own flight

Sometimes, experiments do not fit in any calls for proposal. Thus, another solution for experimenters is to initiate their own mission. If it could seem difficult it is in fact a realistic alternative.

The CRYOFENIX [11] project is an excellent example of a dedicated mission. Initiated by Air Liquide, CRYOFENIX aimed at studying the behaviour of liquid propellant during motor re-start and propelled phases of a launcher. Such results are then used for the European launchers of the Ariane family. If fluidics research under microgravity was already conducted by Air Liquide and CNES on MASER, a dedicated mission was considered to push the study further. Air Liquide initiated the project: a feasibility study was performed while visiting ESC and securing funding by CNES. Air Liquide worked in close collaboration with SSC to adapt a MASER rocket to Air Liquid needs: the mission became CRYOFENIX: a fully dedicated rocket with a dedicated service module, cryogenic control module and a fully developed thrusters' module for the needs of the mission. A fantastic example of initiated mission that successfully flown in 2015.

EOSTRE (Experiment on Outliving Microorganisms under Stratospheric Environment) [12], is another example of initiated mission on a balloon developed by FH Aachen University of Applied Sciences and University of Oulu (former BEXUS team) that flew from ESC in 2020. It was a dedicated mission initiated by the scientists in collaboration with SSC.

If such dedicated missions offer an "à la carte" experience, the main drawback is the costs. Thus, to make the mission affordable, the solution is the rideshare mission. First option for the experimenters is to contact SSC to describe the mission needs. If other experimenters have contacted SSC with compatible payloads, SSC could then initiate a shared mission. Second option for the experimenters is to reach other groups of experimenters and then contact SSC as a shared payload. Then SSC would organise a mission; this is valid for both rocket and balloon missions. Ridesharing is an interesting solution to share the costs of the launch, the launch campaign, and the use of launch systems. Thus, networking is a key for scientists who want to build a mission. Conferences and workshops are an excellent way to get in contact with space agencies, launching companies and other groups of scientists. As an example, the HEMERA workshop is planned for July 2022 [13].

3. Financing your project

Beginning an academic career often implements the need to find funding sources for the desired work field. Same here. Universities often provide the basic frame for research, the facilities, laboratories, and offices, while the team need funding sources to work on the scientific subject. This is locally very different and depending on the structures of the University. Here it is recommended to look out for innovation budgets, research clusters focussing on certain topics and external research budgets.

Funding can be locked to certain purposes. The budget maybe either used for hardware and direct costs such as travelling only, or it is only covering the labour costs for the project lifetime. Development costs and the flight ticket itself are usually another big problem and are addressed in the following. The public funding programmes provide hence different alternatives. Often, it is necessary to combine different funding options for one dedicated research activity. To receive a certain funding source, it might be even mandatory to guarantee the base funding for labour and facilities by another source.

It must be stated, that publicly funded research projects require the publication and sharing of the scientific data. The team of the principal investigator has the exclusive right to work and publish the results for a limited time before the data is made available to the entire research community.

3.1. National Agencies

3.1.1. Swedish National Space Agency (SNSA)

The Swedish National Space Agency offers on their website [15] (currently only in Swedish) support to research in a broad choice of thematic areas. The calls are distinguished in continuously open calls, annual calls, less frequent open calls, and targeted calls.

The Continuously Open Calls provide support for proposal writing, travel and events in preparation of space research missions and support to international collaborative missions. Annual Calls provide career support and PHD position fundings or long-term international missions.

The Less Frequent and Targeted Calls enable research within the Balloon and Rocket Programme, the National Research Satellite Programme or for Technology Development. Furthermore, SNSA provides in the framework extended fundings for international and ESA Science missions.

3.1.2. German Space Agency (DLR)

DLR follows an approach supporting the entire research project (called "Forschungsvorhaben") over a timeframe of 3 years. The funding includes the costs for personnel, material, the implementation, and flight ticket on the selected platform. The experiment concept or research idea is directed to the DLR Agency and throughout an iterative process the project is discussed, defined, and selected for funding. The Agency acts in a

DOI: 10.5821/conference-9788419184405.065

supporting role to find the best suitable platform and project setup for the science teams [18].

3.2. European Space Agency (ESA)

ESA has opens for researchers from the 15 ESA member states in the *European Programme for Life and Physical Science in Space (ELIPS),* opportunities to apply for the funding the access to research facilities providing space or space related environments. The funding opportunities within the *ESA SciSpacE programme* are described below. Concerning microgravity platforms, ESA [16] provides an exhaustive collection of information about the platform and the accessibility through the application processes of which two are described here briefly.

3.2.1. Periodic Announcements of Opportunity (AO)

The AO are issued on a periodic base with funding options mainly for research on board of the ISS and Sounding Rocket platforms. Often are the AO´s linked to the triennial funding cycles of the ministerial conference of the contributing ESA member states, the AO. Opening dates as well as deadlines for the calls, detailed information to the application processes and the requirements towards the formal proposal are thoroughly described on the ESA Website [14].

3.2.2. Continuous Open Research Announcement (CORA)

The call for the fast track for experiment including Parabolic Flight and Drop Tower experiment proposals is continuously open and can provide support within a shortened application procedure. It applies, if the scientific goal can be anticipated to be reached within a single campaign [14]. Those announcements are then continuously open for a dedicated timeframe.

3.2.3. General Support Technology Programme (GSTP)

While the previously discussed funding options focus on fundamental research, the GSTP provides the fundament for technical developments from the concept to the final application. ESA is following a 3 elements approach. The first Element *Develop* supports to raise the Technology Readiness Level (TRL) level from the concept to a qualification state. The second Element *Make* lifts the technology to marketable products, while the third Element *Fly* enables the in-orbit / in-flight application [17].

3.3. Research fostering European Programmes

3.3.1. Horizon 2020

Horizon 2020 was a research fostering programme by the European Commission and supported research projects and developments over a timeframe from 2014 to 2020. The total budget was almost €80 billon. Today, the programme is closed, but it is succeeded by the Horizon Europe Programme [18].

3.3.2. Horizon Europe

Today, the European Commission has an open call for the Horizon Europe programme, which provides funding for research and innovation projects with a budget of €95.5 billion [19]. It is open from 2021 to 2027 and should facilitate the competitiveness of the EU space sector and enhance the access to space. Furthermore, the programme supports developments with funding for In Orbit Verification (IOV) and In Orbit Deployment (IOD) activities. The calls are open within dedicated research field, in which the applicant can receive funding. These fields are mostly narrowly defined. Horizon Europe is mainly supporting working hours and hardware within a limited budget and for a strict timeframe. Thus, this is common for funded projects to re-submit a proposal some years later to pursue the project development.

4. Conclusion

Experimenters shall be aware of existing launch opportunities in Europe and regularly check the calls for proposals. Subscribing to space agencies newsletters is an easy solution to get notifications for example. In addition, although institutional missions represent major part of the missions, scientists could also consider commercial missions and even initiating their own missions if existing opportunities are not suitable for their experiment. Thus, experimenters shall not limit themselves to existing missions but shall be pro-active and initiate their own missions. For this purpose, experimenters are encouraged to contact the actors of the sounding rockets and stratospheric balloons domain. At SSC, we are open to discuss future missions and will work in close contact with you until the launch from ESC and beyond!

As advises, experimenters are strongly encouraged to select wisely the topics of their calls and not to underestimate the work for preparing a proposal. Support from people that

DOI: 10.5821/conference-9788419184405.065

are experts in this challenging exercise should be sought. In addition, visiting launching facilities (payload preparation halls, launch pads…) is also a good way to meet the operational team and understand how we could build a mission together.

5. Disclaimer

This paper does not claim to provide an exhaustive and exclusive listing of research and funding opportunities. It focusses on a few typical examples for the research utilising sounding rockets and stratospheric balloons as vehicles as being familiar to the authors.

Acknowledgements

To write this paper, the authors would like to thank very much: Kristine Dannenberg (SNSA), Michael Becker (DLR), Philipp Maier (IRS, University of Stuttgart), Jérôme Lacapère (Absolut System) and SSC: Mattias Abrahamsson, Maria Ångerman, Christian Lockowandt and Michael Lundin.

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ESA Academy Activities during COVID-19

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Abstract
The ESA Academy is the ESA Education Office's overarching programme for university students. The Academy's portfolio consists of both 'hands-on' activities, and a Training and Learning Programme. Conventionally both of these elements involve a significant number of in person events, for example training sessions, workshops and test and launch campaigns. The educational nature and practical aspects of such events has traditionally necessitated in person participation.

Additionally, most of the Academy's 'hands-on' programmes revolve around student teams designing, building, testing and operating an experiment or spacecraft, activities which rely on the availability and delivery of commercial components, and access to manufacturing, testing and launch facilities, and laboratories.

In March 2020, as the COVID-19 pandemic, and associated restrictions, began to take hold in Europe, nearly all the ESA Academy programmes were affected. Despite the challenges, the Academy continued to deliver activities, and the student teams participating in the Academy's programmes continued to achieve major milestones, including launching experiments to the ISS, CubeSat testing and launch and execution of micro- and hyper-gravity experiments.

This paper explores the challenges faced during COVID-19 and how both the programmes and the students participating in the programmes adapted to meet their educational, scientific, and technical goals. Furthermore, the longer-term adaptation of some of these changes into the future execution of the programmes is discussed.

Keywords
COVID-19, ESA Academy, Space Education,

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DOI: 10.5821/conference-9788419184405.066

Acronyms/Abbreviations

AIT	*Assembly, Integration and Testing*
CDR	*Critical Design Review*
EARs	*Experiment Acceptance Reviews*
ESA	*European Space Agency*
ESEC	*European Space and Security Centre*
FYS	*Fly Your Satellite!*
ISS	*International Space Station*
REXUS/BEXUS	*Rocket/Balloon Experiments for University Students*
S-, D-, F-, O- YT	*Spin-, Drop-, Fly-, Orbit- Your Thesis!*
TLP	*Training and Learning Programme*

1. Introduction

Like many organisations around the world the ESA Academy faced major challenges during the COVID-19 pandemic. Many of the Academy's activities have traditionally revolved around onsite and in person activities, and throughout the pandemic the Academy rose to challenge of continuing to deliver a high-quality portfolio of activities while prioritising the health and safety of participating students and staff.

2. ESA Education and ESA Academy

The ESA Academy is a part of the ESA Education Office and comprises of a portfolio of activities for university students. Like the Education Office in general, the mandate of the Academy is to enable and inspire students to pursue careers and further education in space related domains. This is achieved through a tailored transfer of knowledge from ESA, industry and academia experts, enhancing students' skills and competences and giving them the tools necessary to achieve their ambitions in the space domain.

The ESA Academy consists of two pillars, a portfolio of hands-on educational activities and a **Training and Learning Programme (TLP)**.

The hands-on programmes are recurring programmes which support students, normally in teams, through the design, test and operation of experiments or satellites. These programmes are:

- **Fly Your Satellite! (FYS)** – supporting student teams to develop, launch and operate their own CubeSats.
- **Spin-, Drop-, Fly- and Orbit- Your Thesis! (S-, D-, F-, O- YT)** – supporting student teams with experiments to be operated on a centrifuge, drop tower, parabolic flight, or on the International Space Station (ISS) respectively.
- **Rocket and Balloon Experiments for University Students (REXUS/BEXUS**) – a collaboration programme with the Swedish National Space Agency and German Aerospace Centre supporting student teams with experiments for sounding rockets and stratospheric balloons.
- **Fly a Rocket!** – a collaboration programme with the Norwegian Space Agency and Andøya Space Education, enabling students to participate in a sounding rocket campaign.

The TLP offers a series of training sessions to students, normally individually, on a large variety of space related topics. Prior to the pandemic these training sessions mainly consisted of 4- or 5-day on-site events taking place in the dedicated Training and Learning Facility at ESA's ESEC-Galaxia site in Belgium, and delivered by topic experts.

Within both pillars a large part of the activities have traditionally required on-site working, and to an extent the success and highlight of the ESA Academy programme has been the excellent interactions between students and experts and among the students themselves, enabled by these on-site, in person elements.

3. Initial effects of the Pandemic

As the numbers of infections and hospitalisations increased in Europe, ESA Education took steps to ensure the health and safety of all students and staff participating in its programmes. Throughout the pandemic the health of students and staff has remained a priority, and ESA Education has continuously, ensured it adheres to best practice with respect to the COVID situation, adhering to the guidelines and regulations of the relevant Member States, and often including additional safety measures.

The initial effects of the pandemic included: the cancellation and postponement of **Training and Learning Programme** training sessions and the rapid transition to online delivery [1]; the postponement of the **REXUS** launch campaign, and transition to virtual Critical Design Reviews (CDRs); the postponement of the **Fly a Rocket!** launch campaign and extension of the existing online training course; and the cancellation of site visits for the **Fly Your Satellite!** teams, and major adaptations to satellite testing.

Across all of the hands-on programmes, project development by the teams was also delayed by the lack of access to laboratories and inability to obtain materials.

DOI: 10.5821/conference-9788419184405.066

4. ESA Academy Programmes: challenges and achievements

4.1. REXUS/BEXUS

Within the **REXUS/BEXUS** programme challenges were faced both by the programme, which traditionally includes many on-site events at ESA and partner facilities, and by the student project teams themselves, however with considerable variation between countries.

Where possible programme activities were switched to a virtual format. This was done for the CDRs (May & Jun. '20), Integration Progress Reviews (Jun. – Aug. '21), Cycle 14 selection workshop (Dec. '21), Student Training Week and Preliminary Design reviews (Feb. '22).

After some adjustment virtual events could be held with some routine. It was seen that some effort is required by the virtual host, but this is much less than the organisational effort in an in-person event.

Online events were largely able to meet their technical and educational objectives, but they could not be compared in terms of quality to in person events, missing, for example, the important social aspects and informal exchange.

A major advantage of the virtual format was an increased number of participants, no longer limited by venue capacity, and allowing flexibility around exams and work. The Student Training week hosted +/-150 students and +/-50 experts compared to typical on-site numbers of +/-90 and +/-20 respectively.

Conversely this flexibility meant some students were not always giving the training their focused attention, participating only partially or sometimes doing tasks in parallel, something which is difficult to track or monitor.

Many activities could not be performed virtually, such as Experiment Acceptance Reviews (EARs), integration and testing events and launch campaigns. The postponement of these eventually led to a one-year postponement of the entire programme, meaning there was no selection for new teams in 2021.

At the time of the postponement the participating teams were at the AIT (Assembly, integration and Testing) phase of their projects, however with the extra time, design changes were permitted and validated through additional design reviews.

Additional webinars were also organised, with 70-100 attendees at a time.

Once EARs were possible, they were often performed in a hybrid format, with some reviewers attending virtually and with mixed results. During the team's presentation and project discussion, virtual participation did not constitute a disadvantage, but the main objective of the EARs, hardware inspection and demonstration, could not be performed virtually.

With an improving situation the integration, testing and launch campaigns could resume, with strict COVID measure in place, including proof of vaccination, facemasks, social distancing, daily tests, and strict limits on campaign numbers. The participation limit not only represented a disappointment for the students, but also presented a challenge for the teams to ensure the right expertise was available to support their experiment operation and any anomalies.

With the use of many virtual events the social and informal exchange aspects of the programme were soon lost. This is a particularly important feature in educational programmes which aim to motivate and inspire students and enable knowledge transfer. To mitigate this, events such as virtual coffee meetings and pub quizzes were held, with positive results.

For the teams the problems faced were mainly logistical, such as limited (or no) lab access and inability to obtain materials (compounded by the chip shortage).

Additionally, students' academic careers did not stop, and teams were faced with members 'aging out' and graduating before their experiments were launched, necessitating either older students facing continued participation in the programme into their working lives and/or recruitment of new students and hand-over of responsibilities, a challenge even under normal circumstances.

4.2. Fly a Rocket!

The impact of COVID may be considered less severe than other programmes for **Fly a Rocket!**, although a significant delay was still experienced, with the launch campaign delayed from Mar. to Oct. '21. During this time, the existing online pre-course was extended. Students were given more time to work on the two existing assignments and an additional third assignment was created. Additionally, students were invited to join webinars organised in other programmes.

4.3. Fly Your Satellite!

Unlike REXUS/BEXUS the **Fly your Satellite!** programme has always consisted of a blend of

DOI: 10.5821/conference-9788419184405.066

in-person (reviews, test campaigns, launch campaigns) and online (webinars, status meetings) elements. However, the pandemic significantly altered this balance.

During this period two cycles of the programme were running, FYS-2 with teams at the AIT phase, and FYS-3 with the teams around the CDR stage of their projects.

Within FYS-2 the initial challenges were broadly: The access of ESA Education to the teams for inspection and support with their hardware; the access of the teams to ESA test facilities to qualify their hardware for flight; and the ability of the teams to continue with their AIT activities due to complications with lab access and procurement (as with REXUS/BEXUS).

During the pandemic the LEDSAT team were integrating and testing [3], their protoflight model. This process usually includes ESA visits to the University, as well as testing at ESA facilities, neither of which were possible. However, as the launch was identified, these critical preparations could not be delayed and adaptations were found, including testing at university facilities. The inevitable reduced visibility led to some delays and further work, which may have been avoided otherwise.

Other test campaigns were adapted to allow critical testing, such as the EIRSAT-1 antenna test [5] which was conducted without the team physically present, and with other activities at the University taking place with ESA joining remotely.

Throughout the pandemic the teams showed remarkable resilience and adapted to enable project progress even in the virtual world, for example by enabling elements of remote access to their labs [6], to continue development and functional testing with reduced personnel.

Some activities could be performed onsite again in 2021 with extensive safety measures in place. These included the LEDSAT integration into the flight deployer [7], and EIRSAT Engineering Qualification Model testing [8]. The LEDSAT team were also able to attend a part of their launch campaign [9], although with a very limited number of participants, partly due to a clash in timing with the vaccine roll out in Italy.

Save for a small number of subsystem test campaigns [10], [11], the FYS-3 programme cycle has consisted almost entirely of virtual events.

Like in REXUS/BEXUS, programme reviews were moved online [12] [13], utilising lessons learned from the other programmes. Webinars were also offered throughout, with the added value of opening to other hands-on programme participants. New webinars were also offered, and a virtual soldering course was delivered with a live connection to ESTEC labs.

The Phase-D workshop [14], previously ran as a TLP style training event, was held entirely online in Oct. ‘21.

In addition to the programme adaptations, considerable adaptations were also made by the FYS team including supporting remote internships, online on-boarding of new trainees and virtual participation in conferences.

Despite the challenges and inevitable delays, FYS continued to deliver a high-quality programme for its participants, and throughout the course of the pandemic one satellite was launched, another qualified, and two achieved a Critical Design Review pass.

4.4. Spin-, Drop-, Fly-, Orbit- Your Thesis!

The primary element of the **-Your Thesis!** Programmes affected by the pandemic was the execution of the experiment campaigns, which requires access to specialised facilities (e.g. drop towers and parabolic flights). Other elements of the programmes were shifted online, following the example of the other programmes [15].

However, through adoption of strict COVID mitigation measures and shifting of schedules all campaigns were realised within 6 months of their originally intended date.

In particular the Fly Your Thesis (FYT) campaign was moved from Bordeaux, FR to Paderborn, DE (a lower risk area at the time of the campaign) [16]. An unexpected outcome of the pandemic was that the FYT teams were also able to take advantage of an additional partial-g flight one month after their nominal flight due to the cancellation of other experiments [17].

As seen with other programmes, -YT teams also faced considerable challenges with lab access, with solutions implemented with the help of universities enabling access under strict conditions, and often with limited numbers or the retrieval of hardware to be worked on at home. Procurement also impacted the teams, often reducing the time for testing before the final experiment campaigns.

Despite all the challenges faced, all selected teams and all students eventually participated in their campaign and managed to obtain data from their experiments.

DOI: 10.5821/conference-9788419184405.066

4.5. Training and Learning Programme

The **TLP's** primary challenge during the pandemic was the rapid transition from a portfolio of on-site delivered training courses to an entirely online delivery. However, it may also be said that this evolution was already under investigation, with the emergence/acceptance of relevant technologies and the increased demand for more accessible opportunities.

Initially courses were postponed or cancelled, with already selected students offered participation in the delayed online edition of their training course, or an alternative. However, it was not long before the first fully online training course could be offered in Jun. '20 [1].

Through a culture of continuous improvement, the TLP was able to transition to a successful entirely online portfolio relatively quickly. This also proved excellent support to the hands-on programmes and provided a wealth of lessons learned for online course delivery.

Figure 1 shows the reduced number of training sessions in 2020 and the switch to online delivery.

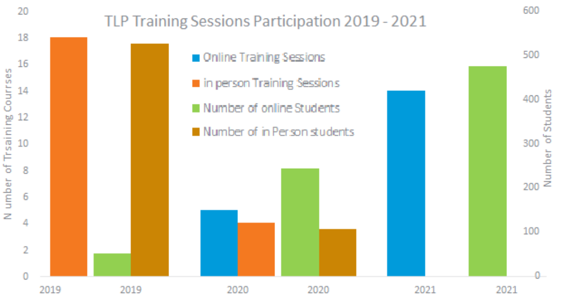

Figure 1: TLP Training Session Participation 2019 - 2021

Some of the main challenges with the transition were around the availability of suitable IT tools allowing quality delivery of the session and meeting relevant legal and regulatory policies (e.g. IT security, data protection). These were mitigated through support from other ESA departments.

As with the other programmes, the 'human' aspect of the sessions was initially lacking, an important aspect for student networking and knowledge exchange, but also for maintaining motivation and attention during the course. To address this several strategies were implemented, with many adopted into other programmes:

- An Ice-breaker a few days before each training session.
- Online informal get-togethers after the day's activities.
- Use of messaging platforms during the sessions.
- Increase of active participation through questions, quizzes, and chats
- A dedicated 15-minute Q&A session for every lecture.
- Re-scheduling from 4-5 full days to 8-10 afternoons, allowing flexibility around schedules and easier participation for Canadian students.
- Increased time allocation for teamwork and the use of breakout sessions with experts.

The transition to online delivery was also challenging for the experts, both in terms of adapting their content to be suitable for this medium and the delivery itself. To mitigate this, guidelines were produced on E-learning and Instructional Design Methodologies and additional test sessions were organised. Students were also requested to have their cameras on during the lectures, allowing for important visual feedback for the experts.

An unexpected outcome of the pandemic was an increase in the average number of applicants per training course. This may be due to a combination of the increased availability of students and the online format offering more flexibility for students to participate who might not have done so otherwise. Interestingly as academic courses began to return, applications numbers decreased, suggesting the TLP may have been filling the gap when curricular activities were reduced.

Despite the challenges the TLP maintained a high standard of delivery, with student and expert feedback continuing to be very positive as illustrated in Figure 2.

Figure 2: TLP Training Course Survey results

5. Lessons learned and adaptations for the future

The experience of the pandemic has provided a wealth of lessons learned for the Academy in

DOI: 10.5821/conference-9788419184405.066

how programmes may be ran with limited on-site elements and the relative advantages/ disadvantages of such adaptations.

The potential for online training sessions to reach more participants has clearly been demonstrated, though the depth of involvement of online attendees may sometimes be less and certainly harder to monitor. However, the consistent positive feedback and experience has demonstrated that the Academy should continue to complement its existing portfolio with synchronous E-learning. Furthermore it's proposed that asynchronous E-learning should also be developed. The implementation of Small Private Online Courses supported by an e-learning Management System Platform, which was already in the longer term planning, will now also be prioritised.

Instructional System Design techniques have also been demonstrated to enhance the interaction between students and experts, showing good potential for future blended training sessions.

The experience of the REXUS/BEXUS programme has highlighted that hybrid reviews may be implemented for training events or early design reviews (when there is no hardware to review), but their effectiveness is limited later in the programme. Their implementation earlier in the programme may also allow participation of more experts from different organisations than have traditionally participated, potentially identifying issues earlier in the projects' development.

Within the '-Your Thesis!' programmes, a blended training session after selection will now be adopted, with an additional online session following the site-based Training Week. This will help conclude the initial design ideas discussion, giving students time to implement decisions made in the face-to-face meetings and come with additional questions to the experts.

The extension of online webinars, previously delivered to only one programme cycle, to multiple programme cycles and to other programmes has proved effective, and will be implemented more systematically in the future.

The important social elements of the Academy's activities were also demonstrated, and measures were implemented to ensure this is maintained as best as possible.

In general, further work will be done to share the lessons learned in the individual programmes and across both pillars of the programme and beyond, in particular exploiting the wealth of experience gained in the TLP.

6. Conclusion

Throughout the COVID-19 pandemic the ESA Academy has adapted and continued to delivery a high-quality portfolio of education activities, without compromising on student or staff safety.

The transition to a hybrid, blended and E-learning scheme has been considerably expediated by the pandemic, and adaptations made in reaction to the situation have allowed testing and demonstration of new methods of instruction and learning. The results show that these methods of distance learning offer important advantages and, when balanced well with a suitable set of onsite and face-to-face learning activities, deserve a place in all elements of the future ESA Academy portfolio.

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Fly a Rocket! ESA's hands-on programme for undergraduate students

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Abstract

The Fly a Rocket! programme is a hands-on project offered by the European Space Agency's (ESA's) Education Office in collaboration with Andøya Space Education and the Norwegian Space Agency (Norsk Romsenter). The programme represents a unique opportunity for entry-level university students from diverse backgrounds to build, test, and launch an actual sounding rocket and obtain otherwise unattainable practical experience. In September 2020, the ESA Education Office announced the third edition of the programme, for which 30 students from the ESA Member States and the Associate Member States were selected. Of these, 24 participated in the launch campaign which took place throughout the second week of October 2021 at the Andøya Space in Northern Norway. The Fly a Rocket! programme comprises an online pre-course with two assignments and a hands-on launch campaign. The pre-course is self-paced and aims to widen the participants' understanding of basic rocket science topics such as the rocket principle, aerodynamics, and orbital mechanics in preparation for the campaign. During their stay at Andøya Space, the students were assigned to one of three teams, each with different responsibilities: Sensor Experiments, Telemetry and Data Readout, and Payload. As members of the Telemetry and Data Readout team, the authors' role was to set up the student telemetry station and ensure that accurate data was collected from the sensors on the rocket. In addition, they were an integral part of the countdown procedure, operating two of the three telemetry stations used for the mission. Following the launch, all the teams worked in conjunction to analyse and present the data according to four previously defined scientific cases.

This paper will be concerned with the activities carried out throughout Fly a Rocket!'s third cycle, with a particular focus on the work done by the Telemetry and Data Readout team.

Keywords

Andøya Space, ESA Education, sounding rocket, telemetry

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Acronyms/Abbreviations

AS	*Andøya Space*
ESA	*European Space Agency*
FaR!	*Fly a Rocket!*
GPS	*Global Positioning System*
IMU	*Inertial Measurement Unit*
ISA	*International Standard Atmosphere*
KDE	*Kernel Density Estimation*
NRZ-L	*Nonreturn to zero-level*
RC	*Range Control*
SNR	*Signal-to-Noise Ratio*
TM	*Telemetry*

1. Introduction

The Fly a Rocket! (FaR!) programme is a European Space Agency (ESA) hands-on programme targeted at undergraduate students pursuing degrees in science and engineering.

The authors were among the 24 students selected to participate in the third cycle of the programme. FaR! comprises a pre-study course with assignments and a launch campaign at Andøya Space (AS).

During the launch campaign, the participants were divided into three teams. The authors of this paper were assigned to the Telemetry and Data Readout team, and they had the responsibility to ensure a good and complete reception of data from the rocket. Furthermore, all students were asked to define various scientific cases to investigate with the obtained sensor data.

This paper will present the Fly a Rocket! programme as it took place between November 2020 and October 2021, as well as an overview of the activities, conducted by the Telemetry and Data Readout team throughout the campaign.

2. The programme

2.1. Application Process

The call for applications to the third cycle of the programme was open between September and October 2020.

The call was aimed at students in the first two years of an undergraduate degree from an ESA Member State, Canada, Latvia, Lithuania, or Slovenia. Although interest in technology and space is crucial for participation in the programme, students from backgrounds other than aerospace were encouraged to apply.

As part of the selection, the candidates were asked to express their motivation to be part of the programme, as well as to propose outreach activities pertaining to the opportunity and an additional sounding rocket payload.

2.2. Pre-course and assignments

To ensure that every participant would have a basic understanding of the science behind rockets, 30 selected students had to complete a pre-course. The pre-course included a publicly available compendium and assignments.

The provided material encompassed various rocketry topics such as rocket engines, rocket dynamics, orbital mechanics, and telemetry. Detailed descriptions of the sounding rocket used in the campaign and its payload were also part of the course.

The assignments were divided into two mandatory parts and an optional third part, added after the campaign's postponement due to the COVID-19 pandemic. The exercises were made to thoroughly assess the students' understanding of pre-course topics, focusing not only on the straightforward calculations but also on the reasoning behind the answers.

During the months leading up to their stay at AS, the participants worked together on the pre-course material and assignments, allowing them to acquire the solution and to get to know each other before the launch campaign.

3. The campaign

3.1. Overview of the rocket

The student rocket is a Mongoose 98 rocket that has been customized to fit the student campaign didactic goals; it is 2.708 m long, 102.8 mm wide [1], and mostly made of carbon fibre. In the front is the glass fibre nose cone that optimizes the antenna gain, followed by the carbon fibre avionics tube, the aluminium avionics plate, and the carbon fibre booster tube with three fins in the rear.

The battery, encoder, transmitter, and sensors are mounted along with the aluminium avionics plate. The battery module is only used during flight. Before that, all setup and tests are carried out with the help of an umbilical connector. The

DOI: 10.5821/conference-9788419184405.067

encoder samples both analogue and digital sensors and outputs them in a Bi-Phase modulated Manchester code signal. This means that both data and clock are in one signal, and it reduces data rate drop and helps the ground station to lock onto the signal after a dropout. From the encoder, the signal is sent to the FM transmitter board. The frequency used in the student rocket is 2279.5 MHz with a transmitted power of 450 mW by two S-band antennas. During the Fly A Rocket! campaigns, a basic sensor kit is always flown on the rocket:

- two-axis accelerometer
- two temperature sensors
- pressure sensor
- light sensor
- two-axis magnetometer
- Global Positioning System (GPS)
- Inertial Measurement Unit (IMU)
- Temperature array

The sensors' locations on the plate were decided based on the scientific cases the campaign tackled.

3.2. *Breakdown of activities*

The launch campaign took place on the scenic island of Andøya in northern Norway where the students were hosted by Andøya Space, an aerospace company with over six decades of operational experience in sounding and suborbital rockets of various configurations.

Between Sunday, 10th, and Saturday, 16th of October, the students set up the Mongoose 98 rocket, learned about scientific rocket campaigns, atmospheric physics, rocket engines & trajectories, and the other ESA educational programs.

Day 1 - Arrival day, welcome and practical information.

Day 2 - Introduction to scientific rocket campaigns, a tour of Andøya Space, and selection of PI-team & responsibilities.

Day 3 - Rocket Integration & telemetry setup, lecture about Andøya Space, lecture about balloons & radiosondes, and the release of the first meteorological balloon.

Day 4 - Final rocket integration & telemetry setup, lecture on operative rocket range work, and presentation about other ESA educational programs.

Day 5 - Launch day, lecture about rocket engine and live demonstration, lecture on rocket trajectories, lecture on Andøya's ALOMAR, the release of the pre-flight meteorological balloon, and post-flight data analysis.

Day 6 - Data analysis, lecture on Aurora physics, preliminary presentation, and end of the campaign.

Day 7 - Departure day.

3.3. *Scientific cases*

The participants were given the task to formulate multiple scientific cases that would focus on various aspects of the rocket's flight, measured by the rocket's payload. The Sensor Experiments team was divided into smaller groups that were each assigned a different scientific case.

The first scientific case (three members) used the balloon, temperature sensor, GPS, pressure sensor and optical sensor to detect the entry, exit and thickness of clouds. They hypothesized that detection of clouds can be performed using an optical, temperature or humidity sensor. Moreover, they thought that detection of clouds with the optical sensor would be the most accurate method.

The second scientific case (eight members) aimed to find out which method would provide the most accurate location of the rocket. The data was compared to the Open Rocket model, which estimates the trajectory of a rocket given its specifications. They hypotheses were:

- Open Rocket will be accurate up to Mach 1, where it is expected that the real values will deviate from the simulation
- At supersonic speed, GPS is expected to be the most accurate
- The IMU will likely drift over time due to its sensors experiencing noise.
- The pressure sensor is expected to provide valid results but the accuracy of these may deviate due to external wind from the holes of the rocket.

Detailed plots were created that compared the data from the GPS and pressure sensor to the data from Open Rocket for the scientific rocket. Unfortunately, the IMU data was lost due to sensor failure.

DOI: 10.5821/conference-9788419184405.067

The next scientific case (two members) used the balloon, pressure sensor and external temperature sensor to collect atmospheric temperature and pressure measurements at different altitudes from the balloon and the rocket. These measurements would then be compared with the International Standard Atmosphere (ISA). The team hypothesized that:

- As altitude increases, atmospheric pressure is expected to decrease following a specific trend.
- At a given altitude, the temperature measured outside the rocket is expected to be higher than ISA/balloon measures.
- At a given altitude, the pressure measured outside the rocket is not expected to reflect the exact atmospheric pressure but should be close to it.

The team was not able to recover GPS data, but it was able to collect pressure data.

The final scientific case (three members) had the objective to determine the spin of the rocket using three methods - light brightness variation, magnetic field strength variation and accelerometer data for the y-axis. The team wished to achieve this using the optical sensor, the accelerometer, and the magnetometer. Their hypothesis was that there is a direct correlation between the acceleration in the direction of travel and the spin of the rocket. Moreover, the direction of the spin would stay the same the entire trajectory (even if the acceleration changes direction in the axis of travel) as the fins are canted.

4. Telemetry and Data Readout

The Telemetry and Data Readout team was composed of 4 members and supervised by two Andøya Space Education teachers. The students were handed out booklets with theory and instructions and familiarized themselves with all aspects of telemetry station operation.

4.1. Setup of the student telemetry station

The hardware of the student telemetry (TM) station, which was set up by the team, includes an antenna, a downconverter, two receivers (for right- and left-hand polarization), a bit-synchronizer and a combiner [2] shown in Figure 1. Additionally, the TM station rack is connected to a DEWESoft decoder unit which feeds the data into a computer. The TM team had to arrange both the wiring and the settings of the rack. To perform this task, the members were divided into two groups, and each was assigned one of the two sides to work on. Once finished, the two groups switched roles so that each student could become familiar with every task. This gave the students an unprecedented opportunity to connect their theoretical knowledge of data transmission with practical experience operating actual hardware.

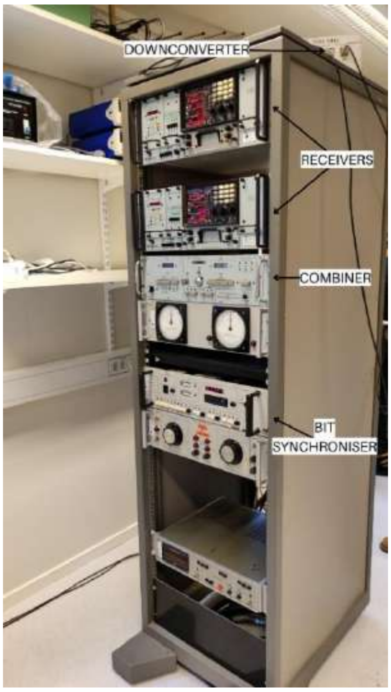

Figure 1. Student telemetry rack

To demultiplex the incoming data from the student rocket, the TM team used two DEWESoft decoders and their associated software. The decoder is connected to the Non-Return-to-Zero-Level (NRZ-L) and clock cables coming from the Bit Synchronizer as well as to a laptop where a setup file decodes the signal into multiple channels that can be recorded by the DEWESoft X3 program. Ultimately the goal was to save and export the data to .CSV files that could be analysed by the Sensors team using a Python script.

4.2. TM and Data Readout role during launch

During the launch day, the students from the TM station were assigned two roles called Student TM and TM Readout with 2 students in each sub-team.

DOI: 10.5821/conference-9788419184405.067

The TM Readout operated a DEWEsoft box connected to the antenna of the Main TM station and was the main source of communication between telemetry and the Range Control (RC) and Payload Manager.

The Student TM had their DEWEsoft box connected to the instruments at the student telemetry rack situated in the Andøya Education telemetry lab, where the students had worked in the previous days.

5. Discussion

5.1. Challenges during the countdown procedure

During the countdown procedure, the RC, the Student TM station, and the TM Readout performed a data storing test and found that the TM Readout team was not receiving any sensible data at that point. The countdown was paused, and the two telemetry stations worked closely together to resolve the problem However, since the TM teams suspected the problem to be the TM Readout's DEWESoft decoder, the team concluded that the countdown procedure should continue and that the data would be received and stored only by the Student TM station and Main TM.

After splashdown, once the recording was stopped and the data was saved, the TM and Data Readout team noticed that the data stream recorded at the Student TM station was very noisy and had a high number of frames missing. A possible cause is that the student antenna pre-set motion failed to track the rocket in real-time causing the station to lose data. Fortunately, the post-processing filtering was enough to provide enough data for the teams to work on their scientific cases and the Main TM station also provided cleaner backup data from the flight. These hindrances highlighted the importance of redundancy in the telemetry system.

5.2. Scientific cases outcomes

From the analysis of the scientific cases, the following conclusions were made:

- The first team managed to identify clouds with the sensors and compared the results to a cloud distribution model, concluding that the optical sensor gave the most accurate results.
- The comparison of acceleration, apogee and velocity showed that there was little deviation between the different methods and Open Rocket, thus proving that Open Rocket provided a surprisingly accurate trajectory.
- The third team found that the pressure data gave a good approximation. However, due to Andøya's location in the Northern atmosphere and due to time of year it was concluded that the 1993 ICAO standard atmosphere was not the best model for the atmosphere in question.
- The fourth team concluded that both the magnetometer and the optical sensor provided good data for a spin and that the spin was at its highest during the first ten seconds, and at its lowest at apogee. The spin of the rocket did not change direction after the apogee

The scientific cases were sometimes difficult because some of the data had a lot of noise and interpreting it correctly was often challenging for the teams. However, in the end, solid conclusions were obtained, and most hypotheses were confirmed.

5.3. Learning outcomes

Actively taking part in international scientific cooperation was one of the main goals this educational programme tried to achieve. Working together on the scientific cases, as well as on the payload integration and telemetry setup, provided for the most exposure to international cooperation most participants had ever experienced. Teamwork was paramount for solving the challenging problems that were presented to the teams and the Andøya staff strongly encouraged them to use the best elements from each person's skillset to solve said problems. If the team ran into problems, they were eager to call for each other's help and see if another perspective on the problem could enlighten them and provide a path to the proper solution. It was astonishing to see how a group of strangers from various countries was able to form an efficient and effective team in only one week, putting their bright minds together and successfully launching a scientific sounding rocket. International scientific cooperation was most definitely an achieved learning outcome.

Moreover, ESA wished to show the participants what working at an active rocket launch site would be like and to give us a glimpse at a

DOI: 10.5821/conference-9788419184405.067

potential future working at an international space agency. By introducing them to Andøya Space, they allowed the participants to experience first-hand how an active launch site and research facility operates. The lectures that were given during the week provided the team with a theoretical background that is often valuable in this field. Being able to walk around the facility gave the students the most accurate representation of what working at such a facility could be like. Most importantly, being able to actively take part in a rocket campaign showed them what it is like to launch a rocket, albeit on a smaller scale and with more limitations due to safety precautions. Nonetheless, it paralleled what the team might expect to experience in the future when given an opportunity to work in the field.

The TM and Data Readout team specifically had a crucial role in this, being the responsible team for making sure the data from the rocket was properly received and processed, enabling the other teams to analyse it. The responsibility of this task gave a good indication of what is expected from scientists at a rocket facility.

5.4. Future work

A possible area of future work involves further analysis of the recorded data by calculating the Signal-to-Noise Ratio (SNR) and applying Kernel density estimates to reduce the noise and "to reconstruct a continuous distribution from a discrete point set", which is the collected dataset. [3]

The SNR ratio is an important measure of signal quality and compares levels of noise and signal. By using a computer programme, it would be possible to sensibly discretise data from the rocket to intervals and calculate SNR for each interval. The result could be then plotted against time and compared with the rocket flight path telemetry antenna setting to better understand what could cause the noise.

Noise is a major concern when it comes to processing signals from a sounding rocket. Therefore, the scope of future work could focus on "proposing a new theoretical and algorithmic framework to evaluate and reduce the noise level" in the signal "based on the Kernel Density Estimation (KDE) theory" [4]. One of the key parameters of KDE is the bandwidth that influences the quality of the KDE. Since bandwidth in KDE is a free parameter, one of the potential areas of work could be dedicated to comparing the application of unit Kernels to Normalized Kernels.

6. Conclusions

After months of preparation, from applying to completing the pre-course and assignments, 24 students from all over Europe came together at AS for the launch campaign that represented the culmination of the third cycle of the FaR! programme.

Over a week, the participants got the unique opportunity to gain hands-on experience working at a rocket range and taking over the traditional roles needed to launch a scientific sounding rocket.

The authors of this paper were assigned to the Telemetry and Data Readout team, working on the setup of the student telemetry rack and of the software needed for obtaining good data stream. Overall, the programme gave them invaluable insights into the skills and knowledge needed to operate a telemetry station, as well as the importance of redundancy for the success of a scientific mission.

Acknowledgements

The authors want to sincerely thank the ESA Education Office and Andøya Space Education staff for the opportunity to take part in the Fly a Rocket! programme.

Additionally, C. Guerra and J. Zemek would like to further thank ESA Education for sponsoring their attendance to the symposium.

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Establishment of the Space Engineering Program in Hungary

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Abstract

The Hungarian space age started in 1946 with the successful Lunar Radar experiment by Zoltán Bay. In the past 75 years, the Hungarian space sector evolved and grew dramatically, achieving international recognition in space communications, material science, picosatellites, dosimetry, and many more domains. However, there was no space engineering related higher education program in the country.

After hosting the 2nd Symposium on Space Educational Activities in 2018 in Budapest, there was an emerging need for starting a space program for engineering students. A summer workshop organized by the Hungarian Astronautical Society in 2018 fostered further the process, and the Budapest University of Technology and Economics (BME) officially initialized the establishment of the space engineering master curriculum in 2019. By the end of 2020, the relevant ministry approved the national space engineering master curriculum. This means that every Hungarian university, which has the necessary competences, can start a space engineering program for their students. In early 2021, the BME Faculty of Electrical Engineering and Informatics at BME requested approval for its space engineering master program. In October 2021, the relevant body approved the program, allowing the first class of space engineering students to arrive to the university in September 2022. The Hungarian space engineering master curriculum is a 2-year-long master program for 120 credits (in the European Credit Transfer and Accumulation System, ECTS). The master's program at the Budapest University of Technology and Economics has 26 subjects and a 4-week-long industrial training. We outline the establishment process of the national space engineering curriculum and introduce the curriculum of BME.

Keywords

university education; space engineering master program; curriculum establishment

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DOI: 10.5821/conference-9788419184405.068

1. Introduction

The training of space engineers is now present worldwide in the higher education structure of individual countries. Space research, space science, and space technology are becoming more and more integrated into our daily lives today, so it is particularly important for educational institutions to provide training programs in this area as well. Every economy needs professionals who can navigate and be able to do real work in this area. In countries with a significant tradition of space exploration, technology and great economic potential, the space industry is of great importance. At the same time, smaller countries can also find areas where space industry opportunities, research and manufacturing potential exist. International organizations such as ESA or NASA provide many opportunities for almost anyone with the right knowledge to get involved in space-related developments.

There are several topics related to space. Basic scientific research aimed at getting to know space better is also well known to ordinary people. In such programs, mostly scientists and equipment development engineers work together. Many types of experiments in materials science, physiology, chemistry, pharmaceuticals, biology, and physics can also only be performed in outer space. Because today's equipment is basically built on an IT background, computing is also appearing in space equipment. Nor can we forget the international regulation of space radio communications, the legal issues of the use of outer space, which also requires appropriate expertise.

The education of all this, the training of professionals is primarily the task of higher education. In this wide-ranging topic, which is related to space, the Budapest University of Technology and Economics (BME) has set the goal of educating space industry professionals in the field of engineering.

The Hungarian space age started in 1946 with the successful Lunar Radar experiment by Zoltán Bay. In the past 75 years, the Hungarian space sector evolved and grew dramatically, achieving international recognition in space communications, material science, picosatellites, dosimetry, and many more domains [1]. However, there was no space engineering related higher education program in the country [2].

After hosting the 2nd Symposium on Space Educational Activities in 2018 in Budapest, there was an emerging need for starting a space program for engineering students. A summer workshop organized by the Hungarian Astronautical Society in 2018 fostered further the process, and BME officially initialized the establishment of the space engineering master curriculum in 2019 [3].

Our university introduced this training program in Hungarian higher education, developed the training conditions, and based on these, launched a master's degree program that will train space engineers in two years from autumn 2022.

In this paper, we will describe the process of starting the space engineering program, and we will also present the structure of the training.

2. Expanding the Hungarian higher education structure

In the structure of higher education in Hungary, the launch of a new, previously non-existent program must be preceded by the definition of the training and output requirements of the program. This document contains the exact name of the new degree, the level of education (MSc in our case) to be obtained and the field of training, which in this case is the technical field. The preconditions for entering to the program, i.e. the type of higher education qualifications that can be applied for, must be defined. In our case, students with a basic degree in technical, informatics or natural sciences can choose the field of space engineering, and with a basic degree in electrical engineering and mechatronics engineering, it is not necessary to examine previously completed subjects. In the case of those coming from other bachelor programs, it may be necessary to examine the subjects taken during the preliminary studies, and in the case of a successful entrance examination, credit extension may be required.

During the training, students receive 120 credits, in which the ratio of theoretical and practical knowledge is defined as balanced.

In the training and output requirements, we defined the purpose of the training and the professional competencies to be achieved. Our intention is to train engineers who are able to perform design, development, production and operation tasks primarily related to space technology and space research. They have relevant knowledge of the specifics of the space environment, the structure of the equipment to be delivered to space and the processes of its creation, as well as the design, construction and operation of equipment and systems for the ground handling of space equipment. They are able to perform research and development tasks at domestic and international space companies and institutes. They are also preparing to continue their studies in doctoral programs.

In line with the structure of the master's degree program in Hungary, the course also includes natural science knowledge, economics subjects and subjects providing space engineering professional knowledge. In the first part of the training period, the students work independently in the framework of a project laboratory, and then they prepare their diploma thesis.

The training and output requirements compiled based on the above are checked by the higher education supervisory authorities, after which the course is included in the list of courses on the basis of which a higher education institution with the appropriate educational and infrastructural competence can start the course.

The master's degree program in space engineering described in the training and output requirements is in line with the master's courses available in various European and other international institutions. Linked to other European curricula, the space engineering master program is primarily technology-oriented. It meets the national policy and industrial requirements related to the field of space engineering, as well as the requirements of the Ministry of Human Resources (our ministry responsible for education) and the national Accreditation Committee. However, during the master's studies, students acquire knowledge that is not available in other fields and is not or only to a limited extent available in other fields. The Hungarian space engineering program has been developed taking into account the international examples, which at the same time fits into the traditional four-semester, 120-credit structure of the Hungarian master's program and also offers the possibility to admit those from various technical undergraduate courses.

3. The space engineering program at Budapest University of Technology and Economics

Following the successful accreditation of the training and output requirements, BME has developed the documents required for the start of the course, which have been accepted by the organizations supervising higher education. This made it possible for the first master's degree program in space engineering in the history of Hungary to start.

The curriculum for both the spring and fall semesters is detailed in the introductory document. It contains the detailed topics of all the subjects of the training and the names, positions and academic degrees of the participants in the education.

The training will be attended by 64 instructors, of whom 51 have PhD degree. The students will study a total of 26 subjects. In addition, one is free to choose from six science subjects and two from 12 professional subjects. Independent project work, internships and diploma thesis tasks are also part of the program.

The literature about space technology [4] has provided a great deal of help in developing the main concepts of the start-up.

Admission to the master's degree program in space engineering is possible from the undergraduate courses in the fields of engineering, informatics and natural sciences. Since students from different backgrounds come to the training, four compulsory elective subjects in the training program help students to deepen their professional knowledge in accordance with their undergraduate education and interests. However, whatever subjects students choose, the totality of the subjects they study ensures that they acquire all the competencies listed in the training requirements.

Given that all students have already received mathematics training, in the case of the space engineering program, the optional subject of advanced mathematics in the science group provides students with the opportunity to expand their knowledge in the most necessary field. Students choose one of four compulsory subjects: stochastics, analysis, advanced linear algebra, and combinatorial optimization. The admission committee of the department provides support in the selection of the appropriate subject based on a written entrance examination for mathematics.

In the case of the elective natural science subject of the group of natural sciences, the students must choose one of six subjects, the choice of the subject depends on the student's orientation.

In the space engineering professional knowledge block, students must choose two of a total of 12 subjects within the framework of Compulsory Elective 1 and Compulsory Elective 2. This option is based on the diverse experience of the BME staff in various fields of space engineering training and provides students with the opportunity to deepen their knowledge according to their interests through two compulsory elective courses during the 120 credits. At the same time, the transfer of the professional knowledge required by the training requirements to all students takes place during the completion of the other subjects of the training. Technically, out of the 12 subjects in the compulsory elective block, some of the subjects will be announced in the autumn semester and some in the spring semester.

Table 1. Groups of subjects in BME's space engineering program

Scientific knowledge
mathematics, physics, materials science, space environment, and profession-specific core subjects;
Professional knowledge
comprehensive theoretical knowledge of the development, design, construction, manufacture and quality control of tools and equipment related to space technology and complex units, and of the complex services created by them, required in the field of space engineering;
Compulsory courses
special knowledge of materials, devices, apparatus, equipment, systems, technology and design required to practice one of the fields of specialization represented in the field of space engineering: digital signal processing in communications, on-board data processing systems, fine mechanical design, photonic devices and optical communication, Earth observation/ remote sensing, the role of small satellites in space technology, special spacecraft and space security, nonlinear finite element analysis, optical remote sensing, rockets, rocket propulsion, design and power supply of space equipment, thermal dynamics of spacecraft; project laboratory; diploma thesis;
Economic and human knowledge
economic, leadership and management skills, coordination of the development of complex space equipment, domestic space activities and the international environment
Free elective subjects from the entire university offer

We plan to announce the master program in space engineering in the spring and autumn semesters as well, offering students the opportunity to be admitted to the training both in the beginning of September and in the beginning of February. Therefore, the training program is provided with both a spring semester start, and a fall semester start. The professional content of the training program is unchanged, but for educational reasons, the subjects are announced in a different order in the beginning of spring and autumn. When developing the topics of the subjects, we tried to avoid overlapping. Therefore, we did not define any pre-study conditions in the subject topics (except for the Project Laboratory 1-2 and the Diploma Design 1-2 subjects, which are built on each other). Even the subjects of the Space Technology Laboratory 1 and the Space Technology Laboratory 2 are not built on each other. Therefore – like other subjects – it is possible to listen to them in a different order in the courses starting in the spring and autumn semesters.

4. Admission to the space engineering program

The aim of the BME master's program in space engineering is to enable the widest possible range of students with basic technical, natural science and IT qualifications to be admitted to the training. Therefore, the entry conditions have been set so that a certain amount of credit points obtained during the pre-studies is already sufficient to apply. At the same time, we organize a written entrance exam for the program. For those with an undergraduate degree in engineering, science, or computer science to be successfully admitted, they are free to choose three of a total of six subjects in their written entrance exam. These subjects are mathematics, physics, computer science, electronics, digital engineering and control engineering. In the case of successful admission, we make suggestions for students regarding the subjects that may be required to expand their knowledge.

The space engineering program provides a high degree of interdisciplinary knowledge, so we are confident that each student will find the knowledge that best suits them during their study. Flexibility is provided by the optional subjects offered in the program.

5. Results

BME announced the program in the Hungarian admission system for applicants starting in September 2022. The application deadline was February 15. Recruitment applications are

DOI: 10.5821/conference-9788419184405.068

currently being processed, so we do not yet have information on the exact number of applicants. Based on the preliminary briefings and forums, the interest is very high, so we hope to reach the limit of 40 people set for this semester.

The first year of graduation will receive its degree in 2024, which will also be a significant milestone for the national space industry, which has significant expectations for graduates.

6. Conclusions

In our paper, we presented the milestones leading to the establishment of a master's degree in space engineering in Hungary. We have described the considerations leading to the development of the training and output requirements of the program, which will serve as a basis for the institutions undertaking to start the program. After the successful accreditation of the training and output requirements, BME developed the start-up document in detail. We have presented the structure of this document, the structure of the training and the subject, teaching and institutional background it contains.

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DOI: 10.5821/conference-9788419184405.068

JSRI Space Design Competitions: Education and Outreach for Emerging Space Countries

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Abstract

As countries around the world are racing towards realizing the common dream of humans creating long-term habitats in space, emerging space countries like Jordan, with no established space agency, are struggling to participate in the development of research and projects in the field. Additionally, due to the deteriorating economical situation in Jordan, students now seek professions with higher market demands and payment rates to ensure a safe career path. This led Jordanian students to overlook emerging fields of study like space. From here arises the need to conduct proper outreach to spread awareness on space research and its benefits, and to incorporate space studies in the Jordanian educational system in order to build a strong base of human resources in the field. Since Jordan is lacking in both educational and theoretical, as well as professional and practical sides, students mostly turn to completing their studies and gaining professional experience in the space field abroad. Therefore, before establishing Jordanian-targeted education programs and initiatives for space studies, there is the need for the establishment of local space institutes, projects, and programs which ensure that students will have access to training programs and practical experience as well as securing future job opportunities, thereby making space careers a viable option. In 2020, under the Moon Village Association's Participation of Emerging Space Countries program, a roadmap for Jordan's contribution to lunar exploration and the Jordan Space Research Initiative (JSRI) were created. This 20-year roadmap focuses on establishing an analog R&D facility in Jordan's Wadi Rum desert, aiming to support the emerging space field in Jordan, while contributing to its national priorities and sustainable development goals. Beginning with the outreach element to foster space education, JSRI launched two space design competitions in 2021 to engage students and professionals interested in the field. These competitions allowed the participants to learn about spacesuit and rover design, as well as develop their own prototypes in a hands-on educational exercise. By providing funding and expert support, JSRI ensured that a diverse group of Jordanians was able to participate, regardless of their backgrounds. This approach proved to be successful in enabling the participation of various segments of the Jordanian society, and has shown that people with a passion for space can thrive through educational initiatives such as these competitions. Building on this success, future partnerships and educational initiatives are being established, aiding in the formation of a space network in Jordan.

Keywords

Education, Outreach, Space Design Competitions, Emerging Space Countries, Jordan

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Acronyms

JSRI *Jordan Space Research Initiative*

HTU *Al Hussein Technical University*

ISRU *In-situ Resource Utilization*

1. Introduction

Emerging space countries, or non-space faring countries, typically have limited resources when it comes to space exploration. It is often seen as not justified in terms of natural or financial resources, and the general public is typically not aware of the benefits it brings to life on Earth. As the space industry grows rapidly around the world, driven by our plans to go back to the Moon, countries without space agencies or established space programs should not be left behind. In order to do so, the gap needs to be bridged and capacity building efforts are required. This paper discusses the importance of space outreach and education in emerging space countries, with a specific focus on Jordan. The Jordan Space Research Initiative (JSRI) was founded in 2020 to help bridge sustainable development and space R&D, building on Jordan's national priorities. For an emerging space country, it is essential to show that investing in space exploration can have benefits to the social and economic well-being of the country and its citizens. In Jordan, a country with a large youth population, interest in space is growing. As initiatives like JSRI are established, outreach and education are playing a huge role in shifting the narrative when it comes to space in Jordan. To provide opportunities to the youth in Jordan, JSRI launched two space design competitions in 2021. Students and young professionals were able to participate, fully funded, and design prototypes for an analog spacesuit and ISRU rover. These competitions were the first step in engaging Jordanians.

2. Overview of Education in Jordan

2.1. Jordan Educational System

The Mandatory Education Program in Jordan consists of ten years of basic education for ages between 6 and 16. Any level of education after that is optional. When it comes to Tertiary or university level education in Jordan, there is a decent number of community colleges and universities; public and private, in Jordan. These institutions offer Higher Diplomas, Bachelor's, Master's and PhD programs. With regard to STEM education in Jordan, it is evident that its importance has been noticed as it has been incorporated in the education system from primary education, where a number of STEM topics are covered and the majority of Jordanian universities offer higher education in Science and Engineering.

There are a number of challenges currently being faced in the higher education system in Jordan. The main challenge with education institutions in Jordan is the linkage between the education outputs and the market needs. According to the British Council [1], there is poor understanding of STEM education as a cluster of interrelated and symbiotic skills, a mismatch of skills taught and the perceived skills required by the employers. Other challenges include the access to education for all and the limited physical and financial resources. Another challenge in higher education in Jordan is the cost associated with finishing a higher degree program. Therefore, despite the major improvements in the educational system in Jordan, a number of challenges remain to be addressed.

2.2. Space Education in Jordan

Space education has been an important topic in Jordan recently. Academic institutions are becoming more active in this field due to its importance and the involvement of various disciplines such as engineering, information technology and science. As an example, Al Hussein Technical University (HTU) supports space education and research through various activities which include funding projects, initiating students clubs, preparing specialized labs, participation in competitions, and collaboration with other academic institutions and companies locally and internationally.

Collaborations between Jordanian academic institutions are important in fostering space education. Current activities include sharing equipment and knowledge in addition to conducting joint research. Jordanian institutions such as HTU are also working with government associations to establish a process that will facilitate importing necessary equipment to build systems relevant to the space education field. This process will also make it possible to build specialized labs and centers that will be main hubs that serve the communities locally and internationally.

Although there are a number of astronomical and space sciences clubs in Jordan, higher education in the space field has been limited. For the longest period, only Al Albayt University offered Master's programs in Astronomy and Space Sciences and currently, these two programs are no longer admitting new students. From a broader perspective, a significant number of higher education programs in STEM are offered at universities in Jordan which can be considered as a base for subsequent education in the space field or as education that is not specialized in space but is applicable to space technology and research. These programs vary in level and cover wide topics in STEM from life sciences to engineering. One specialized program in Aeronautical Engineering is offered at the Jordan University of Science and Technology.

In 2019, the UN-affiliated Regional Center for Space Science and Technology Education for West Asia was officially opened in Jordan. The center is the first of its kind in Jordan and fifth in the world [2]. The vision of the center is to promote regional and international cooperation in the field of space science [3]. This will be done through offering programs in space sciences, space applications, weather, and communications. The center has recently announced, during an event for World Space Week 2020, a new partnership with Jordan University of Science and Technology. Under this partnership, Jordan University of Science and Technology will launch a new master's degree in Aerospace Engineering [4]. As part of Jordan's effort in expanding education in the space field, the Crown Prince Foundation has launched two youth-centric initiatives. The first initiative was the NASA Internship Program Initiative, which provides university students with the opportunity to do an internship at NASA Ames Research Center. The second initiative was MASAR, which was responsible for designing and building Jordan's first satellite in the CubeSat form factor. MASAR had a multidisciplinary team of young engineers with passion for space.

Although Jordan has been moving forward with education in the space field, the progress is very slow due to a number of limitations. The main challenge is the availability of infrastructure and facilities that support space education and the high associated costs of establishing them. Additionally, lack of human resources with experience in the space field in Jordan presents another challenge. One more challenge that must be addressed is the need to establish local space institutes, projects, and programs so that graduates in the space field in Jordan will have access to practical experience and job opportunities.

2.3. Importance of Space Education

The key to advancing in life is innovating and solving common daily issues, and the key to innovation is bright minds who can facilitate their knowledge and experience in finding these solutions. Education in space can play a major role in this; contrary to popular belief, it is not only beneficial to space applications, but can be utilized to make advancement in science and engineering even on Earth. It has been observed over the years that space education often sparks students' curiosity and imagination and encourages youth of both genders to become increasingly involved in the sciences [5]. Therefore, space can play a major role in fostering interest in STEM through presenting space applications. Emerging space countries, like Jordan, can highly benefit from establishing educational programs and projects in the space sector. Developing space applications supports society and contributes to sustainable development. Additionally, space education will have major noticeable advantages and positive effects on economy, technology advancement, international cooperation, and improvement in the quality of life. As reported by a team at the International Space University in 2017, "all countries have challenges that need to be solved. Connecting these problems to solutions that use the space sector as a tool will greatly benefit the country. Conversely, failure to engage in the space sector results in a loss of opportunity" [6].

3. Jordan Space Research Initiative

JSRI was established to help foster a stronger space presence in Jordan. It aims to bridge sustainable development with space R&D to show that space has benefits for life on Earth, while also providing opportunities to Jordanian youth and professionals. JSRI's goals built on two roadmaps created for Jordan and space: a roadmap for space and sustainable development developed by JSRI's founder at the International Space University [7], and a roadmap for lunar exploration in Jordan created during the Moon Village Association's Participation of Emerging Space Countries project. The latter is a 20+ year roadmap outlining future goals for JSRI, as well as its selected research areas: *Agriculture, In-situ Resource Utilization (ISRU) and Robotics,* *Women's Health, Water Resource Management, Renewable Energy, Dust Mitigation, Smart City Infrastructure,* and *Community Engagement.* These areas build on Jordan's national priorities, as well as its industrial strengths.

The nature of Jordan provides various environments for testing space systems. Wadi Rum to some extent resembles the topography of Mars. Towards this end, JSRI aims to establish an analog research facility in the Jordanian desert. In the year since its inception, JSRI has largely focused on the *Community Engagement* goal, creating a local network of stakeholders in Jordan, while engaging the general public over social media. JSRI launched the first two Jordanian space design competitions in spacesuit and rover design. These competitions, held in Wadi Rum, showed the incredible potential of Jordanian youth. Two finalist teams for each topic competed. Local and international judges from space agencies, companies and academic institutions participated in the evaluation process. HTU was part of the judging process as an academic institution and the team saw great potential for space applications and ideas coming out from Jordanian designers and scientists. In addition, the event brought several parties together which broadened the view of the space field in Jordan. The competition revealed the talents and scientific passion of Jordanian students who presented innovative projects. It is suggested that such activities are encouraged regularly in the future with the possibility of inviting international projects.

4. Spacesuit and Rover Competitions

The JSRI Rover and Spacesuit Design Competitions provided participants with a unique hands-on experience to design a rover and a spacesuit for an analog mission for Moon and Mars in the desert of Wadi Rum. These competitions were also a valuable opportunity to reach out to and engage Jordanians with common interest in space exploration and establish a national space network in Jordan.

4.1. Structure and Timeline

The competitions were carried out in two stages over several months (see Figure 1).

The first stage was when the competitions got launched and interested individuals applied to take part. Participants were provided with the competition packages, introducing the challenges, theoretical background, evaluation criteria, and instructions for their preliminary proposal submissions. For this stage, in order to make up for the lack of space related knowledge and resources among the participants, JSRI also provided them with access to the needed resources and international expertise and contacts to guide them through the stage. In collaboration with JSRI's partner LunAres Research Station in Poland, an online webinar series was hosted, where participants and other interested attendees had the opportunity to meet the Hyperion analog crew during their mission at LunAres. Members of the crew shared many aspects of their ongoing lunar analog mission with the participants, and livestreamed their final EVA. This allowed participants to learn more about life in an analog station, as well as the challenges of analog spacesuits and rovers. The first stage was concluded with the participants submitting their preliminary design reports to be evaluated based on the following criteria: *Thoroughness, Credibility, Feasibility, Balance,* and *Innovation*. The spacesuit competition in particular included an additional evaluation criteria for *Aesthetics*.

The second and final stage of the competition allowed the selected finalists to further develop their designs after receiving one-to-one feedback from an expert on their submitted design reports. Since participants came from varying educational backgrounds and experiences, JSRI made sure that all participants had access to workspaces as well as fabrication tools, materials and equipment to build their prototypes. JSRI collaborated with FabLab Irbid, the first digital fabrication laboratory in Jordan. Participants were able to use various equipment to transform their design ideas into prototypes, including 3D printers, CNC machines, and laser cutting machines. Knowing that the prototyping process can be quite costly, each team was provided with financial support to build their prototypes. This stage ended in October of 2021, which also marked the conclusion of both competitions at the span of three days in Wadi Rum where prototypes were tested in an analog desert environment. Rovers had to be successfully driven on different terrains with various topographies, including steep surfaces, with efficient speed and accuracy while taking into consideration energy consumption. Spacesuits had to be worn by a team member

DOI: 10.5821/conference-9788419184405.069

who had to perform physical tasks and run on the various surfaces and terrains to assess the comfort of the suit, effectiveness of the design, and flexibility of movement. The final evaluation of the winners was done by a jury of experts, both Jordanian and international, as well as a Jordanian education representative from HTU.

4.2. Competition Challenges

The competition challenges aimed to focus on theoretically relevant and challenging topics, in order to allow the participants to learn about ongoing space research in a hands-on capacity. For the rover competition, participants had to design an ISRU payload for the Moon or Mars. Requirements also included outlining the mission design and operations, as well as building the rover platform. Similarly, the spacesuit competition focused on specific challenges which analog astronauts face, inspired by a discussion between the JSRI team and Dr. Sian Proctor. These challenges included: anti-fogging solutions for the helmet, dust mitigation inside the suit and habitat, as well as passive thermal regulation. For both competitions, participants were asked to provide a detailed cost estimate for creating their prototypes and a schedule of how they plan to build their prototype, taking into consideration the competition's timeline and deliverables. They also had to research the environmental conditions in Wadi Rum which can be considered similar to the environment on the Moon and/or Mars, and how that influenced their design. This included its atmosphere, temperature, gravity, and terrain. A bonus requirement was considering the sustainability of their design, for which they would get additional points.

4.3. Reach and Participation

In order to reach a diverse audience, JSRI promoted the competitions through the most popular social media platform amongst Jordanians, Facebook, which is also where JSRI has the largest follower base. The advertisement campaigns ran for fourteen days for both competitions. Through this tool, approximately 60000 people were engaged. The audience demographics were set to be more inclusive in terms of background, age, and gender. Initially, a total number of 67 individuals registered for the rover competition and 151 individuals registered for the spacesuit competition. As the first submission date approached, a great number of registered individuals withdrew from the competitions. This was mainly due to time conflicts, inability to address the challenges, or issues related to team formations. In the end, 7 submissions were received for the rover competition and 6 for the spacesuit competition, which is a relatively impressive result given the limited experience of the participants. After an internal evaluation process, 2 rover finalists and 2 spacesuit finalists qualified for the prototyping stage of the competition. The rover finalists consisted of a total of 6 males of which 4 are university students, in addition to one female finalist. The spacesuit finalists saw the opposite case with 5 female students and one male finalist. Among the spacesuit finalists was the youngest participant, a high school student, and the rest were undergraduate students.

5. Discussion

These competitions have provided the participants with an opportunity to utilize the proper tools to design for space in Jordan as an emerging space country. After the conclusion of the competitions, JSRI had the chance to interview some of the participants regarding their experience.

When a member of the winning rover team was asked about the challenges they faced during the designing and prototyping stage, he shared that the biggest issue that they were faced with was the unavailability of some of the parts in Jordan, which forced them to find other alternatives. This resourcefulness allowed them to better design the rover. Additionally, he shared that his Bachelor’s Degree alone was not enough, and he thinks that the best way of gaining practical knowledge is by finding the right scientific resources and references. While he believes that it might be difficult for Jordanian universities to adapt space related studies, youth initiatives like JSRI are key to achieving this. He added that winning the JSRI Rover Design Competition “helped him achieve his educational and professional goals simply by providing him with such an opportunity.”

Another participant who was part of the winning spacesuit team went on to complete her spacesuit design as her Bachelor’s graduation project. She is now representing JSRI in its partnership with Asclepios, a student-run space analog mission in Switzerland, where she is acting as a spacesuit specialist helping manufacture two spacesuits for the Asclepios II mission in 2022.

DOI: 10.5821/conference-9788419184405.069

The success of these students is a testament to the value of these competitions.

6. Conclusions

Ultimately, the success of the JSRI competitions, being the first of their kind in Jordan, shows the importance of providing these educational opportunities to the youth. Past participants have continued their efforts, competing in other international competitions, and collaborating with established analog missions like Asclepios and LunAres. These students with a passion for space do not lack the skills to compete and collaborate at an international level, rather they are only lacking in opportunities to do so. JSRI intends to continue hosting outreach events and competitions in the coming years, while growing the targeted audience. In 2022, a space architectural competition is being planned to allow Jordanian youth to play a role in designing the analog research station in Jordan. By expanding the scope of outreach, the various aspects of space exploration are communicated, providing an opportunity for people from all walks of life to play a role in exploring the cosmos. Both competitions were carried out with the ultimate goal of one day establishing an analog facility in Wadi Rum in mind, therefore JSRI began engaging people at an early stage with the goal of fostering space exploration efforts and research in Jordan. JSRI's success in its first year shows that emerging space countries like Jordan can thrive in space, and educational outreach plays an important role in making that happen.

Acknowledgements

The feedback included in the Discussion was provided by Saif Aldeen and Salam Abulhaijaa.

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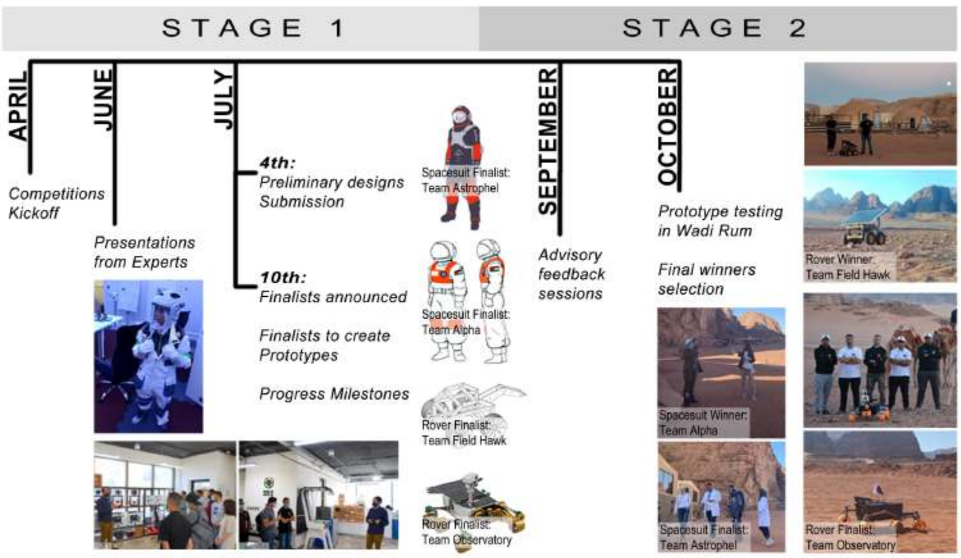

Figure 1. Timeline of JSRI Competitions

DESIGN CHALLENGES, AND OUTCOMES OF BUILDING A SATELLITE THE SIZE OF A SODA CAN

Rovin Perez[1], *Slaveya Abadzhieva*[2]

Abstract

A Mach contest is part of an annual event, organized by UKLSL, which combines both CanSat and rocket competitions. The first Mach event in 2021 was focused on the design of “Simple and Advance CanSats”, and culminated on a 3-day activity at Machrihanish Airbase in Scotland. It involved setup, pre-flight checks, and system adjustments. This paper focuses on the design challenges, and outcomes from building a satellite the size of a soda can by reviewing the event, the mission designed for the competition, and students’ feedback on what could have been improved to prepare the next team competing in Mach-22 which would involve developing a Rocket design and launching an “Advance CanSat”.

The competition allowed undergraduate students at The University of Nottingham to experience a practical learning style by solving real engineering problems and practicing professional development skills through design review presentations and providing a flight readiness review to the launch providers of the competition. The proposed mission statement was part of the “PEAK” category, which involved atmospheric studies, where it acts as a simulation model for measuring the atmosphere on different planets and as a deployable probe from rovers to measure varying atmospheric levels. The competition exposed students to perform AITV (Assembly, Integration, Testing, Verification) processes to their CanSat and constructed procedures to test and validate the recovery system. Results from the first Mach event prove a solid starting point for future CanSat competition and space activities within our university. In the future, there are aspirations to grow a student space society and get students involved in extra-curricular STEM (Science, Technology, Engineering, Math) projects, and allow them to apply the theory and concepts learned in their academics.

Keywords

CanSat, Space Education, Mach-21, Mission design, Spacecraft systems and instruments

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Acronyms/Abbreviations

All used acronyms and abbreviations should be listed in alphabetical order, as follows:

C&DH *Command and Data Handling*

COTS *Customer Off-The-Shelf*

MCU *Micro-Controller Unit*

SNARC *South Nottingham Amateur Radio Club*

TT&C *Telemetry, Tracking, and Command*

1. Introduction

During Mach-21event, University of Nottingham entered for the first time on a CanSat competition [2]. The event was hosted by UKLSL at the Machrihanish Airbase [1] and supported by Gravitilab Aerospace Services, which provided the launch opportunity.

The main driver of entering the competition was to apply concepts discussed in lectures and develop more hands-on activities such as circuit design and programming using a Micro-Controller Unit (MCU).

The team consisted of a pair of undergraduate students studying Aerospace Engineering who aimed to design and manufacture a small satellite the size of the soda can. The team called UON-ADCP (University of Nottingham–Atmosphere Data Collection Probe), was supported by staff member from Department of Mechanical, Materials and Manufacturing Engineering and developed the project as an extra-curricular activity.

The lessons learned from this project gave a baseline for the next competition Mach-22, where the new team would develop an advance CanSat released by its own designed rocket at an altitude close to 1km. In contrast, the CanSat entered for Mach-21 was designed to be ejected at an altitude between 500-700km.

Figure 1. UON-ADCP Logo

1.1. Timeline

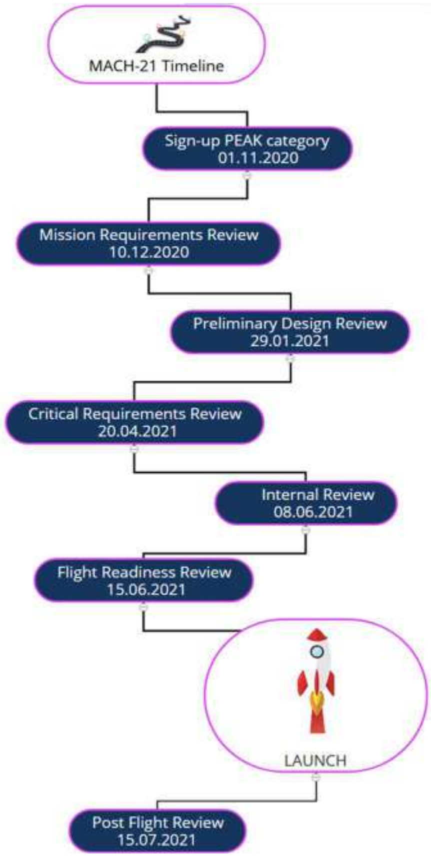

Figure 2: MACH-21 timeline

Figure 2 shows MACH-21 project timeline emphasizing the main project phases and review. The project provided all teams an opportunity to have a 1-1 meeting as feedback for the Critical Design Review (CDR) stage thanks to the involvement of Gravitilab Aerospace, which was called at that time Raptor Aerospace. They also scheduled a virtual seminar with all the teams to highlight testing procedures to consider for the Flight Readiness Review (FRR). In addition, they provided the option to use a standardized CanSat shell to ensure two PEAK CanSat payloads would fit inside their rocket. These solutions and support were extremely useful for the developer team that had the opportunity to have feedback and suggestions to implement the quality of the proposed system.

2. Objectives and Aims

2.1. Mission Profile

An outline of the mission profile can be seen in Figure 3. The CanSat would undergo pre-flight checks a day before the launch, which would involve checking the all the system of the CanSat are in operation. On the day of the launch, it would be integrated in the rocket by Gravitilabs Aerospace. After, launch and

DOI: 10.5821/conference-9788419184405.070

ejection phases, the CanSat would descent with a passive parachute deployment and send GPS data for CanSat retrieval.

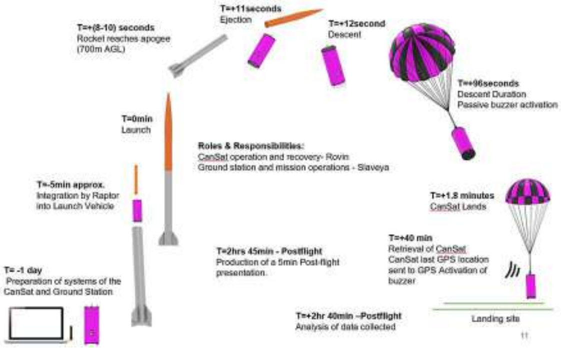

Figure 3:Mission profile diagram for ADCP CanSat

2.2. Aims

The CanSat's mission was to collect information about the air pollution around the launch site (and chart comparison to Nottingham, where the team was based) and to track its flight path in real-time.

During the competition, the team had an opportunity to gain practical experience in electronics, material selection, mechanical design, manufacture, and full system testing.

2.3. CanSat launch objectives

Considering the declared mission statement the CanSat:

- act as a simulation model for measuring the atmosphere on different planets.
- act as a probe for rovers or spacecraft in orbit to measure atmosphere levels.

The main mission requirements can be condensate in

- Use onboard sensors to measure atmospheric data
- Transmit Live telemetry to the ground station
- Be able to recover CanSat using GPS and buzzer to locate

The established mission success criteria are:

- Collect atmospheric data
- Collect temperature and pressure data
- Transmit live data to ground station
- Descent and landing – no mechanical or electrical damages to the CanSat

2.4. CanSat overall mission objective

The main overall mission objective for this project was to gain hands-on experience with using electronics and applying spacecraft systems and design methods on a practical project. Moreover, the team followed the ESA design processes on developing a satellite, covering the design review stages required.

3. CanSat Design

3.1. *Science Payload*

The payload of the CanSat to measure temperature, pressure, and atmospheric data to compare the results at two locations, primarily in Nottingham and at Scotland.
To achieve this goal, the following sensors *where selected* (Table 1):

Table 1: Sensor modules overview

Altimeter Module MS5607	Temperature range: -40 to +85°C with <0.1°C resolution
	Pressure range: 10-1200 mbar
Air Quality Click 5 Sensor Module	Contains RED, OX and NH3 sensor
	Measures carbon monoxide (CO), nitrogen dioxide (NO2), ethanol (C2H5OH), hydrogen (H2), ammonia (NH3), methane (CH4), propane (C3H8), and isobutane (C4H10)
Adafruit Industries 746 GPS	Position accuracy: 3m
	165dBm sensitivity
	Internal storage

3.2. Electrical System

Figure 4 shows the block diagram of the UON-ADCP CanSat electrical system. It consists of a master power switch, two alkaline batteries, voltage regulators for voltage regulation of the two main power lines (3.3V and 5V) and a LED for power indication.

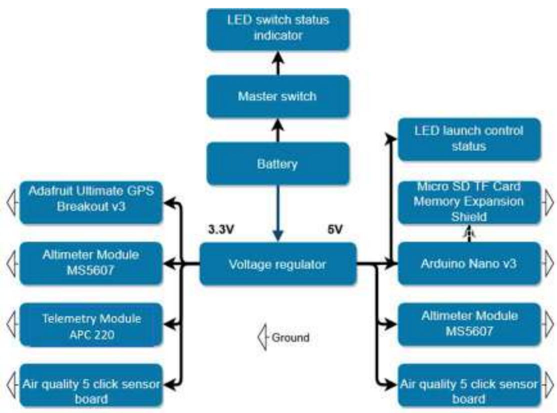

Figure 4: Electrical system layout block diagram

3.2.1. Programming

The CanSat used an Arduino MCU and Arduino IDE to write and develop the program for the CanSat BUS.

3.2.2. Data Transmitting

To remotely collect the data, a radio module was used to send telemetry down to a portable ground station which consisted of an APC220

DOI: 10.5821/conference-9788419184405.070

radio module. The CanSat was able to transmit sensor data to the ground station.
The team conducted testing of the module set-up to ensure the telemetry could be verified.

3.3. Structures and Mechanisms

An exploded view of the CanSat structure can be seen in Figure 5. It has been produced using 3DExperience CAD software.

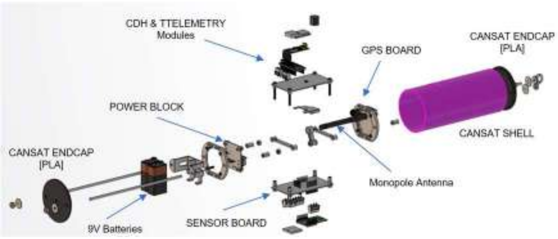

Figure 5: Exploded view CanSat structure

3.4. Recovery System

The recovery system is a critical element of the design because the system would be responsible for ensuring the data can be retrieved if the ground segment of the mission fails to collect any data. The system also has a set requirement to have a 10m/s descent rate and not to drift 500m from the launch site.

3.4.1. Parachute Sizing

UON-ADCP recovery system features the use of COTS (Customer Off-The-Shelf) parachutes from BlackCat Rocketry which included a bridle swivel and shock cord. The size of the parachute was selected based on the estimated descent rate it would provide as shown in Table 2 2. The result of this would be used to calculate the kinetic energy it would experience during impact.

Table 2 2: Calculated Descent Rate Estimates

Descent rate (m/s)	Area (m^2)	Diameter (in)	Comment
13.121	0.0506	10	Very High
10.931	0.0729	12	High
7.284	0.1642	18	Selected

3.4.2. Estimate Wind Drift

To predict the landing site of the CanSat, wind drift estimates were performed to ensure the operation of the CanSat is within the confines of the airbase.

Figure 6: Landing Site Estimates - Launch Pad A and B locations in Red. In Pink dashed lines shows the effect of wind drift and shows landing region.

4. Design review Stages

4.1. Mission Requirement Review (MRR)

Mission Selection was determined on the analogy to follow the rule of KISS (Keep It Simple Stupid). The primary role of the mission review is to determine the selected payload for the CanSat. Ensure a more robust solution was decided to maximize the chances of a successful mission.

4.2. Preliminary Design Review (PDR)

At PDR, a conceptual design was completed, sensors were selected, and a preliminary layout of the components was selected for all subsystems. At the PDR stage, a damping system with springs was planned to be developed to protect the electronics from the shock load and vibrations during launch.

4.3. Critical Design Review (CDR)

Before the CDR stage, it was decided a complex damping system was not required.

The telemetry module was also changed from the Onethinx OTX-18PSoC®6xLoRaWAN module to the APC 220 due to procurement issues.

At the CDR stage, most of the components had been ordered, the recovery system and internal structure had been fully designed, and the manufacturing process and the electrical configuration had been fully defined.

4.4. Flight Readiness Review (FRR)

At the FRR stage, the CanSat was fully compliant with the competition requirements.
Testing performed included waterproofing test, visibility test, drop tests, battery performance and environment testing (in hot +30C and cold -10C conditions), and sensor testing. The telemetry and the altimeter calibration had yet to be done.

4.5. *Post-Flight Review*

After the recovery of the CanSat, the team analysed the data and produced a document

4.5.1. Data collected

The system was able to perform the first phase of the mission, where atmospheric data was collected at Nottingham several days before the launch event.

```
MICS-6814 Sensor Sample
Calibrating SensorOK!
NH3: 578/559 = 1.08 => 0.58ppm
CO: 589/584 = 1.05 => 4.01ppm
NO2: 608/584 = 1.13 => 0.17ppm
NH3: 622/559 = 1.30 => 0.43ppm
CO: 627/584 = 1.22 => 3.38ppm
NO2: 642/584 = 1.28 => 0.19ppm
```

Figure 7: Atmospheric sensor results sample - Nottingham

4.5.2. *Structural* damages

Post-flight the CanSat was inspected for structural damages. Two main issues were found. The GPS breadboard was heavily damaged (see Figure 8), although the testing revealed the GPS module itself survived the impact.

The bottom endcaps, which should have protected the batteries, failed and they had taken significant damage (see Figure 9) which could have compromised the safety on-site. The root cause of the problem was the material selected for the endcaps as it was unable to take the +60G impact from the piston ejection of the rocket.

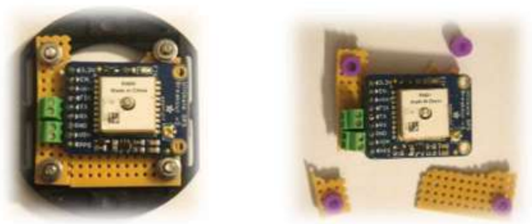

Figure 8: Post-flight damage on GPS board

Figure 9: Post-flight damage to the batteries

4.5.3. Other issues

Telemetry bus had an issue in connecting on launch day and the team decided that the system would not have the radio module during launch and would only store the data collected on an SD card connected to the Arduino.

5. Design Challenges

5.1. *Risk assessment and mitigation at FRR*

Potential points of failure have been carefully considered and steps have been taken to eliminate them, where possible, and mitigate them if not.

Table 2 is a summary of the risk assessment undertaken.

Table 33: Risk assessment and mitigation

Failure Mode	Part	Cause	Effect	Mitigation
Critical failure	Sensors	Water damage	Incorrect/ no reading	Waterproofing the switch and LED gap with parafilm
	Power block	Water damage	Short circuit	Waterproofing the switch and LED gap with parafilm
	Power block	Wires disconnected or exposed wires connected	Short circuit/ Sensors not reading	Wire terminals and silicon glue for insulation
	Power switch	Wires disconnected	Power off	Strong connection, silicon insulation and shock test
	Battery	Battery running out	Not enough power for operation	Two parallel 9V batteries and battery performance test
	Parachute	Parachute fails to open/ disconnect from CanSat	Screw unscrewed/ parachute attachment breakage	Loctite thread locker and drop test
Critical/non-critical failure (depending on the severity)	Buzzer	Buzzer not activated/ too quiet	Difficult recovery	Passive buzzer; disconnect tested
	SD card disconnect	Shock on deployment/ landing	No backup memory storage	Glue to the shield module and shock test
Non-critical	GPS backup battery disconnect	Shock on deployment/ landing	No backup power for the GPS	Silicon glue and shock/ drop test

5.2. *Internal layout of the electronics*

The internal layout has been iterated multiple times throughout the design stages to optimise the CanSat BUS and the structural design. The biggest challenge was obtaining the CAD files from the COTS vendors, which impacted the chosen layout of the electronics and mechanical interfaces inside the CanSat.

6. Discussion and Results

6.1. *Lessons learned*

6.1.1. Procurement

Using COTS components usually have fluctuating delivery times, which is important to consider because this can delay or stall the project's progress.

Bring and order spare parts and components during the development of the engineering and flight model because this is critical to mitigating the risk and delays of the project. Moreover, it would be useful if all major parts come from the same suppliers for easier integration.

6.1.2. Power distribution

More reverse voltage protection (diodes) and resistors to smooth out current was required to protect the microcontroller and sensors, and to ensure the data collected was not affected by current irregularity.

DOI: 10.5821/conference-9788419184405.070

6.1.3. Software development

The team would suggest working in GitHub, or a similar hosting platform to allow past versions of the software to be logged and tracked because it would be more efficient to track changes made on multiple programmes.

6.1.4. Testing

Comprehensive testing after the CDR is critical in the development of a full Flight Model (FM). The team experienced several issues with its FM at the launch event in Scotland. To resolve them, the functionality of the flat sat model was verified on-site, the CanSat subsystems were assembled and then tested again. The test of the fully assembled systems revealed that it was not storing the data consistently.

A stack testing would need to be performed for future missions because this area was highlighted as the main reason it failed to record data at the launch event.

Ensure the (FM) Flight Model and (EM) Engineering Model are at a stage of completion and procedures have been conducted.

6.1.5. Management

Ensuring the management of the project was found to be a critical factor to ensure the success of the project. For example, the number of iterations for the electronics configuration was developed until the final FM was produced.

The team learned that the design must be frozen just after the CDR to allow for thorough testing and verification of the electronics and portable ground station.

Based on Akin's 3rd Law of Spacecraft design, the number of iterations should be "One more than the number you have currently done" [3]

Lastly, documentation of system developments was critical because this would allow a hand-over procedure to take place and keep records of the project as teams complete their undergraduate studies.

6.2. Overall mission result

The team considers the mission as a success ending up with an overall 3rd place in the competition in both categories and finished 2nd place in the PEAK category which consisted of the marks received on the design review stages for developing a simple CanSat architecture.

The team is also aware that several improvements can be done to optimize the system and its working on that for the future competition.

7. Conclusions

The project has found that there is a huge benefit in tackling hand-on activities outside lecture-based projects. It has allowed the students to develop new practical skills such as soldering, creating bread-board models to test their circuit designs, and project management. An extremely useful part was for sure the assembly, integration, test and verification phase for the mission.

The results the team has achieved have encouraged more students to participate in Mach-22 where a combined entry of an advance CanSat and Rocket is being developed.

Acknowledgements

The authors want to thank the UoN CubeSat Team, who helped supporting on software development and CanSat BUS peripherals, and the South Notts Amateur Radio Club (SNARC) who supported the selection of the frequencies and radio module used for the competition.

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AMORE - Mission concept overview for a progressively independent and self-sustainable lunar habitat

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Abstract

Throughout the last decade a renewed interest for lunar space exploration has been expressed through the announcements of many ambitious missions such as Artemis. Annually the Space Station Design Workshop (SSDW) tasks students and young professionals to design a space station concept in a concurrent engineering environment. In line with the elevated interest on the Moon this year's SSDW was centred around a self-sustainable lunar habitat. This paper presents the conceptual design of Team Blue at the SSDW 2021. Advanced Moon Operations and Resource Extraction (AMORE) is conceptualized as a public-private cooperation for the creation of a lunar platform that acts as an outpost for human exploration and robotic In-situ Resources Utilization (ISRU). AMORE's proposed location is near the rim of Shackleton Crater at the Lunar South Pole. This location provides opportunities in science and ISRU and favourable sun coverage and thermal conditions. The terrain offers a natural shield for debris and storage advantages for ISRU. The mission architecture allows for incremental crew size increase through a modular dome structure, an initial prioritization of ISRU and a sustainable resource management strategy. Based on the identified system requirements, the initial configuration envisions one core module and two modular structures that would serve as greenhouses or living spaces. The phasing of the base assembly is designed to allow for adequate conditions of an increasing crew size capacity. The greenhouse modules are designed to provide all required oxygen and most required food supply. The modules are constructed using lightweight inflatable structures, while a regolith shell will provide radiation as well as thermal and micrometeorite protection. For reliable communication, a custom relay network named Lunar Earth Telecommand Telemetry Relay (LETTER) is proposed. The mission architecture analysis includes several methods to financially utilize the mission. These include a range of services on the lunar surface such as training facilities for deep space missions, leasing habitats to other Moon explorers, and performing scientific and technological demonstrations. A variety of rovers will be used throughout the mission that will assist in various aspects. In addition to this, a scalable hybrid power generation system that utilizes the abundant sunlight and nuclear energy assures a sufficient power supply throughout the entire mission lifetime. This research presents a holistic architecture for a Moon base, which provides an approach to initially utilize the Moon. Within this context, the mission concept is primarily based on already existing or currently in-development technologies. Hence, AMORE offers an approach for a financially and technologically feasible as well as a continuous and expandable human presence on the lunar surface.

Keywords
Moon, Lunar-base, space-exploration, ISRU, self-sustainability, SSDW, AMORE

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Acronyms/Abbreviations

SSDW	*Space Station Design Workshop*
AMORE	*Advanced Moon Operations and Resource Extraction*
ECLSS	*Environmental control and life support systems*
LETTER	*Lunar-Earth Telecommand Telemetry Relay*
RTG	*Radioisotope Thermoelectric Generator*

1. Introduction

SSDW is an international and multidisciplinary workshop which is held annually by the Institute of Space Systems at the University of Stuttgart, Germany. SSDW 2021 consisted of two teams of twenty-five individuals each, from diverse educational backgrounds and skillsets. In 2021 the task was to design an increasingly independent and self-sustainable lunar base. This base could eventually function as a gateway for deep space missions. Given this context, team blue designed a crewed space station on the lunar surface, which could establish human presence on the moon as well as improve the robotic capacity for lunar operations. The proposed concept focuses on two main objectives: Human and robotic exploration of the lunar surface and research opportunities beyond Earth. To fulfil these goals in an economical fashion and to become self-sustainable, the proposed architecture relies heavily on In-Situ Resource Utilization (ISRU).

2. Methodology

To sufficiently develop the concept, it was decomposed into several segments: a launch segment in charge of transporting equipment and personnel to the lunar surface, a communications segment to facilitate transporting data between the habitat and earth as well as a lunar segment consisted of the actual habitats. The lunar segment was further composed of a core module, transported in a pre-assembled state for astronauts to live in while the expansion modules are constructed, inflated, and commissioned. As time progresses, different types of expansion modules from greenhouses to Environmental Control and Life Support System (ECLSS) and science modules would further expand the base.

To facilitate in the development process, the systems engineering team distributed relative material to different teams to help avoid "blank-page syndrome". Besides that, material was made available to individual systems teams, by SSDW's organizers, in the form of recipes.

Valispace was used with a concurrent engineering approach. This immensely supported a rapid iterative development, as teams could easily access the most up-to-date numbers of other subsystems. To combat inaccuracies, a margin philosophy was also defined, roughly based on ESA's margin philosophy for science assessment studies. As the SSDW 21 took place fully digitally the use of "Gather town" was crucial to the team's success. Gath-er town facilitated a sense of "presence" and improved overall team cohesion.

2.1. *Assumptions*

At the beginning of the project various assumptions were made. AMORE space station utilizes different systems, which is assumed will be operational:

- Lunar Gateway by early 2029
- SLS Block 1B in early 2029
- SpaceX Starship in 2034.

For logistical aspects, it was assumed that the vehicle transporting crew to the lunar base would also carry enough consumables (food, water, oxygen, clothing etc.) to comfortably survive 30 days. Quantities and schedules regarding radioactive material for RTGs and RHUs should be compatible with AMORE to allow for launch of the core module in 2029. To fit into the launch sequence timeline, SLS Block 1B needs to be operating and available for a launch cadence of six months by 2030 and three months by 2034. Lunar Earth Telecommand Telemetry Relay (LETTER) and Gateway would need to make their communication systems available for relay operations. In early 2029, the Earth orbit relay satellite net-work and corresponding ground stations on earth would need to be available to facilitate communication between them.

2.2. *Requirements*

Several mission-level requirements were established, allowing communication between teams in a concurrent way. Given the harsh nature of the lunar environment, various issues that impact the mission were considered. All systems should be either radiation-tolerant or radiation-

DOI: 10.5821/conference-9788419184405.071

shielded. Systems must be able to withstand enormous temperature swings between day and night cycles, as well as periods of over six months of continual solar exposure or darkness. Regolith dust must either be tolerated or insulated from systems. The same criteria as on any spacecraft apply to accommodate human life for extended periods of time, with the addition of increased radiation protection and dust mitigation.

The cognitive needs the base needs to cover were studied through the scope of Environmental Psychology. Given the expanding nature of the base, and the different durations of stay for different crews, the expansion of both space and variety in uses was made apparent.

Finally, the role of plants in the environment was considered, as a result, a Closed Loop Environmental Control and Life Support System (ECLSS) was proposed, which included plants as part of the system for the overall well-being of an Astronaut.

3. Discussion

3.1. Mission Design

Several requirements had to be met by the landing site both imposed by other subsystems and by the mission planning. The landing place was narrowed down in several steps. ECLSS and TCS pointed towards the lunar poles because of the unique lighting conditions, the utilization of gateway then led to the lunar south pole. Scientific goals can also be fulfilled as a wide variety of geological features is available there.

The selected landing site at the slopes near Shackleton crater fulfils all critical request given by the other subsystems except for a requirement by Human Factors Engineering demanding a line of sight to the earth for psychological reasons. To mitigate this, an early deployment of a crewed rover is planned that will allow the travel of crew to a viewing spot on top of the hill.

3.2. Mission Architecture

For the implementation of the mission, mainly existing and proposed vehicles were used. These included: i) SLS Block 1B, ii) Falcon Heavy (with recurring launches) and once available, iii) Starship. These vehicles would bring cargo from Earth to Lower Lunar Orbit and from there to the AMORE station.

For Crewed missions, a Standard Transfer from Lower Earth Orbit to the Near-Rectilinear Halo Orbit is selected as this is proposed for the selected flight hardware and therefore professionally researched. While for cargo missions, a Weak Stability Boundary Transfer is chosen to increase efficiency and payload mass. This trajectory takes up to two months to reach the Lower lunar orbit but is more fuel efficient than the crewed transfer.

To bring the crew to the lunar surface, NASA Gateway and HLS programmes will be utilized, which will make use of an ORION vehicle to bring the astronauts from Earth to Near-Rectilinear Halo Orbit using an SLS Block 1B Crew variant, and the HLS Starship, by SpaceX will transport the astronauts from Gateway to the AMORE station. AMORE requires a landing system for transporting a crew of four from the Gateway to the lunar surface before the HLS is available, therefore, two custom-designed human landers will be transported along with the first crewed missions. These vehicles utilize an oxidizer/fuel combination which can be sourced from lunar ISRU operations.

3.3. Mission Outline

The AMORE Operation can be split into three initial phases and one late expansion phase, each with a dedicated purpose and function.

i. Phase 0 (2027-2028): On the first launch planned in 2027 a group of scouting rovers would be deployed to the landing zone to determine the exact landing/building spot, search for ISRU options and provide basic construction. A communications network would be deployed into a stable lunar orbit. On the final launch of this mission the Core module should be ferried and deployed onto the moon to be then buried in regolith by the rovers.

ii. Phase 1 (2028-2031): The first two missions would bring their lander with them and leave it on the gateway station after departure to provide a lander for the following missions. These initial missions continue construction and scouting as well as construction of the first inflatable structures and greenhouses to vali-date ISRU concepts and prepare the base for increasing crew numbers.

iii. Phase 2 (2032-2035): expands the ISRU and scientific capabilities of the station by deploying more mining and processing equipment, additional living. A larger fleet of rovers and support vehicles is also deployed, and the crew is raised gradually to twelve individuals.

DOI: 10.5821/conference-9788419184405.071

iv. Phase 3 (2035-x): continues the expansion with additional core modules, living quarters, greenhouses, processing facilities and gradual increase of the crew as per demand of probable future objectives.

3.4. Human Factors

Human factors were prioritized early in development of concept. Requirements were generated to address three different aspects.

i)Physical factors: Regarding physical factors, requirements were pulled from NASA's Technical Standards and Handbooks. [1,2]

ii)Cognitive factors: For the cognitive factors, a combination of environmental psychology's approach to the interaction between a user and their environment [3] was analysed to identify existing issues in space stations design.

iii)ECLSS solution: Understanding the cognitive requirements of the astronauts, an ECLSS was proposed that utilized plants to produce food, recycling of water, O2, and CO2.

Lastly, the main architectural design drivers that were generated called for: i) segmentation of modules to loud and quiet spaces, ii) interconnected and complex floor plans, avoiding zoning of uses, iii) complexity and variety in privacy levels in different spaces, iv) modularity and reconfigurability and lastly, v) the strong recommendation for windows that made use of exterior vistas towards the Earth.

3.5. Habitat Design

Inflatable solid-framed structures should be coated with a 3D-printed moon regolith to create the HEART modules, which thus protects against all physical threats. To achieve good conditions for the psychological well-being of the crew, all modules have soft zoning into different gradations of privacy, from sleeping to working areas.

The first CORE module differs from the HEART modules, in that it would be launched from the ground in a ready-made form. This unit is cylindrical for transport efficiency. To avoid permanent stress by noisy facilities such as those used in ECLSS or other systems, there are two different HEART modules. One of them contains all the functions that cause negative exposure and the other hosts compatible systems and crew living areas. The design connects all the spaces but makes entry into the private areas unattractive. This ensures easy access, emergency escape, and ease of retreat.

The generic system of 3-axis domes with adjustable functionalities allows the base to be expanded in line with requirements that emerge over time. To create a good working environment for scientists, training and exploration, the mission is expected to install nine HEART modules on top of the CORE module and host four crews of four until 2040. The approaches to scalability, adaptability and ISRU make it a sustainable concept for the development of a lunar base.

3.6. Radiation and Thermal Control System

To protect astronauts from the harmful deterministic and stochastic radiation, a composite of regolith, aluminium, HDPE, Kevlar, and Nomex is used. For emergency situations (such as Solar particle events), the core module is additionally equipped with a reinforced radiation bunker with thicker walls. This allows for reduced absorbed doses during intravehicular activities and gives more opportunities for longer stays in the base or longer duration EVAs

The temperature fluctuations on the lunar surface range from -180 to +120°C, but the internal temperature of these structures must be maintained at an ambient temperature of 22-25°C for optimal performance of equipment and astronauts. The thermal control system of these structures was designed to adapt itself to lunar nights and days where the temperature reaches extreme limits. Regolith along with a composite of insulation is added on the outermost wall which acts as an excellent insulator against external temperature conditions such that regardless of external temperature almost no heat is conducted to the interior of the structure. The heat produced inside the structure by life support missions would be dissipated into space using a radiator.

3.7. Habitat Structure

The habitat structures have been designed by considering environmental conditions such as vacuum environment, radiation shielding, and micro-gravity. The core module is designed to host the astronauts until the completion the HEART modules. Aluminium is used as the construction material for the core module. Hybrid structures are used in the design of the modules, which takes advantage of both inflatable and rigid. An inflatable habitat supported by

DOI: 10.5821/conference-9788419184405.071

rigid structural elements has been preferred due to its high strength, low mass, and volume. Titanium is selected for the attachment fittings of composites and fasteners due to its high strength and low mass. The HEART Module is the module to be expanded from the core module. Sandwich structures have been used for the support systems due to the shape of the HEART modules. Aluminium tubes are planned to be transported in smaller pieces and then assembled by the crew using fittings and rings. Both structures that are proposed would, after deployment, be covered with a one-meter-thick layer of regolith.

3.8. Communication

The communication subsystem ensures payload downlink and telemetry and telecommand (TTC) exchange. Furthermore, video and audio communication between AMORE station and mission control and audio only between astronauts is provided. A 99.99% link availability shall be realized for the first permanently inhabited lunar station. For compatibility and availability reasons the dedicated LETTER network including three orbiters is designed. At least three dedicated ground stations form the ground interface. The high-speed link in the Ku-band is assumed to only provide 99.90% availability in downlink, due to rain attenuation. Gateway might reduce these weather dependent gaps as backup station in future. The worst-case LETTER to Earth transmission is considered to demonstrate the feasibility of the high data rate concept: The radio telescope payload generates the most data and is downlinked with the Data Downlink System. Eight virtual channels are available, respectively for video and audio calls in the Crewed Mission Support System. Those systems function as the high-speed line with 159.92 Mbits uplink and 335.5 Mbits downlink. This is achieved with a transmitting antenna diameter of one square meter and a receiving antenna diameter of thirteen square meter with an antenna gain of 63.02 dBi. With a DVB-S2 waveform with 8PSK modulation, 2679 user bits per symbol and a code rate of 9/10 the required Energy per Bit to Noise Density results in 6.70 dB. The provided Energy per Bit to Noise Density characterizes various aspects of the link and comprises with 11.15 dB a system margin of 3.45 dB. While the voice loop can be used during work hours, payload data is downlinked during recreational hours, when the video calls can be used limitedly. For psychological and emotional recreation, a local entertainment server with music, series and movies is planned. The low-speed S-band link is unaffected of rain and fits the human factor requirement for emergencies. TTC utilizes the low-speed line with 0.05 Mbits uplink and 1.39 Mbits downlink.

3.9. Electrical Power Systems

AMORE, being subjected to a cycle of twenty-two lunar days and six lunar nights needs two power sub systems. The primary should be a solar array farm and the second an RTG farm. The solar farm shall have a dimension of five hundred m2. AMORE, despite being located on a peak with a solar radiation factor of 100 cannot cover the energy expenditure during lunar nights. To compensate for this energy, an RTG developed by Lockheed Martin is used to charge Li-ion batteries during the lunar days. AMORE is proposed to run in a minimal safe operating mode during lunar nights to compensate for the limited power production. To distribute energy evenly through the different phases, a power control distribution unit should regulate power during different operating phases of the mission.

3.10. EVA´s and Robotics

Robotics will play an integral role in the success of such a mission. The robotics payload of the system consists of units that should fulfil three objectives: ISRU, exploration and base assembly. For the ISRU objective a three staged set of payloads is foreseen. The ISRU robotics system shall investigate the locations close to the lunar base for volatiles that can be extracted. The actual extraction stage will make use of a rocket mining system under development by Masten Space Systems [4]. Finally, as part of an R&D campaign, a tethered mining drone concept would be put to test to see if mining of permanently shaded regions is a feasible solution for long term missions.

The exploration robotics system would include autonomous drones, which would be able to explore lava tubes nearby. This would create a high scientific exploration output [5].

Finally, robotics will be used to prepare the base prior to astronaut arrival. The ATHLETE rovers designed by National Aeronautical Space Agency are the current foreseen robotic system for this task. As suggested in studies [6] the ATHLETE rovers would use tools adapted to fit their legs and conduct tasks such as excavation and 3D printing. In addition, to serving as a construction operations tool, the ATHLETE can be adapted to fulfil extra vehicular activities with astronauts thanks to its modularity and high mobility over the lunar terrain.

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3.11. Costs and Risks

This cost estimate should be viewed as an early preliminary estimate using various simplifying assumptions. The module development costs have been estimated through the “Advanced Missions Cost Model” pre-purchased modules and operation costs are estimated by analogy with known and available costs in literature. So-called “Wrap factors” are used to quantify different less predictable costs, and “Beta functions” have been used to accurately spread production costs over the mission’s timeline [7]. Lastly costs estimated in older US$ have been transformed into 2021 US$ with the NNSI [8] and then changed into 2021 EUR. As a result, the estimated total cost for the program’s initial duration (2022-2035) is calculated to be 70 billion 2021 EUR. However, this cost estimation shall only be seen as a tool to get a grasp on the order of magnitude for the mission costs.

4. Conclusion and Outlook

The concept that was preliminarily developed and showcased through this paper highlights that a lunar settlement is within reach in the next decade. The technologies that need to be utilized exist or are currently under-development. The aspect we need to overcome is the political and financial capital needed to undertake such a task. The proposed base has the capacity to function as an outpost of permanent human presence on the moon and as a gateway for humanity’s expeditions to other deep space exploration. This workshop also showed the inherent value of interdisciplinary teams in developing such concepts in a concurrent way. The team explored and better understood the intricacies of a crewed exploration mission. Participants were exposed to a variety of scientific and engineering disciplines. From propagation and planetary mechanics to propulsion technologies and inner architecture.

This workshop allowed for both teams to explore the field of space exploration and better develop their passions, while exploring previously unseen aspects of it.

5. Acknowledgments

We are grateful to the entire team of SSDW organizers along with all the experts from University of Stuttgart and the Institute of Space Systems. Furthermore, we are thankful for all experts and supporters as well as supervising experts during the workshop including ESA, DAAD, Airbus, DLR, PRICE, ValiSpace, Tesat and Astos Solutions. We would also like to acknowledge the contribution of members of our team during the workshop: Al-Barwani Amran, Stankovic Ana, Spieker Anselm, Tokarz Dominik, Ryszkowska Kamila, Georgousi Mary, Hengstmann Maximillian, Rafael Y Rivera Vargas, Pitta Sidd

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Deployment mechanism for an L-Band Helix antenna on-board the 3Cat-4 1U CubeSat

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Abstract

Earth Observation (EO) is key for climate and environmental monitoring at global level, and in specific regions where the effects of global warming are more noticeable, such as in polar regions, where ice melt is also opening new commercial maritime routes. Soil moisture is also useful for agriculture and monitoring the advance of desertification, as well as biomass and carbon storage.

Global Navigation Satellite System - Reflectometry (GNSS-R) and L-band microwave Radiometry are passive microwave remote sensing techniques that can be used to perform these types of measurements regardless of the illumination and cloud conditions, and -since they are passive- they are well suited for small satellites, where power availability is a limiting factor.

GNSS-R was tested from space onboard the UK-DMC and the UK TechDemoSat-1, and several missions have been launched using GNSS-R as main instrument, as CyGNSS, BuFeng-1, or the FSSCAT [1] mission. These missions aim at providing soil moisture [2], ocean wind speed [3], and flooding mapping of the Earth. L-band microwave radiometry data has also been retrieved from space with SMOS and SMAP missions, obtaining sea ice thickness, soil moisture, and ocean salinity data [4].

The 3Cat-4 mission was selected by the ESA Academy "Fly your Satellite" program in 2017. It aims at combining both GNSS-R and L-band Microwave Radiometry at in a low-power and cost-effective 1-Unit (1U) satellite. Moreover, the 3Cat-4 can also detect Automatic Identification System (AIS) signals from vessels.

The single payload is the Flexible Microwave Payload 1 (FMPL-1) [5] that performs the signal conditioning and signal processing for GNSS-R, L-Band microwave radiometry and AIS experiments. The spacecraft has three payload antennas: (1) a VHF monopole for AIS signals; (2) an uplooking antenna for the direct GPS signals; (3) a downlooking antenna that captures reflected GPS signals, and for the Microwave Radiometer. The downlooking antenna is a deployable helix antenna called the Nadir Antenna and Deployment Subsystem (NADS) which has a volume of less than 0,3U when stowed, achieving an axial length of more than 500 mm when deployed.

As part of this mission, the design of the NADS antenna, its RF performance, as well as the environmental tests performed in terms of structural and thermal space conditions will be presented.

Keywords
CubeSat, GNSS-R, microwave radiometry, earth observation, nanosatellite

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1. Introduction

Recent studies have shown the possibility to obtain soil moisture [2], ocean wind speed [3] and flooding with GNSS-Reflectometry. Moreover, the capabilities of GNSS-Reflectometry and Microwave L-Band Radiometry to improve soil moisture and ocean salinity measures [3].

The [3]Cat-4 mission [6] aims at demonstrating the technologies to perform with a 1 Unit (1U) CubeSat dual-band (L1 and L2) GNSS-Reflectometry, and Microwave Radiometry. The payload is implemented by the Flexible Microwave Payload 1 (FMPL-1) [5], the LHCP Nadir Antenna and Deployment Subsystem (NADS) and RHCP uplooking active antenna.

The NADS includes an L-Band helix antenna. This solution was implemented to have a directive LHCP antenna in a reduced space. Previous studies have been done with these types of deployable antennas [7,8,9], but most of them are focused on the radiofrequency design, and performance of the antenna rather than in the deployment mechanism itself, which is a critical part.

This article presents the design, functional and environmental results of a deployment mechanism for such a helical antenna. Section 2 describes the different mechanical parts of the NADS, and their functionalities. Section 3 presents the ambient tests, vibration tests and thermal vacuum tests results. Finally, section 4 presents the conclusions.

2. Antenna Deployment Mechanism

The NADS has two different configurations stowed, Figure 1, and deployed, Figure 2. The antenna is stowed during launch, and deployed once in orbit.

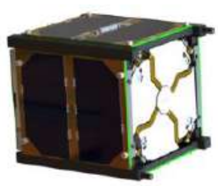

Figure 1 - NADS in stowed configuration

Figure 2 - NADS in deployed configuration

The deployment mechanism has been designed to ensure safety and functionality during launch, i.e., no unexpected deployments and resonances below 100 Hz. Moreover, the design also ensures the correct deployment of the antenna, and the expected RF performance once it is deployed. The different parts that conform the subsystem can be seen in Figure 3.

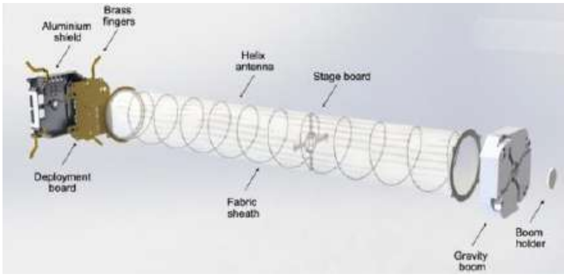

Figure 3 - NADS exploded view

In stowed configuration the NADS is held by five melting lines. One melting line holds half of the antenna, this line is secured in the Stage Board. Two more melting lines hold the gravity boom keeping the whole antenna stowed. Finally, four brass fingers prevent the antenna and gravity boom from moving, these fingers are secured by the boom holder. The boom holder is also held by two melting lines. Both the gravity boom and boom holder have redundant melting lines to prevent an unexpected deployment in case of failure on one of the lines.

The melting lines are arranged in the Aluminium shield so that there is contact between the lines and the burning resistors placed in the deployment board. There are primary resistors and redundant resistors.

The deployment is performed in three stages. The first stage releases the boom holder and the fingers, the second releases the gravity boom deploying half of the antenna, and the finals step deploys the complete antenna by releasing the stage PCB.

DOI: 10.5821/conference-9788419184405.072

The deployment board includes feedback switches. The switches indicate if the melting lines are burnt, i.e., stage deployed, or not.

The deployment is executed through telecommand (TC). There is one TC for each melting line and the deployment sequence only proceeds to the next stage if the previous one has positive feedback from the switches.

Once the antenna is deployed the fabric sheath maintains the shape of the helix.

3. Verification Campaigns

In order to verify the design of the deployment mechanism a qualification model of the subsystem has been tested in ambient conditions by performing antenna deployments. Moreover, it has also been tested in the environmental conditions that will be experienced during launch including vibration tests, and in orbit with thermal vacuum tests.

3.1. Ambient Tests

The verification of the antenna design has been conducted by performing multiple deployments in ambient conditions.

To perform these tests the antenna is placed on a test bench, which holds the aluminium shield of the antenna as well as the gravity boom. This configuration allows to deploy the antenna in a horizontal position, minimizing the effect of gravity.

Figure 4 shows the deployment performed in one of the ambient tests.

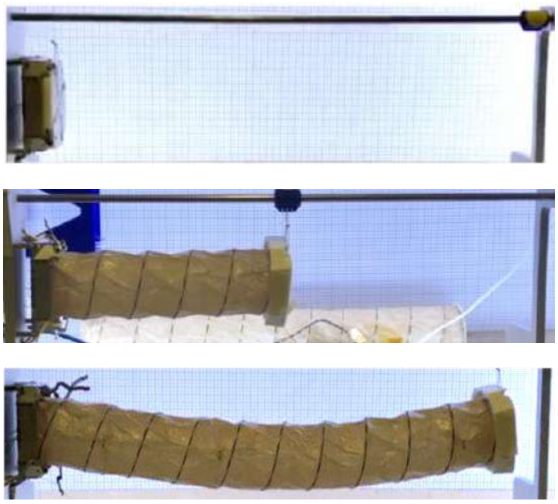

Figure 4 - NADS ambient deployment test sequence

3.2. Vibration Tests

The goal of vibration testing is to ensure that the first resonance of the subsystem is above 100 Hz and that the subsystem is able to withstand the structural stress suffered during launch by being functional after.

The NADS has been vibrated in all three axes and the metrics have been obtained using monoaxial accelerometers. The setup for the tests is shown in Figure 5.

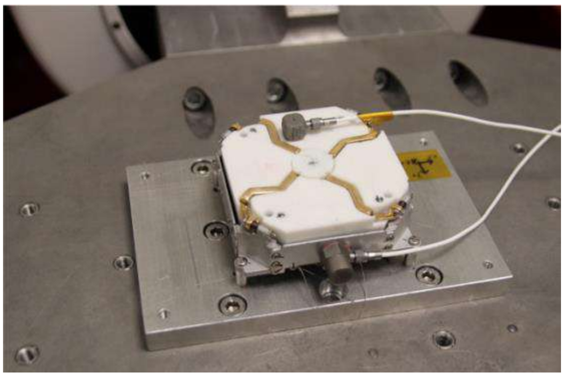

Figure 5 - NADS assembled in the Shaker slip table

The subsystem has also undergone a sine sweep test, which emulates the acceleration of the launcher. As well as, a random vibration test, emulating the structural stress induced by the rocket.

Out of the three accelerometers, one is the control, which adjusts the stress put to the subsystem. The other two are measurements of the subsystem. The resonant frequencies can be found in Table 1.

Table 1. First resonant frequencies

	X	Y	Z
Resonant Frequency (Hz)	600	700	500

The success criteria for the test campaign are based on a visual inspection and an ambient deployment test.

The NADS showed no movement in parts or fasteners after the vibration tests and the antenna was able to fully deploy, considering the test campaign successful.

3.3. Thermal Vacuum Tests

DOI: 10.5821/conference-9788419184405.072

The goal of the Thermal Vacuum Tests is to verify that the NADS is capable of deploying in vacuum and with extreme temperatures. This emulates the environment that the subsystem will face when it is in orbit.

The Thermal Vacuum test performed consists of deploying the antenna at -35 ºC. The test was setup so it would recreate the ambient tests by placing the antenna assembled in the test bench inside a Thermal Vacuum Chamber (TVAC).

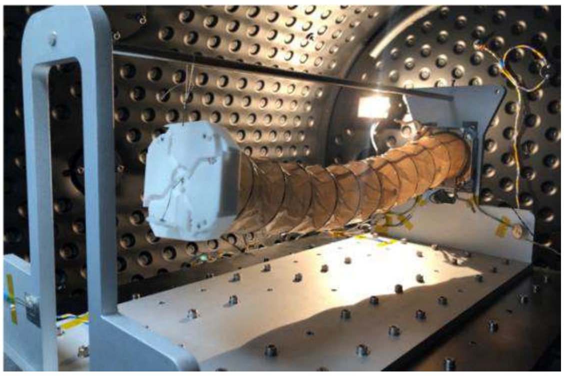

Figure 6 - NADS deployed inside ESEC-Galaxia TVAC

The test was considered successful since the antenna was deployed in vacuum conditions and at -35 ºC.

4. Conclusions

This article summarizes the design and characterization tests of a deployment mechanism for a helical antenna, following the CubeSat standard. This mechanism will fly on the ^{3}Cat-4 satellite, it conforms the NADS.

The NADS has two different configurations, it is stowed during launch and deployed when the satellite is in orbit. The design has considered safety, functional and performance requirements to ensure success on both configurations and also on the deployment of the antenna.

The subsystem has been verified through ambient testing, performing deployments of the antenna in order to verify the design. It has also been vibrated, to ensure the correct functionality during launch and the capability to deploy once it is orbiting. Finally, the correct deployment of the antenna in space conditions has been verified through a thermal vacuum test at -35 ºC.

Acknowledgements

This work was supported by the Spanish Ministry of Economy and Competitiveness, by the Spanish Ministry of Science, Innovation and Universities, "Sensing with Pioneering Opportunistic Techniques", grant RTI2018-099008-B-C21/AEI/10.13039/501100011033, also funded in part by the Secretaria d'Universitats i Recerca del Departament d'Empresa i Coneixement de la Generalitat de Catalunya 2017 SGR 376 and 2017 SGR 219.

This work has also been founded by the grant PID2019-106808RA-I00 funded by MCIN / AEI / 10.13039/501100011033.

Finally, this research was possible thanks to the FI-2019 grant from AGAUR-Generalitat de Catalunya.

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DOI: 10.5821/conference-9788419184405.072

Lessons learned during the development of LEDSAT from the students of the S5Lab

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Abstract

The LEDSAT 1U Cubesat, a satellite roughly 10x10x11cm, was developed between late 2016 and 2021 by students of Sapienza University of Rome. The project was conceived with the help of the University of Michigan and started being developed by space engineering master students of Sapienza in a class context. The team of the S5Lab (Sapienza Space System and Space Surveillance Laboratory) continued the project and applied for the Fly Your Satellite! Programme of ESA Education, which has followed the development of the CubeSat, providing important expert support and periodic reviews. The approach brought to the students an invaluable educational experience as they participated actively in the development of a spacecraft with the typical milestones of satellite projects. The mission objectives of LEDSAT include the use of onboard LEDs for improved orbit determination, experimental attitude determination and backup light communication. Each of the six sides of the CubeSat houses an LED board of a different color (red, green, and blue) with opposite sides with paired color. The LEDs can flash a pattern predefined by radio telecommand and the light is observed using ground telescopes. The design of the spacecraft started in late 2016 and was presented at the selection workshop of the Fly Your Satellite! Programme in May 2017. Final assembly took place in mid-2020 after which the team performed functional and environmental testing between October and December 2020, with the objective of ensuring the survivability of the spacecraft in the space environment and characterization of its behavior. After successful testing, the spacecraft was integrated inside the deployer in July 2021 in Brno, Czech Republic and was launched from Kourou, French Guiana on August 17th, 2021, aboard the Vega VV19 launcher. The spacecraft is now in orbit and operating nominally, with the LED flashes having been observed several times. The development of the spacecraft was not without difficulty, with preventable issues arising through testing that imposed design changes and further analysis - the paper will walk through the project since its conception, throughout the development, the functional and environmental testing of the payload and at system level, emphasizing the lessons learned by the students.

Keywords

CubeSat, nanosatellite, lessons learned, education

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Acronyms/Abbreviations

All used acronyms and abbreviations should be listed in alphabetical order, as follows:

FYS	*Fly Your Satellite*
ESA	*European Space Agency*
CDR	*Critical Design Review*
AIV	*Assembly, Integration and Testing*
TLE	*Two-Line Element*
FFT	*Full-Functional Test*
MT	*Mission Test*
CSF	*Cubesat Support Facility*
VIB	*Vibration*
TVAC	*Thermal-Vacuum*
TID	*Total Irradiated Dose*
LSA	*Aerospace System Laboratory*

1. Introduction

LEDSAT is a 1U CubeSat developed by Sapienza University of Rome, in collaboration with the University of Michigan [1], [2]. The mission aims at verifying the functionalities provided by on-board LEDs for the orbital determination and experimental attitude determination from ground, using telescopes to observe the satellite [3]–[7]. The idea was developed in 2016, in the context of a spacecraft design class in a Master's course in engineering and was presented to be part of the Fly Your Satellite! Programme (FYS) of ESA Education in 2017. The programme followed the development of the spacecraft through CDR (Critical Design Review), AIV (Assembly, Integration and Verification) and launch. A picture of the satellite can be seen in Figure 1.

The satellite was successfully deployed in orbit on August 18th, 2021, and observation of the LEDs began as soon as possible. Within a week, the team had confirmed the object number assigned by NORAD for the TLE (Two Line Elements).

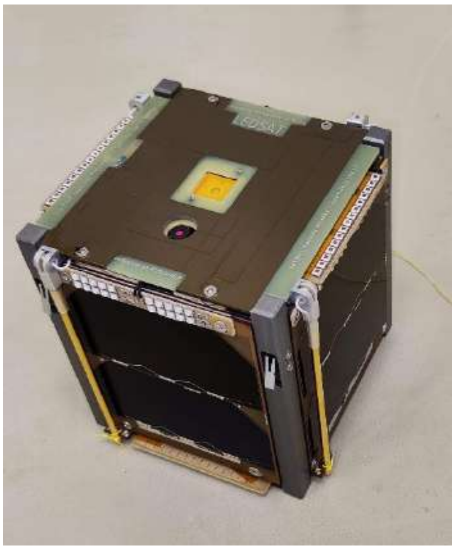

Figure 1: LEDSAT before integration into the deployer.

2. Mission timeline

The concept was developed in 2016 by the University of Michigan and was followed on by a spacecraft design class in Sapienza University of Rome in the second semester of 2016 (Figure 2). There, students turned the mission concept into a 1U CubeSat, designing and sizing the components of the nanosatellite in order to sustain the payload. What was developed within the class was used to draft the proposal for FYS, to which the team applied in 2017.

Figure 2: Students that developed the mission concept.

The Selection Workshop for FYS took place in May 2017 in ESTEC, Noordwijk, where five students presented the mission to an ESA experts panel for the admission into the programme (Figure 3).

DOI: 10.5821/conference-9788419184405.073

Figure 3: Students presenting LEDSAT at the FYS Selection Workshop.

The CDR took place between fall of 2017 and spring of 2018, with co-location meetings that took place in ESTEC, Noordwijk in December of 2017. During the co-location meetings the team defended the design to several experts for each major subsystem and went through all the design changes (Figure 4).

Figure 4: Students at the co-location meetings at ESTEC.

Before assembly the team underwent a testing campaign related to the LED payload with the help of the FYS Team. In particular, the LEDs were subject to radiation testing (December of 2017) at the Co60 Facility in ESTEC. At the Co60 facility the team performed TID testing (Total Irradiation Dose) and learned how space hardware is tested against a gamma ray source.

The payload boards also underwent vibration and thermal-vacuum testing at the CubeSat Support Facility (CSF) in ESEC Galaxia in November of 2019 (see Figure 5), where the students familiarized themselves with the test equipment, the procedure writing and the operations [8].

Figure 5: Students performing the TVAC testing on the payload at the CSF.

Assembly of the spacecraft took place in the beginning of 2020, after which the satellite underwent functional testing in July 2020, with a Full Functional Test (FFT). During the FFT, an anomaly in the GPS receiver was found that made it unable to get a position fix. The root causes of the problem were found and fixed, after which the testing resumed from the FFT and through the Mission Test (MT) [9].

With all the functionalities tested, the team performed the environmental testing at the end of 2020, with both Vibration Testing (VIB) and Thermal-Vacuum Testing (TVAC) performed at the facilities of Sapienza University of Rome, at the Aerospace System Laboratory (LSA). The tests were originally planned to be performed at the CSF, but due to travel restrictions causes by COVID-19 they were performed at the university. A picture of LEDSAT in the TVAC chamber in Sapienza can be seen in Figure 6.

DOI: 10.5821/conference-9788419184405.073

Figure 6: LEDSAT inside the TVAC chamber.

Upon changes on the environmental requirements from the launch authority, it was found necessary to perform additional tests on the CubeSat. To this end, the team travelled to the Astrofein facilities in Berlin to perform a shock test on the payload EM (Engineering Model) in May 2021 and to the CubeSat Support Facility (CSF) in ESEC Galaxia in June 2021 to perform new vibration and thermal-vacuum testing on the PFM (Proto-Flight Model), see Figure 7.

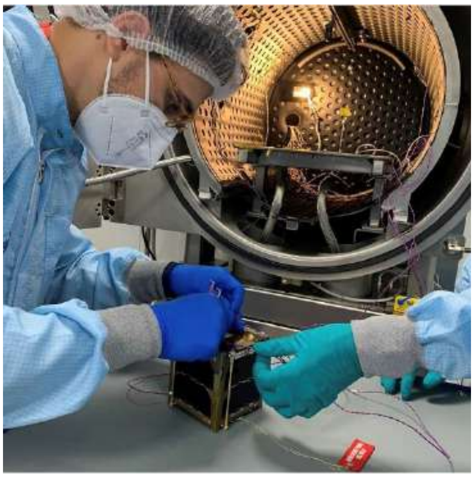

Figure 7: LEDSAT being prepared for TVAC testing at CSF.

The CubeSat was finally integrated into the flight deployer in Brno, Czech Republic in July 2021. The team assisted in the integration of the deployer on the PLA (Payload-Launcher Adapter) at CSG (Guiana Space Center) in French Guiana at the end of July 2021 (Figure 8).

Figure 8: Students and FYS Team member at CSG, next to the PLA.

Deployment of the satellite into orbit took place on August 17th, 2021, brought to orbit by the Vega VV19 launcher. First contact with the spacecraft occurred soon after deployment, from the Ground Station (GS) in Rome.

The first observations of LEDSAT took place one week after launch and were successful, confirming which object was LEDSAT among the five released by the launcher. Operations continue with the observations of different patterns, optimizing the observation times and testing the experimental attitude determination. An example of LEDSAT flashes can be seen in Figure 9.

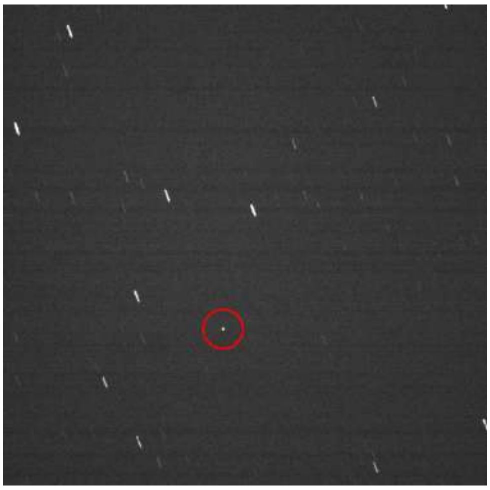

Figure 9: LEDSAT flashing during an observation session.

3. Specific Lessons Learned

3.1. Difficulty in increasing team size

It was difficult to allow new students to join the team and to let them participate in AIV activities. While in the order of 40 students have participated in some way in the

DOI: 10.5821/conference-9788419184405.073

LEDSAT mission, only 6-7 were actually involved in the development of the hardware. The main difficulty was due to the steep learning curve necessary to work with the hardware safely, and the difficult problems that required experience in the mission to solve. It was difficult to divide the work into smaller tasks that new students could perform. A solution could be to give small preparatory courses to train the students and introduce them to the CubeSats environment.

3.2. Test procedures

One issue that was noted soon was the difficulty in writing good test procedures. Producing an effective procedure was an important lesson during the development of the satellite, but since most things were done for the first time it was difficult for the procedure writers to imagine the steps necessary and for the operators to perform them. In the end, the result was over-detailed procedures that could not always be followed fully during the operations, or that slowed the operations altogether. In addition, since most of the time the procedure was written by the same person performing it, most of the details were unnecessary. A solution to this problem could be to structure the step-by-step procedures to be more like checklists.

One of the main benefits of a step-by-step procedure is to have good traceability of what was performed on the spacecraft, but this can easily be replaced by pictures – in fact, the team found that looking at pictures taken during the operations was a far better and faster way to recall and retrace the details of what was performed. With this mindset, the operators should take pictures at every key point of an operation, with ideally an operator assigned specifically to this task.

3.3. Keeping good documentation

An important lessons learned during the project was the need to keep good documentation updated. The documentation helped a lot to recall old details of the project easily, keeping track of all the changes to the design and all tests. One will never know when a particular information will be needed and must plan for the future. In addition, the documentation helps in allowing new personnel to join the team and to share the details across the team.

3.4. Help from the radio-amateurs

Since the satellite uses radio-amateur frequencies in UHF, it is also received by radio-amateurs. The team has found that the radio-amateur community is happy to help in receiving the satellite and help in the first phases of the mission, where receiving the first signals is crucial. To this end, the community has developed the project SatNoGS, whose objective is to provide an open source network of satellite ground stations. The team provided the information necessary to demodulate and interpret the data of the telemetry and the stations of SatNoGS regularly schedule and receive the satellite signal, also storing the received telemetry in their databases. This can be very useful when there are problems at the ground station, and highlights the importance of transmitting a periodic beacon with the vital telemetry inside.

3.5. Focus on the flight operations

The team found it was very important to focus on the real-life operations to be performed while the satellite is in orbit, and to this end the Mission Test was crucial. Working with the satellite in ground, with the different debug connection, easy access and other aids is very different then operating the spacecraft in orbit, where visibility of the on-board software and short access times limit what the operators can do. At the same time, the space environment is different in many aspects, like temperature and battery charging profiles that could affect the operations.

It is key then to test the different scenarios however possible, recreating the access times and communication speeds to see if the operators have good control of the

DOI: 10.5821/conference-9788419184405.073

spacecraft or if some function needs to be changed.

4. Conclusions

The LEDSAT mission developed by students of the University of Rome in collaboration with the University of Michigan between 2016 and 2021. The satellite is currently in orbit and performing nominally, with the observations of the on-board LEDs continuing. The project involved about 40 students, between Bachelor, Masters and PhD students and was part of the Fly Your Satellite! Programme, which provided extended help in the project, both technical and educational. Several lessons were learned in the project, which are used in current and will be used in future projects of the laboratory.

Acknowledgements

The LEDSAT team acknowledges the ESA Education office and the Fly Your Satellite team for their support. The team also thanks the Italian Space Agency (ASI) for the financial and technical support in the framework of the IKUNS Programme (Accordo IKUNS-Italian/Kenyan University Nanosatellites – n.2015-031R.1-2018). The team also acknowleges the University of Bern (AIUB) and the ASI Center of Space Geodesy (ASI CGS), New Production Concept Srl (NPC) for their support in designing and manufacturing the CubeSat structure, Profilocolore Srl for the equipment used for radiometric measurements and Optical Panzieri Srl for providing mechanical fasteners for the CubeSat.

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O-ZONE: affordable stratospheric air dynamic sampling device

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Abstract

The current situation regarding air pollution, global warming and the world approaching the point of no return have led the United Nations to focus on improving the environmental situation through the SDGs [1]. In line with these ambitions, O-ZONE team, was born in 2019 with the clear objective of taking concrete action against climate change [2].

The team's goal is to build a compact, low-cost, and reusable device to sample stratospheric pollutants, at various altitudes and thus provide air quality indications in mid-range areas for monitoring, prevention, and rapid intervention in case of unpredictable events.

The O-ZONE team was therefore born as an idea of some students from the Aerospace Engineering course at the same University. The students took part in the REXUS/BEXUS project by Swedish National Space Agency (SNSA), Deutsches Zentrum für Luft- und Raumfahrt (DLR) and European Space Agency (ESA) [3]. As in each of these projects, the team tackled the various steps of space missions but, in this case, with extra constraints. They had to work during the lockdown with various complications due to the pandemic. Although the launch was delayed, the students carried on with their motivation and then launched their device on board the BEXUS 30.

The prototype launched in Kiruna - Sweden (at the Esrange base), and which reached an altitude of 27.8 km, is a sampling system for Volatile Organic Compounds (VOCs), such as NO_X and SO_X, Particulate Matter (PM) and Chlorofluorocarbons (CFCs) responsible for the depletion of the Ozone layer [4].

These types of samplers [2] fill the technological gap in atmospheric analysis; the current state of the art allows air to be monitored only statically from ground stations or by satellite analysis [5], while O-ZONE presents an accessible, easy-to-use and rapid in situ sampling method.

This paper describes the technical specifications and design aspects of the device and the experience that has allowed the students to grow as a team, especially in terms of personal skills and the ability to work with concurrent engineering and interdisciplinarity.

Finally, the experiment results will be shown.

Keywords

Atmospheric Pollution, SDGs, Sampling, CFCs, BEXUS30.

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Acronyms/Abbreviations

CFCs	*Chlorofluorocarbons*
DLR	*Deutsches Zentrum für Luft- und Raumfahrt*
DMAC	*Dimethylacetamide*
DPPO	*Diphenyl-p-phenylene oxide*
EDX	*Energy Dispersive X-Ray Analysis*
ESA	*European Space Agency*
ESEM	*Environmental Scanning Electron Microscopy*
FT-IR	*Fourier-Transform InfraRed*
GC-MS	*Gas chromatography coupled to a mass spectroscopic detector*
IAC	*International Astronautical Congress*
LCA	*Life Cycle Assessment*
LQM	*Limit of quantification*
LOD	*limit of detection*
PM	*Particulate Matter*
PVDF	*Polyvinylidene fluoride*
SDGs	*Sustainable Development Goals*
SNSA	*Swedish National Space Agency*
SSC	*Sweden Space Corporation*
SSEA	*Symposium on Space Educational Activities*
TVAC	*Thermal vacuum chamber*
VOCs	*Volatile Organic Compounds*
UV-VS	*Ultra Violet Visible Spectroscpy*

1. Introduction

The point of no return on global warming highlighted by the United Nations and environmentalists is leading, perhaps too slowly, to an unprecedented social and economic revolution [1]. To accelerate the process of change, institutions and governments need to give a stronger push. They should use appropriate legislation to encourage companies to update their production cycle through the now increasingly widespread Life Cycle Assessment (LCA). Obviously, this intervention must have a technological and scientific basis that allows for the intensification of controls and the subsequent tightening of penalties for those who violate what has been sanctioned.

Starting from the current problems related to pollution and especially regarding the emission of pollutants into the atmosphere [4], the O-ZONE project was born to act concretely in the fight against climate change [6] [7].

In 2019, a group of students from the aerospace engineering course at the University of Padova, supported by Alessandro Francesconi, Professor of Aerospace Systems and Systems, and Roberta Bertani, Professor of Chemistry for Aerospace Engineering, came up with cheap and easily deployable alternative technologies for atmospheric monitoring [2]. After officially becoming part of the innovative projects of the University of Padova and then obtaining economic support, their adventure to build a pollutant sampling device began [6].

In October 2019, the application was then submitted for the BEXUS project of SNSA, DLR, and ESA [3]. This project allows a student team to place their innovative experiment on board the "Gondola" (support structure) of a stratospheric balloon, together with other teams from all over Europe. The balloon reaches an altitude of around 25 km and allows a variety of instrumentation and tests to be carried out. This opportunity immediately interested the O-ZONE team, who wanted to analyse atmospheric air at different altitudes in order to understand how pollutants such as VOCs, PM, and CFCs, are distributed and stratified in the various atmospheric levels up to 25 km.

The submitted application was accepted and plunged the team into a real space mission with phases of verification, review, design, and development of their device. O-ZONE then expanded to 17 operational members who oversaw developing the testing subsystems and disseminating their extraordinary experience [7]. There were a few complications along the way, the most obvious being the Coronavirus pandemic, which tested the team's perseverance and resulted in the launch being postponed for a year. The O-ZONE team did not give up and, taking advantage of the "extra" time, decided to design a second version of the prototype, with even better performance and even more compactness.

In October 2021, the O-ZONE experiment flew aboard the BEXUS 30 successfully completing all assigned tasks, landed safely and ready for recovery.

This paper will therefore describe what was designed, developed, and tested during the three years of the project, with a focus on the launch, the technologies used, and a hint of the results obtained.

2. Design of the experiment

The experiment consists of a set of filters that use a pneumatic system and a pump to suck the atmospheric air and trap air pollutants. Thanks to the on-board computer, valves are activated to differentiate the samples collected at different altitudes and to understand, after landing and subsequent analysis, the distribution of PM, VOCs and CFCs over the 25 km or so covered by the stratospheric balloon [8].
The components necessary for its proper operation of the experiment are installed inside a box made up of aluminium plates. Going into details, the skeleton of the structure is made of aluminium profiles on which the plates protecting the device during the landing phase are fixed while 40mm thick polystyrene panels complete the external design to ensure proper thermal insulation. Considering the internal structure, this is characterized by 3 different levels (aluminium plates, see Figure 1), each of which is dedicated to host a different subassembly; from the bottom to the top level there is the pneumatic subsystem (Figure 2), the electrical subsystem, and the sampling bag. This final design has been chosen after several iteration and allows an easy and quick access to all the components since it considers the main *design for assembly* principles. To conclude, rubber bumpers are used to connect the experiment box to the Gondola system preventing damages to the internal components during the landing phase.

Figure 1. O-ZONE experiment exploded view.

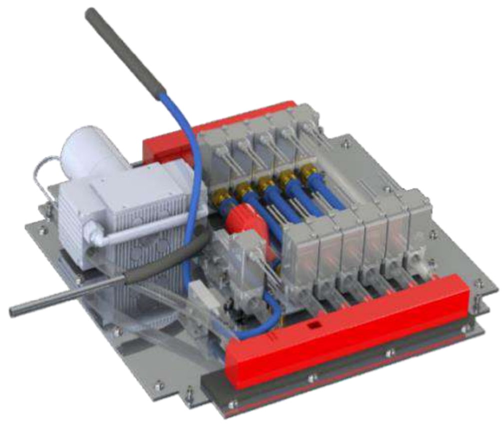

Figure 2. O-ZONE base level (CAD view of the pneumatic subsystem plate).

The external box protects the central system, the core of the experiment. The pneumatic system's functionality is guaranteed by a diaphragm pump, which is needed to suck the air the device rises into the atmosphere. The diaphragm avoids possible contamination of the air with the oil of the gears. Moreover, this model can work at low pressures because it has a minimum pressure limit of 25 mbar.
The air that flows inside the circuit was regulated by 2 flowmeters to obtain an accurate reading. Once through the pump, the air is conveyed into the various tubes through the opening and closing of solenoid valves.
In order not to compromise the samples and to safeguard the mechanical and electronic components, thermal solutions were adopted.
An external insulating shield, made of aluminium and panels of Polystyrene, protects the experiment from the thermal flows that can heat or cool down overly the device. Furthermore, thanks to continuous temperature control, the system can switch on and off the active thermal system made of heaters.

2.1. Pneumatic subsystem

The heart of the project is the pneumatic system (Figure 3): it is responsible for the suction and distribution of air within the pneumatic circuit. The system is essential and compact, this to be contained in small spaces, and thanks to this feature it can be easily scaled and reproduced. Going into details, as mentioned above, the main component of this subsystem is a diaphragm pump which aim is to suck the external air at different altitudes. With the membrane technology, contamination between the air (to be analysed) and the oil used for the lubrication of the rotary mechanisms is avoided; furthermore, the pump must be able to work at low pressures, indeed it has a minimum pressure limit of 25 mbar. The power supply to

DOI: 10.5821/conference-9788419184405.074

the pump is adjusted according to the flow of air that passes through the pneumatic circuit: 2 different flowmeters are used to obtain an accurate reading of the flow, placed at the beginning and at the end of the circuit respectively. The airflow is then led inside the pneumatic circuit thanks to 12 solenoid valves which are opened by an Arduino Due at different intervals based on the altitude reached by the experiment [6]. This allows a dynamic sampling and a complete isolation of the air between the different phases.

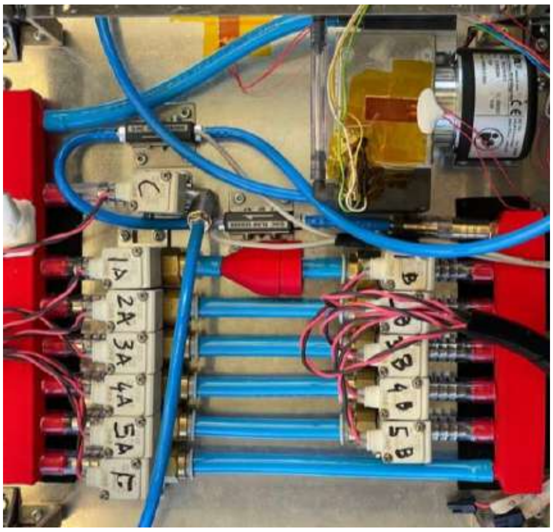

Figure 3. Top view of the pneumatic subsystem.

The pump model is particularly suitable for the experiment because it is light and small and at the same time it guarantees excellent performance for our requirements even at low pressures and temperatures as it was verified in the thermal vacuum chamber (TVAC). The self-imposed constraint of the device's overall cost influenced some key decisions during the design phase. It was chosen to adopt 4 pollutants filters, each responsible for sampling the air in an interval of 4.5 km of altitude during the ascending phase. During the first interval, a PM filter is used, capable of trapping organic and inorganic molecules. In addition to this first chemical system, the device contains a sampling bag that will be filled during the last part of the ascent and the floating phase (expected between 22.5 and 25 km).
As mentioned above, the air is collected at different intervals based on the reached altitude; the complete sampling sequence is therefore explained in Table 1.

2.2. Sampling subsystem

The aim of the experiment is to sample air at different altitudes, from 0 km to 25 km, using a system consisting of a sampling bag and three different kinds of filters. Therefore, the sampling system is namely composed by three different technologies.

2.2.1. Adsorption filters

Stainless steel thermal desorption tubes composed of a three-layered system made of Tenax TA/Graphitized Carbon Black/Carbonex 1000. The first layer consists of Tenax ® TA (35/60 mesh), a macro-porous semicrystalline diphenyl-p-phenylene oxide (DPPO) polymer [6]. The second one is made of Graphitized Carbon Black (40/60 mesh), a nonporous adsorbent which interacts through Van der Waals' forces [7] [8]. The third layer is Carboxen 1000 (60/80 mesh), a Carbon Molecular Sieve. With only one tube it is possible to sample compounds with different volatilities in such a way that the least volatile compounds get trapped in the weakest material (the third layer, Carbonex 1000) and the most volatile ones get trapped in the strongest compound (Tenax TA). The analytes can then be extracted via thermal desorption or solvent extraction, using CS2. The flow rate is kept constant at 0.05 L/min during the sampling phase [7] [8].

2.2.2. PM filters

The second sampling system is made of particulate matter filters consisting of a Whatman® QM-A quartz filter, with a pore size of about 2.2 μm and a diameter of 25 mm, and an ATTP microporous hydrophilic polycarbonate filter, with a constant pore size of 0.8 μm and a diameter of 25 mm. These filters are capable of sampling organic and inorganic particles [8]. The filters are placed into a custom-made 3D printed support. The arrangement of the filters is such that both can be used in the same pipe. The polycarbonate membrane is cut in half and one portion of the two is placed onto the intact quartz filter. The flow rate is kept constant at a known flow rate of 3 L/min.

2.2.3. Sampling bag

A 3 litres polyvinylidene fluoride (PVDF) sampling bag is the last sampling system adopted in the experiment. Its purpose is to collect and store the air during the last phase of the flight. PVDF sampling bag has previously been proved to be excellent at storing VOCs, to be resistant to abrasion and chemicals and to do not produce background levels of Dimethylacetamide (DMAC) or phenol [7] [8].

DOI: 10.5821/conference-9788419184405.074

3. Launch Campaign

The launch campaign took place at the Esrange base in Kiruna between 24 September and 4 October 2021. Initially, flight preparation tests were carried out, and these included verifying the experiment's correct mechanical and electrical connections with the gondola and communication with the ground station. After the pre-flight tests, the experiment was placed aboard the gondola at the Sweden Space Corporation (SSC) space base. The balloon, hosting four other experiments, began its ascent that lasted about an hour and a half and then remained floating for another four hours. The gondola reached an altitude of 27 km, where the external temperature was below −60°C and a pressure of 17 mbar. Before the launch campaign, several tests were carried out in a vacuum chamber to verify the correct functioning of the experiment under these critical conditions. Vacuum and thermo-vacuum tests were carried out using dry ice to simultaneously simulate temperature and pressure at high altitudes. During the tests, the flowrate through the filters was monitored, and an automatic and a manual adjustment method was created for the flowrate based on the altitude (therefore the pressure). In the same way, the thermal control system was tested, and the power consumption was checked [8].
The experiment followed the various phases planned (Table 1), filtering the air with all the available filters and filling the sampling bag. The behaviour of the experiment was nominal in all phases; the times were respected, as were the airflow rates and temperatures. Communication with the ground station was optimal and allowed the experiment to be guided through the entire flight without considerable signal losses that could compromise the device's functionality.
Recovery took place promptly (24 hours later) to minimize the time between sampling and analysis.

Table 1. Process flow table.

	Altitude [km]	Sampling method
I phase	0-4.5	PM filter
II phase	4.5-9	1st VOCs filter
III phase	9-13.5	2nd VOCs filter
IV phase	13.5-18	3rd VOCs filter
V phase	18-22.5	4th VOCs filter
VI phase	22.5-25	Sampling bag
Last phase	0	Analysis

4. Results

Various analytical techniques can be used to study the samples collected, such as Fourier-Transform InfraRed (FT-IR) or UV Visible spectroscopy (UV-VS), gas chromatography coupled to a mass spectroscopic detector (GC-MS), and electrochemiluminescence devices. The latter are common analytical methods used to directly quantify chemical pollutants in the air, such as VOCs and CFCs in air samples [9]. Therefore, the results obtained can be compared with those reported in literature if additional validations confirm the reliability of these techniques at high altitudes. These analyses are performed in a laboratory, indeed if the analyses are carried out on-site an accurate calibration is needed to ensure the correlation between the instrumental response and the concentration of target molecules. Thus, after the sampling the filters and the sampling bag undergo different tests which comply with several methods. The adsorption filters are analysed by GC-MS with a thermal desorption program to detect very low concentrations, in the order of magnitude of ppb, expected for many of the examined analytes. The method employed is NIOSH 2549 1996 [10] [11]. The particulate matter filters are studied qualitatively and examined by Environmental Scanning Electron Microscopy (ESEM) [8]. The sampling bag is analysed by gas GC-MS with the methods EPA 3C 2017 and EPA TO 15 1999) [8]. The latter are commonly used for the characterization of environmental samples containing mixtures of volatile organic compounds. Many VOCs are revealed in a concentration below the limit of quantification (LOQ) only qualitative considerations can be made.
However, from a qualitative point of view, their presence in the collected sample is ascertained since their concentrations were higher than the limit of detection (LOD) of the analytical method involved. The polycarbonate filter collects scattered particles, both organic and inorganic with dimensions ranging from 5 to 10 μm. Their composition is identified by using the Energy Dispersive X-Ray Analysis (EDX) analysis.
This prototype is proved to be operating, but the data extracted so far are not enough to either validate the method or to estimate the sampling error. Thus, further tests need to be performed to verify the reliability and integrity of this promising and low-cost sampling tool [12].

5. Discussion

During the three-year project, the students not only had the opportunity to build a device and improve its design from a 1.0 prototype to a second 2.0 version, but also to develop personal skills, soft-skills and to enter the world of research and work. The testing phases engaged them the most and proved to be the winning strategy for the operation of the device in flight. In particular, the thermal vacuum test was an example of the team's commitment to thoroughly testing an experiment under realistic flight conditions for the first time in the history of BEXUS. The team also had the opportunity to present their achievements at major international conferences, the most important of which was the International Astronautical Congress (IAC) [7].

6. Conclusions

After two years of development and improvement, the experiment took part in the BEXUS 30/31 launch campaign in Kiruna (Esrange base) at the end of September 2021.
The experiment worked as planned during the flight despite a minor problem with the GPS, but thanks to the implementation of both an autonomous and manual mode the device was able to sample the air in all the filters and collect enough air on the sampling bag.
The analyses of the filter and the air conducted in Italy were successful. During the whole BEXUS program period the team experienced a very effective growth in both teamwork skills and interdisciplinary knowledge.
The results demonstrated the functionality of the experiment and enabled the team to achieve the objectives initially set. The work carried out by the team can be found in the Student Experiment Documentation (SED), which is available online [8].

Acknowledgements

Thanks to all the people who supported O-ZONE during its development: the students involved: Federico Toson, Dumitrita Sandu, Giovambattista Valente, Luca Vitali, Simone Sandon, Mauro Pulice, Marco Bertoncin, Davide Bonetto, Carlotta Segna, Giovanni Righi, Luigi Antoniazzi, David Magnani, Stefano Lopresti, Antonino Pitarresi, Andrea Conte, Daniele Panariti, Federico Palisca, Gasperino Kamsi, Marco Furiato and Matilde Pavan. Thanks to Professors Alessandro Francesconi and Roberta Bertani, the University of Padova, the Department of Industrial Engineering (DII), CISAS 'G. Colombo', SNSA, DLR, the REXUS/BEXUS team and to supporters such as Rotary Club Abano Montegrotto, Metalco, RESTEK, SMC, Zoppas Rica, and StratoFlights. Special thanks to all the people who accompanied us such as Lorenzo Olivieri, Koen De Beule, Armelle Frenea-Schmidt and all the colleagues we met along the way.

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The role of the key educational paths for ESA new member states as a risk reduction index for the newcomers.

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Abstract

The new ESA member states are an important factor in the development of European sustainability and independence in space. Cooperation between European countries in the field of space, gives a strong conviction that we operate without borders in space. It is therefore necessary to create not so much international links, but rather supranational ones. This also applies to space education. One of the primary missions of ESA is to create a community of highly specialized engineers, managers, as well as scientists who will focus on developing the space economy and allowing societies to understand our role and interactions with space.

Based on the experience gained in the period after Poland's accession to ESA, the authors would like to emphasize the role of key educational pathways that can guide ESA officers in new member countries and in any country that has already entered ESA structures or plans to enter in the near future. The authors would like to emphasize that there are several ways to share and improve knowledge and would like to present the main insights of the study conducted in this respect.

Drawing on the Polish space industry and using it as a reference basis, but also applying some observations from the Czech Republic and now Latvia, the authors identified the following main learning paths:

- The activity of students within student associations, who implement space projects through dedicated programs;
- The role of YGTs who, after a period of training at ESA, return with a set of knowledge to their countries;
- The importance of the know-how of the international space market, in particular global companies setting up subsidiaries in new ESA member countries and bringing their experience and knowledge there;
- Dedicated educational programs for people who do not have a formal space education (engineering) but want to develop in various areas of the space industry;

The sequence of the presented educational pathways is not accidental. The authors want to present the role of each pathway and show how it can be applied in practice. The authors recognize some deficiencies in the presented pathways, as well as note a trend towards strengthening interest in dedicated educational programs at the undergraduate and postgraduate levels. Based on their own educational experience and taking into account the status quo of space education (at least) in central Europe, the authors would like to present ideas for structuring professional education in the space industry, taking into account its recent changes, where the demanding factor of business competition should be added to the technological factor. So, where an interdisciplinary approach should be adopted. Each educational pathway has been analysed from the point of view of risks and opportunities. This analysis can be applied by new participants in the commercial space market (understood as new companies or scientific groups), but also by new ESA member states at the institutional level.

Keywords

space education, space economy, risk management

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1. Introduction

The authors' aim is to examine the main educational pathways that can be crucial for risk mitigation in the development of the space market in the country and beneficial for the European space community. The paper presents the state of the space market in Poland before joining the ESA structure. The authors then present a research methodology leading to the identification of the educational pathways of a few groups of skills in space sector. Each of these educational pathways is analysed. The authors focus not only on engineering education, but also on management education. Based on the identification and analysis carried out, an investigation of the shortcomings is carried out, which is discussed and concluded.

The authors are aware that the investigation carried out can help new member states or emerging countries to focus on areas where they are not yet present, but which can have a great impact on the development of this part of the industry in the country. The approach leads directly to risk mitigation, but more importantly, it leads to the identification of risks that can be managed in a further step.

2. Research methodology

The research methodology applied in this paper based on review of:
(1) Literature, publications,
(2) Documents published by: Administration, Business and Professional associations,
(3) Analysis of Space studies programmes
(4) Analysis of postgraduate studies available on the market,
(5) Trainee programmes organized by Industrial Development Agency
(6) Others: Foreign companies offices in the Country; structure of the polish entities, which takes parts the ESA market.
(7) Organization maturity level, measured by at least possessed certified quality management system.

The investigation shall answer the main questions:

- The basic education paths are enough to provide technical specialist in the market?
- Do the engineers have the wide possibility work in space companies?
- Does the market see the need for managerial / economical / law competencies?
- Are there possibilities to increase the increase the “soft” skills?
- Are there dedicated programmes to provide condense knowledge for administration or “new comers”?

The analysis included in the paper concern the space sector understood as "all entities involved in the systematic application of engineering and scientific disciplines to the exploration and use of space" [10]. Non-coincidental and multiple involvement is important. Several criteria for belonging to the space sector are proposed in this regard, including: documented participation in the European supply chain, developing R&D competencies, conducting implementation or industrial work related to space technologies and satellite techniques. The concept of the space sector is not the same as that of the space economy, which generally encompasses the activities of entities involved in the development, provision and use of products and services related to space activities [11]. The analysis included in the paper concerns solely the space sector.

3. The educational paths before joining ESA

The history of formal cooperation between ESA and Poland started in 1992. That time Poland had cooperation agreement with ESA. 10 years later, in 2002, there was signed prolongation agreement. In 2001 ESA defined dedication program called “Plan for European Cooperating States” PECS. Poland joined this program in 2007. The biggest advantage was possibility to participate in ESA programmes.

That long period from establishing ESA and Poland accession to its structures, does not mean that Poland was not active in space activities, but that, due to political reasons, focused on cooperation with Soviet Union. In in the 70s of last century, Institute of Aviation (ILOT) was developing a metrology rockets with the attitude of near 100km. In 1977 there was established the Space Research Centre of Polish Academy of Sciences (CBK). From that time, many instruments were designed, developed and launched by CBK [1].

The carrier development paths form 1977 till 90s last century, was focused on scientific or engineering development paths. The education path followed the clear scientific path. Engineering activities in institutes were leading with respect to getting the scientific title, which assured the employment. From 2007 the possibility of entering the space sector started to increase. Still the major role was being played by the Scientific Institutes, however on universities, which were closely collaborating with scientific Institutes as ILOT or CBK, students associations were starting to be set.

The background of engineering knowledge was available mainly in scientific institutes, which was due to a limited number of faculties related to space sector. This knowledge was well established as a lot of instruments were design and developed. Participating students started to gain more and more technical knowledge. New projects started to be run in students associations with, not well known at that time, knowledge about ESA standards.

4. Educational paths in the course of 10 years in ESA.

4.1. Technical development

4.1.1. Technical development needs

The needs of education and technical development seem to be a fundamental issue in the space sector. These needs developed in Poland in the last decade, initially much faster than educational opportunities, due to the rigid general rules of conducting and creating new fields of study. Thus, technical education was generally possible at only a few universities in the fields of aviation, aerospace and astronomy. This changed in 2011, when Polish higher education institutions (academic departments) were allowed to autonomously create and define new fields of study, both in terms of educational results and curriculum. Units with the right to habilitation received the possibility of creating new majors independently. Thanks to this amendment, it was possible to set up new faculties of studies in Poland strictly oriented to the issues of space engineering, starting from 2014.[7]

After 10 years, can these needs be considered satisfied? The answer to this question is facilitated by a sectoral survey conducted by the Polish Space Agency [6] on the assessment of knowledge and skills (including technical skills) of graduates of technical faculties, taking up a job in the space sector. And so, according to the survey, most employers indicated mediocre technical preparation. This seems to result not from a low level of studies programme, but rather is attributed to the lack of practice of people admitted to internships and work, as well as lack of information on what tools are used in the enterprises. Respondents answering a question about the specific technical knowledge needed to work in the sector indicated deficiencies in general knowledge of on-orbit operations, methods for analyzing the impact of the environment space environment, and ECSS.

In order to construct advice for students and to learn about the so-called "recipe for success," respondents were asked what factors they consider most important in preparing for a job in the space sector. In their answers, they indicated participation in internships and apprenticeships, workshops, and platforms that foster knowledge exchange.

4.1.2. Technical development possibilities

At the moment (though the data are subject to continuous fluctuation), the possibilities of technical development are guaranteed as first and second degrees of studies in the field of astronomy and aerospace engineering or space engineering. Basic educational pathways refer to the bachelor's or master's degree programmes offered in the country. According to ESPI [2], there are between 20 and 40 degree programmes in Poland that deal with space education.

First and second degree studies in astronomy in Poland have an established high position in the system of Polish higher education. As regarding engineering education, according to the data gathered by POLSA [7] most Polish universities conducting aerospace studies do not have in their educational content subjects directly related to space engineering. The only exception is Warsaw University of Technology, which at second degree studies conducts classes in aerospace specialization, where the educational content to a large extent includes the subject of space engineering. In addition, 2 universities independently and 3 universities of Pomerania jointly lead programs which directly includes the topics of space engineering.

A third Degree Studies should also be mentioned. Two Polish Institutes of the Polish Academy of Sciences provide education at the 3rd degree level. Space Research Center of PAN is the only Polish institution conducting 3rd level studies in the area related to space engineering. They are addressed to expert level - preparing specialists for technical industry. In addition, the M. Kopernik Astronomical Center of the Polish Academy of Sciences conducts third-degree studies in the area of astronomy with elements of astrophysics.

Even taking into account the rather large potential of regular technical education in space techniques and technologies at the disposal of individual Polish (technical) universities, they are not able to build the comprehensive competencies required to operate in the space sector. To this end, the initiative 'Network of Space Universities' in Poland was established. As it was stated in the manifesto of its establishment: 'As individual universities we have a lot of potential to offer, such as unique faculties, modern equipped laboratories or joint research with other universities. However, only as a Network of Space Universities we have a chance to appear in the awareness of world leaders'. Space Universities Network aims primarily at developing Polish science in the area of space research, education in the field of space engineering, realization of joint research and its commercialization [13].

In addition, there are various internships for recent undergraduate and postgraduate students in Polish space companies (for example, organized by Industrial Development Agency). These possibilities form a Polish Space Fellowship Program which is an extended formula of the first internship program: "Development of Human Resources for Space Sector". The aim of the program is to educate and develop young personnel in the space sector and to support knowledge transfer between universities and companies of the space sector.[8]

Thus, answering the first question, from the Polish point of view, the technical background provided by the educational institutions at the current level of development of the Polish industry is sufficient.

4.2. Non-technical development

4.2.1. Need for non- technical skills in space sector

Looking at the structure of space companies based on [4], 78% are small and medium-sized enterprises. The other 14% are large companies, 8% are R&D institutions. The large companies are mainly national companies or subsidiaries of foreign companies. The SMEs are spin-off companies from universities or scientific institutions. Looking at the structure of SMEs, 48% are micro-enterprises, 39% small and 13% medium-sized.

Businesses that develop skills begin to grow. As the number of employees increases, so do the demands on management. Considering that the owners and managers in the companies are engineers with limited management background, this issue becomes more and more important. It must also be taken into account that the space sector needs elevated management skills. The structure of ESA programmes, financial rounds, ministerial meetings, delegate structure and programmatic requirements need to be known and understood not only by engineers but also by management. From this perspective, a new area of management specialization is being sought in the market.

Identification of non-technical skills in the Polish space sector, among young staff was made based on research conducted by the Polish Space Agency [6]. Numerous skill deficiencies of Polish graduates were indicated there, and consisted mainly in lack of project management skills, sense of being a part of the project, teamwork and independent work, lack of communication skills and preparation of technical documentation. From the other side, among students and young graduates interested in the career path in the space sector, there is little interest in fields such as administration, accounting, finance, space law, HR, or media communications and standardization management. Respondents most often cite competency gaps in areas such as expertise and practice. This pattern of responses may suggest the need to look into the content of education at universities in the topics of interest to us.[6]

4.2.2. Need for non- technical skills in space sector

In the European market, there are only few opportunities to develop managerial skills for the space market. The best known is the International Space University. Of course, there are also specialized management courses, but the space industry is not the first choice of graduates. The natural way to develop management personnel is to progress within the company from engineer to project manager and then to middle or high management level.

Subsidiaries of foreign companies play a special role that is not always visible. These large companies entering the market of a new Member State have well-defined corporate structures, management processes and knowledge of business development. Employees have the unique opportunity to acquire this knowledge and know-how as part of their normal work. This gives them the opportunity to acquire practical skills in a relatively short time to become an expert in the growing market. After 10 years of Polish

DOI: 10.5821/conference-9788419184405.075

presence in ESA, there is a visible trend of migration of such specialists from large companies to the SME sector. From the subsidiaries' point of view, this is not a desirable phenomenon, but from the national market's point of view, SMEs gain the knowledge, when a person decides to change employing enterprise.

The need for general space market, space project management and space law knowledge has been identified and space studies have been defined at the business universities, the example of which may be Kozminski University. From 2020, there is a special programme for entrepreneurs, engineers and start-ups. From this point on, the interest in a special educational programme is increasing. The last two editions were in Polish, i.e. aimed at the national market, but the great interest comes from the new member states, which gives confidence that the next editions will be international and in English.

5. Identified deficiencies

From one side, lots of universities offer technological education at a good level, from the other side, the space employers observe lack of basics needed for the work in the space sector. It is probably due to the fact that the education at this stage consists rather of knowledge and not skills transfer and even in that context is transferred without a context, that could be practical for the future work. Such a context is missing especially with respect to the current situation and structure of the Polish space sector and its tight links with ESA projects. The reason for this may be seen also in lack of practical knowledge among the Professors themselves and thus focusing on theoretical knowledge.

As results from the analysis, both based on the study made by POLSA and the content of the curricula of technical studies (of I, II and even III degrees), no space-related skills, or knowledge is taken into account. What is more, the students and post-graduates even don't show the interest in deepening their skills in finance, administration, project management specific to space sector, etc. claiming that they use the standard tools, learning them in practice. Same time, the space employers note the lack of such skills and knowledge as a serious gap in qualifications needed in the work for space sector.

6. Discussion of findings

Though it is proclaimed that in the Polish space sector, universities are one of the strong determinants of the sector's development [9] as they are a source of qualified staff and graduates, and basic knowledge and technologies used by space sector enterprises, and they make available specialized knowledge and infrastructure (laboratories, equipment, studios) to space sector enterprises – some doubts must be raised in this respect.

The deficiencies identified in the analysis lead to the conclusion that the graduates of the I and II degrees of the studies are mainly engineers theoretically prepared for entering the space sector. Though, the theoretical knowledge is often without a context which makes them during the first period unsuitable for the work on space projects.

This, then, leads to the conclusion that while universities have an important role in preparing for the space sector, their role is overestimated as the sole source for acquiring knowledge and skills for that purpose, or they should not be limited to transferring knowledge, but through scientific activity they should shape entrepreneurial attitudes [9]. In cooperation with the space enterprises, sharing the results of research conducted by the university and participation in the creation of new entities should foster the transfer not only of knowledge but also of skills. Also companies can implement joint projects with universities, resulting in improved curricula adequate to market needs, knowledge transfer and development of entrepreneurship.

Another issue worth discussing is how to combine the acquisition of knowledge with the acquisition of skills needed specifically for the space sector. Even just focusing on technical knowledge, it is important to consider whether apprenticeships during studies or, as in the case of the Young Graduate Training at ESA, the acquisition of practical skills only after the completion of the second stage of studies, are an effective way to train personnel for the sector. No doubt YGT forms a great opportunity to gain extensive experience that could open doors to a long-term career within Europe's space sector and is visible as such in Poland[12]

No doubt, that promotion of participation in such ESA education projects would allow increase the participation of Polish teams in the projects [6]. The effect of this would be an increase in the skills and experience of Polish students and young professionals. Alternatively, due to limited capacity of schemes led by ESA in that respect, there should be considered additional /alternative schemes developed both nationally and in the CEE region. The success of the ARP Academy, Kozminski University program on “Entrepreneurship in Space Sector’ and similar initiatives shows the right direction in that field.

An issue that has received increased attention is the lack of non-technological skills as well as the lack of interest in them among students and graduates. This attitude, as already mentioned, is due to the lack of building entrepreneurial attitudes by universities. It is a source of quite a serious risk for the development of the space sector in such countries as Poland or other CEE countries.

7. Conclusions

Having in mind the above analysis the authors identified the main recommended learning paths for the purposes of developing work force suitable for space sector. The sequence of the educational pathways should be as follows and consist of:

- Formal education (technical or other)
- The activity of students within student associations, who implement space projects through dedicated programs
- The role of YGTs who, after a period of training at ESA, return with a set of knowledge to their countries [12]
- The importance of the know-how of the international space market, in particular global companies setting up subsidiaries in new ESA member countries and bringing their experience and knowledge there;
- Dedicated educational programs for people who do not have a formal space education (engineering) but want to develop in various areas of the space industry;

It is highly desirable to create a pan-European space carrier development paths. This need is clearly visible in the new Member States, where the ESA market is not always well understood. This misunderstanding or lack of understanding that ESA is a kind of commercial market where high technical but also management, project management, legal and quality competences are equally important. The authors believe that the ESA can take the leading role in cooperation with national agencies, universities or entrepreneurs. There may already be a solution, such as the ESA Lab, but the scope of activities could be broadened.

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What They Want and What They Need: The New Role of the Jurist in Assisting the Young Space Companies

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Abstract

'New Space' economy is an all-inclusive concept that synthesises a real economic revolution in the space industry. It is characterised by the proliferation of new private actors that operate separately from institutional and governmental structures to seek their place in the market. Their primary objective is to allow low-cost access to space technologies, establishing themselves as one of the major growth engines of the space economy, fostering market competitiveness and technological development. Aware of this key role played by these new actors in the future development of the space industry, this paper adopts an empirical approach in order to obtain relevant information from those directly concerned, with the aim of identifying the crucial factors for their successful integration into the market and for their long-term permanence in the market. We have conducted 50 live interviews with founders and executives of small scale and start-up space companies from all around the world. The interviews are recorded and answers quantified to produce meaningful statistical data. Based on these results, the paper will focus on one of the fundamental problems for new actors. It will analyse these and further present possible inputs that can contribute to the development of the new space economy: The legal and bureaucratic dimensions in which new space companies are born and how they develop. In particular, the paper will explore the need to improve access to legal services from an economic point of view, with a focus on paralegal services; the difficulty shown by those directly concerned in guiding legislation on space activities and the need to rethink the training of lawyers, to make it more adherent to the peculiarities of the new space economy. In conclusion, after a reflection on the impact of the new space economy on the current market dynamics, with the analysis of the area of interest identified above, the paper will infer useful elements to set up some guidance suggestions for the implementation of the pathways of integration and development of young companies operating in the space market. This perspective, includes a reflection on the multidisciplinary dimension involving space activities and the opportunity to stimulate educational programmes with a training offers that reflects the now inevitable need for a less sectoral preparation that allows professionals in the space sector to acquire a more comprehensive view of the dynamics of the market.

Keywords

New Space; New Actors; Legal Services.

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1. Introduction

Space activities present themselves as one of the most promising sectors of the world economy. The growing interest in the space market is articulated in a progressive increase of actors involved and the multiple uses to which outer space lends itself [1].

The story of the 'New Space' economy begins in the late 80s, it is an all-inclusive concept that synthesises a real economic revolution in the space industry. It is characterised by the proliferation of new private actors that operate separately from institutional and governmental structures to seek their place on the market. Their primary objective is to allow low-cost access to space technologies, establishing themselves as one of the major growth engines of the space economy, fostering market competitiveness and technological development [2]. The impact that the new space economy has on the market is extraordinary [3], it is the beating heart of the space industry, the product of the vibrant dynamism of young entrepreneurs determined to push technological progress.

Therefore, one cannot ignore the role of these new players and, consequently, the importance of identifying their needs, in order to build a market in which they find the best opportunities for development.

We believe it is crucial to listen to the voice of those directly concerned, which is why we opted for an empirical approach, doing a series of interviews with the founders of space start-ups [4], with the aim of identifying the difficulties that they encounter in their path, from the entry into the space market, to the possibilities of profitable permanence in it.

In this paper we focused our attention specifically on the legal and bureaucratic dimensions in which new space companies are born and how they develop. From the results of our research, emerged, in particular, three fundamental needs, closely related to the contribution that can offer the figure of the jurist: the critical issues that arise in the communication between entrepreneurs and lawyers and the consequent need to rethink the training of lawyers; the need for improving access to legal services and the difficulty in guiding legislation on space activities.

2. Methodology and Findings

2.1. Data Collected [5]

We conducted online semi-structured interviews with founders of 50 space start-ups, based in 18 countries [6]. The total revenue of all companies represented in the study at the time of interviewing was estimated to be around $76 million, equaling roughly 1.33% of the global investment in space startups.

An interesting data to report is that the participants were mainly males, accounting for 47 or a little over 90% of the interviewees.

With regard to the educational and professional background of the participants, the majority was engineering, accounting for 69% of all participants, or 27 interviewees; business and management for 15%, science for 15% and “any other background” including legal accounted for 1%.

It should also be noted that 59% of the participants were already working in the space industry in some capacity before starting their own companies and that 21% of the interviewees considered themselves “serial entrepreneurs” and were running more than one company at a time.

2.2. Analysis Methods [7]

The chosen method of analysis is based on the observation of the direct source of information, the founders of space start-ups, with the realization of a

questionnaire related to their personal experiences as entrepreneurs that operate within the context of the space industry. These sets of questions covered several topics such as idea formulation, budgeting, investment plans, perspectives on the current state of the industry and background. The interviews were analyzed using qualitative methods attempting to uncover and track patterns regarding the regulation of space activities and their relationship with starting businesses and their finances. In fact, the initial intention of the study was to provide a picture of the average space entrepreneur and advise on business planning for aspiring space founders.
However, certain trends emerged in the interviews that piqued our interests, including information relating to the legal and bureaucratic dimensions in which new space companies are born and how they develop and the role played by the jurist.

2.3. Findings [8]

Based on the results of our research, in order to evaluate the role of the Jurist in the dynamics of the new space economy, we can highlight a series of factors that emerged clearly.
First of all, as we noted in our research on the background of participants, most of them came from a technical background that reduced their ability to read, understand and interpret legal documents and terminology.
Therefore, it was evident that, to ensure the legal compliance of their companies and technologies, they needed the guidance and assistance of a legal expert.
In relation to this premise, we noted, however, that while 74% of participants asked for expert advice when founding their space companies, a mere 19% budgeted for professional legal advice. The main consideration when contacting legal specialists was the cost. Most respondents reflected on the need to recruit or employ people with the right skills, however it has been acknowledged in several interviews that hiring a law firm to assist them in legal initiatives is often costly. This lead us, in particular, to carefully evaluate the potential offered by more flexible paralegal services [9].
Another factor related to the above premise concerns difficulties encountered in the regulatory guidance on space activities [10]. From the analysis of the interviews it became clear that the legal regulation of space companies both nationally and internationally is often frustrating and confusing for their founders and operators.
Finally, a fact that has become clear is that, besides the affordability of legal services, many respondents noted that there is an evident shortage of skills among lawyers, they do not necessarily understand the specifics of the space industry and the legal requirements these starting companies need to comply with. It emerges, in this regard, the need for reflection on the communication between entrepreneurs and lawyers (*rectius*, jurists), as well as on the multidisciplinary dimension involving space activities and the opportunity to stimulate *ad hoc* educational programmes [11].

3. Discussion and results

3.1. Importance of improving access to legal services

A large number of founders of space startups are from STEM backgrounds (69.3%). Out of the 50 companies involved in this research only 10% had budgeted for any legal services. Whereas 10.2% companies admitted during the interview that they faced issues with legal work or legal paperwork.

Legal issues faced by a majority of companies boil down to having a weak foundation in terms of a lack of structured employment contracts, founders agreements and division of equity held by each members of the company. Very often these startups find themselves stuck in a loop as they do not invest in legal help initially due to limited funds and then fail to attain funding from investors due to a lack of structure and accountability in their company. A large number of these startups start off with little to no funding and bank on the investments as they go along. Unfortunately, many are unable to receive the funding needed due to a failure to represent their company to be built on solid foundations, with reliable employees. At the end of the day investors are often seeking to form a partnership with startups which not only have good ideas and ambitions in place but also have paperwork in place to avoid any issues caused due to fundamental errors which lead to the company falling apart and going into loss. Proper legal advice in the developmental years of a startup could be considered crucial to set up relevant documents and create a strong foundation. Space startups often attempt to avoid the heavy legal costs by avoiding to hire legal professionals in the initial stages and assume they should only approach lawyers when a 'real' legal issue arises. Although this might save them some funds initially it can have major repercussions in the future such as lost investors and higher legal fees due to the spiral of issues that they've created by postponing reaching out for advice.

Another issue that arises in space innovation quite frequently is that of patenting and registering the technology created by the companies. The patenting procedure in itself remains imminently time consuming and expensive on top of which the company may face various issues if the innovation was developed in collaboration with other parties. Thus, making it essential to consult legal professionals throughout the innovative process. A way to avoid the exponential costs would be to opt for paralegal services. Whereas document creation services are concerned paralegals are capable, skilled and trained to produce the same quality of work as a solicitor and often charge much lessed for their expertise. Document services may include a variety of contracts, non-disclosure agreements etc. Paralegals may also prove to be beneficial in providing legal advice and signposting where needed while setting up the start up and creating a strong foundation to avoid facing problems in the future.

3.2. Difficulty in guiding legislation on space activities.

Founders have often displayed a lack of legal know-how and inability to gather necessary legal information. Many participants in the study mentioned the time it takes to carry out paperwork as one of the most frustrating aspects of setting up a company and carrying out administrative functions. Since a majority of the participants came from a technical background their ability to understand and interpret legal documents and terminology is limited to quite an extent. Their academic and professional training often varies substantially from what is required of them to secure the legal compliance of their business and technologies. Difficulties may also arise due to the vague nature of many treaties governing space law. Founders admitted to struggling to discern lengthy bureaucratic processes to attain the legal documents and licensing for their technological innovations. As well as with trivial administrative matters including filing taxes, registering a limited company as well as serious legal concerns including international regulations and multilateral agreements. A solution to this would be incorporating legal and business education into STEM university degrees or attending legal informational seminars, which could also help understand legal advice better.

3.3. The Need to rethink the training of Jurists

The field of space activities falls into a multidisciplinary dimension, a mixture of sectoral knowledge (scientific and technological, economic and financial, legal and bureaucratic) that must find their harmony in the current complex economic framework.

The new entrepreneurs have a background mainly oriented to scientific and economic knowledge [12] but they need, in order to guide their activities, to engage with legislation and more specifically bureaucratic aspects of the path that can lead them to gain a position on the market. It is therefore necessary to equip the jurists with the necessary tools to deeply understand the dynamics of the space sector.

It would be useful to act directly on the training of the jurists, inserting specific modules in law school curriculums, focused on the process of entrepreneurship. But extra-curricular programs, specifically focused on the world of space activities, are also an excellent resource. In this regard, there are, on the international scene, valid models of educational programs that are moving in this direction and that should be implemented for the future.

A first example is the Master in Space Institutions and Policies, organized by the Italian Society for the International Organiszation and the Italian Space Agency in collaboration with the Institute of International Legal Studies of the National Research Council [13].

This initiative is geared to forming a new professional figure, in line with the specific needs of the space market, equipped with all the necessary tools to operate in the field, with knowledge not only legal, but also institutional, technical, scientific and socio-economic.

Another good example is the ECSL Summer Course on Space Law and Policy, organised every summer by the European Centre for Space Law in cooperation (ECSL) with a host institution (for example a university) [14]. The course offers to participants intensive lectures and seminars giving them the opportunity to meet not only important university professors but also professionals of the space industry. This is a very relevant aspect, because, although the course is based on the study of the legal and political frameworks that regulate space activities, it offers a comprehensive learning dimension that allows a more complete view of the entrepreneurship phenomenon.

These two examples show the ongoing change in the educational offer in the field of space law and policy, in response to the demand for an academic and professional path that is able to fully understand the phenomenon of space activities.

4. Conclusion

Thanks to our research, specifically related to the phenomenon of New Space economy, we have highlighted the indispensable help of a jurist in the conduct of space activities, emerged from the identification of the primary needs of young entrepreneurs in the legal and bureaucratic sphere, which are the need of improving access to legal services e the

DOI: 10.5821/conference-9788419184405.076

difficulty in guiding legislation on space activities.

We then pointed out the difficulties in the communication between jurist and entrepreneur, determined by the multidisciplinary dimension of the space industry, which requires specific preparation in the field of space law as well as an adequate understanding of the business dynamics and technicalities of the space sector. On the basis of these considerations, we draw the conclusion that it is time to rethink the educational path of jurists which allows a declination of their role with respect to the specific dynamics and requirements of the new space economy, bringing some virtuous examples from the international scene.

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11. see par. 3.1. *Critical communication between entrepreneurs and lawyers. Need to rethink the training of lawyers Improving access to legal services*.

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RITA: A 1U multi-sensor Earth observation payload for the AlainSat-1

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Abstract

The Remote sensing and Interference detector with radiomeTry and vegetation Analysis (RITA) is one of the Remote Sensing payloads selected as winners of the 2nd GRSS Student Grand Challenge in 2019, to fly on board of the 3U AlainSat-1. This CubeSat is being developed by the National Space Science and Technology Center (NSSTC), United Arab Emirates University.

RITA has been designed as an academic mission, which brings together students from different backgrounds in a joint effort to apply very distinct sensors in an Earth Observation mission, fusing their results to obtain higher-accuracy measurements. The main payload used in RITA is a Total Power Radiometer such as the one on board the FSSCat mission. With these radiometric measurements, soil moisture and ice thickness will be obtained. To better characterize the extensive Radio-Frequency Interferences received by EO satellites in protected bands, several RFI Detection and Classification algorithms will be included to generate a worldwide map of RFI. As a novel addition to the ^{3}Cat family of satellites and payloads, a hyper-spectral camera with 25 bands ranging from 600 to 975 nm will be used to obtain several indexes related to vegetation. By linking these measurements with the soil moisture obtained from the MWR, pixel downscaling can be attempted. Finally, a custom-developed LoRa transceiver will be included to provide a multi-level approach to in-situ sensors: On-demand executions of the other payloads will be able to be triggered from ground sensors if necessary, as well as simple reception of other measurements that will complement the ones obtained on the satellite. The antennas for both the MWR and the LoRa experiments have been developed in-house, and will span the entirety of one of the 3U sides of the satellite. In this work, the latest development advances will be presented, together with an updated system overview and information about the operations that will be conducted. Results obtained from the test campaign are also presented in the conference.

Keywords

Microwave Radiometry, Hyper-spectral camera, CubeSat, RFI, LoRa, GRSS

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1. Introduction

Desertification and flooding events are becoming more extreme, and sea level is steadily rising. It is very important to acquire accurate measurements of Essential Climate Variables (ECVs) related to the water cycle such as the soil moisture (SM), and the ocean surface salinity to be able to provide better decisions and informed solutions. For vegetation and water-related measurements, L-band Microwave Radiometry (MWR) is the most accurate technique, and despite the coarse resolution, it can be used by pixel downscaling techniques **[1]**.

Currently, four satellite missions have used L-band MWR payloads to monitor these changes (SMOS **[2]**, AQUARIUS **[3]**, SMAP **[4]** and FSSCat **[5]**), but L-Band measurements are often hindered by Radio Frequency Interference (RFI) **[6]**, corrupting them. Hyper-spectral imagers are used to retrieve soil and vegetation-related measurements with enhanced resolution and resiliency, but are costly and difficult to integrate due to the size of the lenses. The RITA payload will attempt to provide a cost-effective solution by integrating all of the aforementioned instruments in a 1U space inside of a 3U CubeSat (**Figure 1**) using commercial off-the-shelf products to keep the cost low, and to develop it in an academic environment.

Figure 1. Section view of the AlainSat-1, with the MWR and LoRa antennas in ocre, and the RITA payload shown in the foreground.

2. System Design

The RITA payload's processor is based on a System-on-Module (SoM) containing a Zynq-7000 Field-Programmable Gate Array (FPGA) with an embedded ARM Cortex-A9. Through the Interface Board, it controls the hyper-spectral camera and the RF Front-Ends and communicates with the platform. The image sensor is a 2048x1088 CMOS pixel array with an integrated 5x5 Fabry-Pérot filter array that filters to a narrow spectral band from 600 nm to 975 nm (Red to NIR), packaged by Photonfocus AG. On the same board as the FPGA, an Analog Devices 9364 Software-Defined Radio (SDR) is used for MWR, LoRa communications, Radio-Frequency Interference (RFI) detection and S-Band downlink. The overall configuration can be seen in **Figure 2**.

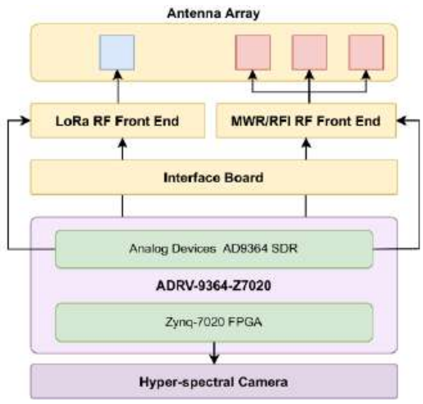

Figure 2 Block diagram of the payload components. In orange, the parts developed in-house. In purple, COTS components.

The payload also integrates a hyper-spectral camera instrument, that is composed of three parts: a 16 mm fixed focal length optics, an in-house manufactured C-mount and internal baffle, and a hyper-spectral image sensor integrated into a set of two PCBs with an additional third board that interfaces with the SoM/FPGA. The combination of the selected lenses and sensor size set a horizontal field-of-view (FoV) of ~38.8º, which matches the radiation pattern of the MWR antenna array.

Table 1: Summary table of the main characteristics of the MWR and Hyper-spectral camera payloads

Hyper-spectral camera	
Ground Sampling Distance (GSD)	206 m
Swath	224,4 km
Focal Length	16 mm
SNR	40,4 dB
Dynamic Range	60 dB
Shutter time range	0,013-349 ms
Pixel resolution	2048x1088
Filter Layout	SSM 5x5
Microwave Radiometer	
Radiation pattern	120^{o} x 31.6^{o}
Swath	317 km
Δ T	100ms
RFI Detection Algorithms	Kurtosis, Spectrogram
Receiver Noise Temperature	237,35 K

The cross-track swath is aligned with the 2048-pixel array, whereas the along-track swath is aligned with the 1088-pixel array, thus translating to a Ground Sample Distance (GSD) of 206 m/px. More information about the Hyper-spectral camera can be found in **Table 1**.

The mount to fix the lenses to the structure has been designed to match the C-type mount diameter and flange with a focal distance of 17.526 mm, and it also incorporates an internal structure to act as a baffle, blocking and reducing the possible internal reflections in the space between the sensor and the lens.

3. Mission Analysis

As a hosted payload, the mission analysis for RITA is tightly coupled with that of the platform and the other payloads. Every experiment in the RITA payload has a different requirement in terms of consumed power and data generated. Due to the high data yield from the hyper-spectral camera, a custom S-Band transmitter has been developed in-house exclusively for the scientific data downlink.

Table 2: Mission analysis focusing on the Hyper-spectral Camera

Limited by download capacity	Picture periodicity	11	s / picture
	Mean CAM oper. power	4.43	W
	CAM acq. allowed	4.5	pic. / orbit
	CAM duty cycle	0.891	% orbit
	Mean CAM power/orbit	39.4	mW / orbit
	Mean S-band power	4.42	W
	S-Band duty cycle	3.1	% orbit
	Mean S-Band power/orbit	135.9	mW / orbit
	Total avg. power/orbit	175.3	mW / orbit
Limited by target areas	Mean time over targets	233	s / orbit
	CAM duty cycle	4.19	% orbit
	CAM acquisitions	21.2	pic. / orbit
	Mean CAM power/orbit	185.3	mW / orbit
	Mean S-Band power/orbit	135.9	mW / orbit
	Total average power/orbit	321.2	mW / orbit
	Data rate required	2296	kbps

The other experiments are similar in terms of power consumption, as they use the same SDR platform, and also produce comparable amounts of data. They have been explored separately to obtain the worst-case scenario for the mission analysis. **Table 2** contains a summary of the different scenarios, with the limiting modes and results in bold type.

3.1. Camera mode

This mode includes only the use of the hyper-spectral camera, allowing for non-overlapping snapshot-based operation and acquisition of the 25 optical bands between 600 and 975~nm. In this acquisition mode both the FPGA and the hyper-spectral camera are powered on. The FPGA is responsible of the high-speed communications with the camera, both for control and for image retrieval, and it needs to be powered on continuously, whereas the hyper-spectral camera can be powered on and off only when needed due to the fast booting times. In terms of data generation, each picture occupies around 2~MB.

3.2. MWR and RFI Detection

The lowest-power operational mode includes only the L-Band MWR and the RFI detection and mitigation algorithms. Information about this mode can be found in **Table** *1*. In this mode, continuous acquisitions can be performed, including a mapping of RFI events over the ground track. It needs to power the FPGA, SDR, and RF Front-End during the entire acquisition. This mode is also the one which generates the smallest amount of data, since the MWR is storing only the total power received, and the calibration values.

3.3. Camera, MWR, and RFI Detection

In this operational mode hyper-spectral imaging, L-band radiometry and RFI detection and mitigation are performed. All the remote sensing instruments are powered on and operate in their nominal mode, taking measurements and simultaneously storing them into the payload memory. This makes this mode the most demanding one in terms of power-consumption and data generation.

3.4. LoRa experiment

The LoRa experiment will communicate with ground sensors using a novel LoRa transceiver implemented in an SDR. Due to the transmission mode, it will consume more power than the other RF experiments. In terms of data generation, it will only store logs and metadata of the transactions with ground sensors, and occasionally the collected scientific data.

3.5. Target Areas

Several target areas have been selected either due to their interest for continued scientific monitoring, or because their brightness makes them suitable for hyper-spectral camera calibration. Each area has an associated operational mode, that allows to, once in orbit, decide which areas the mission will take measures according to the

Table 3: Extract of the target areas planned for the RITA Payload

Area	Operational Mode	Main purpose	Secondary purpose
African Evergreen Forest	MWR+RFI	Vegetation	
Amazonas	CAM+MWR+RFI	Vegetation	Soil moisture
Arabian Sea	CAM+MWR+RFI	Algae Blooms	
Australian Forests East	CAM+MWR+RFI	Vegetation	
Bangladesh	CAM+MWR+RFI	Soil moisture	Vegetation
Borneo	CAM+MWR+RFI	Vegetation	
Cocos Island	CALIBRATION	Calibration	
Gulf Mexico	CAM+MWR+RFI	Oil spills	Algae blooms
Japan and Coast	MWR+RFI	Vegetation	
Lake Erie	CAM+MWR+RFI	Algae blooms	
Netherlands	CAM+MWR+RFI	Soil moisture	
Panama	CAM+MWR+RFI	Oil Spills	
Persian Gulf	CAM+MWR+RFI	Oil Spills	Algae blooms
Sahara Desert	CALIBRATION	Calibration	
Salt Lake City	CAM+MWR+RFI	Soil moisture	
Spain	CAM+MWR+RFI / LORA	Soil Moisture	Vegetation

power and data downlink capacity available. All areas have a scientific purpose associated to them, allowing for flexibility in the acquisition depending on the associated study. The number of target areas and execution times that will finally be executed will depend on both the Data Budget, which depends on the characteristics of the S-Band downlink, and the Power Budget, which depends on the platform. Examples of purposes associated to the areas would be RFI detection over East Asia, where RFI events are very common, soil moisture monitoring over the Amazonas, to monitor vegetation health of one of the largest nature's reservoirs, algae bloom detection over lakes such as Erie or Urmia for human safety, and oil spills detection over the Gulf of Mexico and Panamá. Some of these target areas and their planned operational mode can be seen in **Table 3**.

4. Conclusions

RITA is a miniaturized payload incorporating a number of instruments and devices for soil moisture, vegetation analysis, and RFI detection and monitoring. RITA is currently under development and is scheduled for completion in June 2022. The low-cost approach taken by this payload aims to pave the way for further educational missions in the field of Earth Observation. The project has provided an opportunity for training and engaging multicultural and multidisciplinary student teams. The payload will be launched aboard the AlainSat-1 in Q4 2022.

Acknowledgements

The authors would like to thank the IEEE Geoscience & Remote Sensing Society (GRSS) for their support and funding, and the National Space Science and Technology Center, UAE for sponsoring the satellite bus, launch and operations, and for their technical advice. We would also like to thank Photonfocus AG for their sponsorship of the Hyper-spectral camera. Adrian Perez-Portero (FISDUR2020/105) and Lara Fernandez (FI2019/1183) were supported by grants for recruitment of early-stage research staff of the Agència de Gestió d'Ajuts Universitaris i de Recerca (AGAUR) - Generalitat de Catalunya, Spain.

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Implementation of Space Clubs in Kenya

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Abstract

The Kenya Space Agency Strategic Plan 2020-2025 identified the need for capacity building in infrastructure and human resource as a priority focus area to enable Kenya to tap into the potential of the space industry. With this in mind, several initiatives were put forth to encourage innovation, education and awareness on space related matters. The concept of Space Clubs in Kenya was mooted in 2020 as an education and outreach program that comprises of interactive scientific activities, competitions, events and learning sessions with students from schools around Kenya.

The Space Club initiative is aimed at creating awareness and interest on Geography, Science, Engineering, Arts and Mathematics by educating the next generation of learners on the significance of these subjects in supporting the space industry. It seeks to broaden and enhance the quality of education for Kenyan students and allow them to understand and actively pursue the opportunities that Space related disciplines portend for them. With the support of teachers in primary school (our current target audience) in Kenya, KSA has created an all-rounded program that encompasses a variety of aspects pertaining to space.

The initiative has identified and prioritized four disciplines that are critical for the advancement and growth of Kenya's space sector. These include; Space Systems Engineering, Information Technology and Robotics, Space Science and Astronomy and Earth Observation. The development of the initial learning and training content on these focus areas was concluded in November 2021. The first phase of the project has seen the development of 12 topical student's books and 4 comic books. These materials, which are under review, will be free for use and will be hosted on the Kenya Space Agency website.

Since July 2021, the Space Club team has been hosting a mentorship and training program aligned with these focus disciplines. The Space Club team use of tools such as Cubesat models, water rockets, robotics kits, telescopes and portable planetariums to engage students in hands-on activities.These events have elicited a lot of interest and curiosity amongst students with many expressing interest in Space related careers. The team has noted the significance of student mentorship for the space industry and would recommend that programs of a similar nature be developed, more especially in developing countries, to build a strong foundation for the growth of a vibrant and indigenous Space industry.

Keywords

Education and Outreach, Kenya Space Agency, Space Club,

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Acronyms/Abbreviations

EO	*Earth Observation*
Geo-STEAM	*Geography, Science, Engineering, Arts and Mathematics*
GLOBE	*Global Learning and Observation to Benefit the Environment*
IT	*Information Technology*
KSA	*Kenya Space Agency*
SDG	*Sustainable Development Goals*

1. Introduction

The Kenya Space Agency (KSA) was established on 24th February 2017 with the overall mandate to promote, coordinate and regulate national space related activities in the country. The Kenyan government aspires to utilize space technology and space-derived data for national development.

Through the KSA Strategic Plan 2020-2025 which was officially launched on 21st October, 2020, the agency has prioritized the following key objectives to nurture and growth Kenya's space sector;

- Delivery of Space related Services
- Developing National Space Capability
- Sector coordination and leadership and
- Corporate positioning and sustainability

Developing national space capability encompasses activities related to assessment of Space potential, investments in human capacity, acquisition of critical infrastructure, promotion of research and undertaking education and public awareness.

One of the sub-themes under the development of national space capability as outlined in the strategic plan for 2020-2025 is education and outreach. The agency is involved in a number programmes that seeks to promote Geography, Science, Technology, Engineering, Art and Mathematics (Geo-STEAM) related subjects at all levels of education and training.

By working with students, KSA hopes to inspire and prepare the next generation of learners to exploit Space-related opportunities and create public awakening and awareness on Space applications, services and Space derived products.

2. The Space Club

The Space Club is an educative program established by the KSA Education and Outreach department in September 2020. It involves interactive scientific activities, competitions and learning sessions with students in various learning institutions around the country with the aim of educating the next generation on Geo-STEM and the significance of these subjects in supporting the space industry. The club currently consists of members in primary school and is in the process of being extended to high school and university levels.

The Space Club focuses on FOUR disciplines which that are critical for the advancement and growth of Kenya's space sector. These include:

- Earth observation (EO);
- Space Science and Astronomy;
- Information Technology (IT) & Robotics; and,
- Space Systems Engineering

The four disciplines are structured to promote a varied perspective approach to the use of space. Each sphere of operation highlights numerous specific contributions to the space industry while illustrating a visible link amongst them all.

2.1. Objectives

By imparting knowledge on different elements pertaining to space, the club seeks to broaden and enhance the quality of education for students and therefore allow them to understand and actively pursue the opportunities offered by the Space Sector. The objectives of the Space Club include (but are not limited to):

- Educating children on the fundamental components of space and their relevance to our daily existence.
- Encouraging young individuals to develop interest and skills in Geo-STEAM, earth sciences such as Geographic Information Systems and space science in order to expand the human resource capabilities for the future space industry through exciting, lively and interactive activities.
- Allow students to interact with equipment used in the space industry such as telescopes, cubesat prototypes, space craft models, geospatial images and maps and space science educational applications such as the portable Planetarium.

DOI: 10.5821/conference-9788419184405.078

- Address Sustainable Development Goals such as seeking to ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.
- Provide teachers and educators with the required skills and understanding to explore and facilitate Geo-STEAM related learning in formal and informal settings.
- Creating awareness on the potential of the space sector and its contribution to the livelihood of Kenyans to ensure there is citizen support for other space related activities in the country.

2.2. Structure

The Space Club is organized to operate in both the formal and informal setting. In the formal set-up, this would be in schools and in informal set-up this could be enthusiast activities with an individual or group level.

In the formal set-up, the Space Club team conducts its outreach by establishing and supporting space clubs in learning institutions. The current focus is majorly on Primary school and this will be expanded to Secondary/High schools in the coming years.

In these institutions space club activities are to be carried out during the academic year in the general setting of a regular school club. Each term, club members meet weekly and carry out a club session that may entail learning or carrying out space club activities and experiments. The aim of each session is to learn, investigate and actively engage in space education using a hands-on approach.

The literacy materials known as students' modules are the main tool used for space club activities in a school setting. These books include information on specific topics within the four core disciplines and instructions on how to carry out different activities and experiments.

During the holidays, the KSA Space Club team hosts webinars, camps and fairs. The team runs numerous competitions, challenges and webinars throughout the academic year in collaboration with stakeholders.

Social gatherings of the club such as camps and fairs bring students with similar interests together and allow them to share experiences and information on their different perspectives as space club members

Figure 1: A space camp facilitated by KSA at the Apollo Science Park on February 6th 2021

3. Mentorship Program

The mentorship program was developed under the Space Club program in July 2021 to encourage, guide and inform the aspiring space industry professionals. This program aims to give learners an opportunity to connect with established industry professionals in order to develop an understanding of their career aspirations and industry and give them guidance on relevant paths to achieving their career aspirations.

The Mentorship program which is undertaken monthly or on a need-basis at the KSA offices has 5-15 students being mentored on the different disciplines and core competencies required to work in the Space Industry. Some of the mentorship activities are illustrated in Figure 2-6.

Figure 2: A KSA Geospatial Engineer sharing his insights to a student on Earth Observation

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Figure 3: Students at the KSA headquarters after the inaugural mentorship program event

Figure 4: Students assembling a nanosatellite model at KSA Offices

To increase the impact and beneficiaries of the program, the team expanded the program to school visits in December 2021. The aim is to visit several schools around the country through-out the year.

Figure 5: Students at St. Scholastica School use a water rocket to learn about aerodynamics

Figure 6: Students from St Agnes use a GPS device to geo-locate their positions at their school

4. Literacy materials

In September 2022, the Education and Outreach team embarked on the process of developing content on Space Clubs to be used primary school students. This process entailed the development of content on three topics on each of the four identified core space related disciplines (See Table 1). The twelve workbooks are referred to as student modules.

This process was concluded in November 2021 and this was followed by the development of four comic books aligned to each of the four core disciplines. The content of four out of the twelve workbooks and one comic book is currently under review. The initial batch of student workbooks will be published in April 2022. The remaining eight workbooks and two comics will be reviewed and published by mid this year (2022). The soft copies of all these workbooks and comic books will be hosted at the KSA website and will be freely accessible.

Table 1: List of Student's modules developed by KSA Team

Space Systems Engineering	Space Science and Astronomy	Information Technology & Robotics	Earth Observation
Space Flight	The Solar System	Robotics	Earth Systems
Cube-Satellites	Stars and Constellations	Data Analytics	Remote sensing and GIS
Electronic components	Fundamentals of Space exploration	Programming	Applications of Earth Observation

The student modules contain topical lessons and activities for students and is being reviewed to ensure their suitability for students. Two of the module cover pages are shown in Figure 7 & 8.

Figure 7: Space Flight module for students

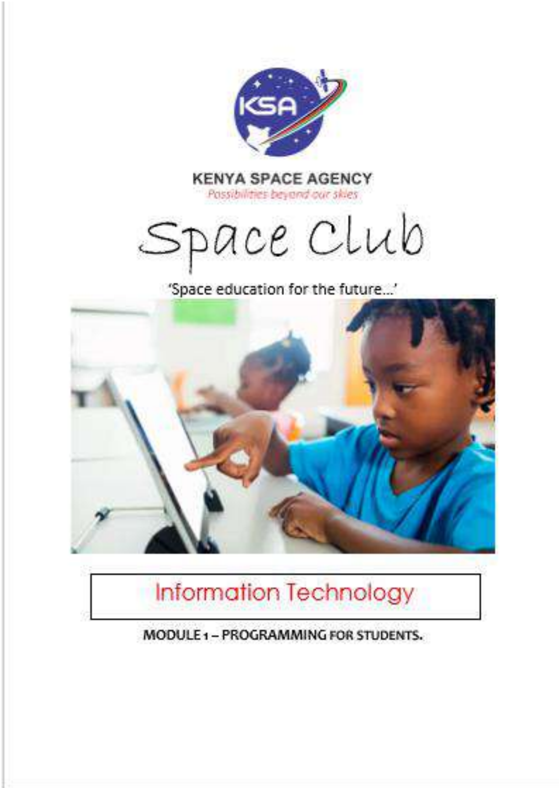

Figure 8: Programming module for Students

The team has also developed topical comics for space education entertainment. The first comic is derived from the Solar System module and features two fictitious students from a village in Maralal, Northern Kenya who use their imagination and knowledge obtained from the Space Club to travel through the Solar System. The cover page of the comic book is shown in Figure 9.

Figure 9: The comic book named Sereya and Manu's Safari to Jupiter cover page

5. Core values

The club encourages certain core values amongst members and patrons which are important traits that can gear them towards greater heights in the space sector and in other spheres of their lives.

These core values have been selected as they have been witnessed amongst the greatest space entrepreneurs, scientists, explorers and professionals and are incorporated in the club's activities. By impressing these values on children, the club seeks to set them on character paths that will aid them in their current and future endeavors.

The core values identified and inculcated to the Space Club members include:

- Ingenuity
- Hard work

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- Discipline
- Respect
- Team Work
- Science Culture

A picture on the core value on science culture with a student is shown in Figure 9.

Figure 9: A student holds a cube satellite model next to the Science Culture core value

6. Discussion

Since its establishment in 2020 the Space Club has interacted with nearly a thousand students in its activities and has collaborated with other organizations and initiatives such as the World Space Week, GLOBE Program, 4K Club and the Young Scientists of Kenya in undertaking joint activities or sharing a common platform.

The KSA Space Club team members have learnt content development, research, teaching and communications skills that have allowed them to enhance the visibility and impact of space education and mentorship.

The Space Club Students modules have enabled KSA to avail relatable and locally developed local content that addresses the gaps in our education system.

Later in the year, the team will commence the development of content for High School and subsequently target post-secondary level.

7. Conclusion

Space education and outreach activities undertaken by KSA with support from our stakeholder has sparked a lot of interest on Geo-STEAM (geography, science, technology, engineering, arts and mathematics) disciplines by students.

The students that have participated in KSA Space Education and Outreach have expressed interest in Space related careers. We are using the Space Clubs for Kenya to grantee the future of the space sector and gradually build up the human resource capacity for the local and global space sector.

The KSA Space Club's aspirations and objectives are aligned to the Sustainable Development Goals (SDG) such as ensuring quality and equitable education opportunities for all and promoting Industry, Innovation and Infrastructure.

Acknowledgements

The achievements of the Space Club have been made possible with the financial and technical support of the Kenya Space Agency under the continued direction of the Acting Director General, Hillary Kipkosgey.

We want to thank all the teachers and students that are piloting the Space Club in their schools.

Figure 10: Group photo of students of St. Scholastica School after a mentorship program

Thermal Characterization Testing of a Robust and Reliable Thermal Knife HDRM (Hold Down and Release Mechanism) for CubeSat Deployables

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Abstract

Thermal knife HDRMs (Hold Down and Release Mechanisms) are commonly used in CubeSats and other small satellites. However, detailed information on proven designs is difficult to find. Design of a robust and reliable mechanism can present technical challenges which may only become apparent during testing, and often only when tested in a space representative environment.

A custom thermal knife HDRM was designed and built for the antenna deployment module of EIRSAT-1 to deploy four coil spring antenna elements, but the same or a similar design could be repurposed quite easily to release a wide range of CubeSat deployables. In this design resistors are used to cut dyneema lines.

For robustness and reliability, the thermal response of the mechanism must be well understood. To reach the melting point of the dyneema (150C) the power dissipated in the resistors must often exceed the maximum rated value. Therefore, choosing the operating current and the burn time is a careful trade-off between ensuring that the resistor reliably cuts the dyneema line and ensuring that the resistor, solder joints, PCB and nearby components are not damaged by the high temperatures. These choices are further complicated by the requirement that the mechanism operates over a range of temperatures.

A thermal vacuum test campaign was carried out to better understand and characterise the thermal behaviour of the EIRSAT-1 mechanism. For the test a model of the mechanism was built with several temperature sensors installed. Two of these sensors were installed directly on the body of the resistors using a thermally conductive epoxy. Burn tests were performed in vacuum at temperatures between -37C and +56C.

The test shows many interesting results including the effect of the dyneema lines on the thermal response, the possibility of desoldering the burn resistors and a comparison between the performance at ambient and vacuum conditions. Finally, a summary is given of the key technical challenges associated with this type of mechanism along with some recommendations to help make future designs more robust and reliable.

Keywords

CubeSat Deployable, EIRSAT-1, Hold Down and Release Mechanism, Thermal Knife

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Acronyms/Abbreviations

ADM	*Antenna Deployment Module*
EGSE	*Electrical Ground Support Equipment*
EIRSAT	*Educational Irish Research Satellite*
HDRM	*Hold Down and Release Mechanism*
UCD	*University College Dublin*
UHMWPE	*Ultra-High Molecular Weight Polyethylene*

1. Introduction

Thermal knife HDRMs (Hold Down and Release Mechanisms) are commonly used in CubeSats and other small satellites to constrain deployables before release on orbit [1, 2]. These mechanisms typically use a tensioned meltline (usually a short piece of fishing line) to hold a spring-actuated deployable element in place. The meltline passes over a heating element which thermally cuts the line when activated, releasing the deployable element. These mechanisms are present in many commercial CubeSat products and therefore have extensive flight heritage. However, detailed information on proven designs is difficult to find in the literature. Design of a robust and reliable thermal knife mechanism using inexpensive components, as may be required in university CubeSat projects, can present technical challenges which may only become apparent during testing, and often only when they are tested in a space representative environment [3], which may not be feasible early in the project.

EIRSAT-1 (Educational Irish Research Satellite 1) [4] is a 2U CubeSat being built by students and staff at UCD (University College Dublin) as part of ESA Education’s “Fly Your Satellite! 2” programme. A custom thermal knife HDRM was designed and built at UCD for this mission. On EIRSAT-1, the HDRM is used in the ADM (Antenna Deployment Module) [5] to deploy four coil spring antenna elements, but the same or a similar design could be repurposed quite easily to release a wide range of CubeSat deployables, including solar panels, large antennas, drag sails and booms. In the ADM mechanism the meltline material is UHMWPE (Ultra High Molecular Weight Polyethylene). Also known as dyneema, this material was chosen mainly for its relatively low melting point of approximately 150C. In this case the heating elements used, mainly for ease of assembly are ordinary through hole thin film resistors (burn resistors).

For robustness and reliability, the thermal response of the mechanism must be well understood. This became apparent during the earliest development tests of the ADM. To reach the melting point of the dyneema the power dissipated in the burn resistors must generally exceed the maximum rating of the component for a short period. Therefore, choosing the operating current and operating time is a careful trade-off between ensuring that the resistor reliably cuts the meltline, and also ensuring that the resistor itself, the solder joints, PCB and any other components nearby are not damaged by the high temperatures involved.

These choices are further complicated by the requirement that the mechanism operates over a wide range of environmental temperatures. The burn resistor must get hot enough to cut the meltlines at the lowest expected operating temperature but not hot enough to cause damage at the highest expected operating temperature. When testing at ambient, heat lost from the resistors by convection may also considerably change the thermal response from that seen in vacuum.

A thermal vacuum test campaign was carried out to better understand and characterise the thermal behaviour of the ADM. The main objectives for this test were

1. to compare the performances of the mechanism in ambient and in vacuum conditions at different operating temperatures,
2. to investigate the effect of the meltlines on the temperature reached by the burn resistors, and
3. to stress test the mechanism by carrying out several burn tests over several thermal cycles.

For the test a special model of the ADM was built with additional PT1000 temperature sensors installed on the module. Two of these sensors were installed directly on the body of the burn resistors using a thermally conductive epoxy. This test was carried out in conjunction with an acceptance test for another satellite subsystem, which dictated the temperature limits. During the test, burns of the resistors were performed in vacuum at temperatures between -37C and +56C. The test shows many interesting results including the effect of the dyneema lines on the thermal response, the possibility of desoldering the burn resistors, and a comparison between ambient and vacuum conditions.

This paper is structured as follows. Section 2 gives a more detailed description of the device under test, its operation and the installed temperature sensors. Section 3 describes the temperature profile used for the TVAC test and when different tests of the mechanism were carried out. Section 4 presents and discusses the main results of the tests. In Section 5 the main conclusions of the work are summarised including a list of the key technical challenges associated with this type of mechanism and recommendations that will help make future designs more robust and reliable.

2. Test Item Description

The ADM has an aluminium base which supports the mechanical components. The main X-shaped PCB which contains the module electronics is mounted in this base. Figure 1 shows a single HDRM. This is replicated four times, at each corner of the module, one for each antenna element. The four antenna elements are attached to spring actuated doors which are held closed by the meltlines. Each mechanism has two meltlines and two burn resistors (primary and secondary) for redundancy, in case one line should break prematurely or one resistor should not operate correctly. Good contact between the lines and the bodies of the resistors is ensured by the tensioning springs and by passing each line over the primary resistor and under the secondary resistor as shown. The dumbbell shape of the burn resistor also helps to centre the meltlines on the body. Each coiled element also presses a switch that detects when it is successfully deployed.

The burn resistors have a nominal value of 82 ohms and are operated at 12V, dissipating a nominal 1.76W. Primary and secondary resistors are operated by independent control chains to maximise redundancy. The module has two 12V inputs. The primary resistors use one of these 12V inputs but are switched on independently by transistors on the module. The secondary resistors are connected in parallel directly to the other 12V input and so must always operate together.

For the characterisation test, four PT1000 temperature sensors were installed on the module. Figure 2 shows two of these viewed from the top of the module. Sensor 1 is attached directly to the top side of X+ secondary burn resistor. Sensor 2 is attached to the underside of the Y+ primary burn resistor. The other two sensors are attached to the underside of the module. Sensor 3 is directly below the X- burn resistors and sensor 4 is attached to the centre of the PCB.

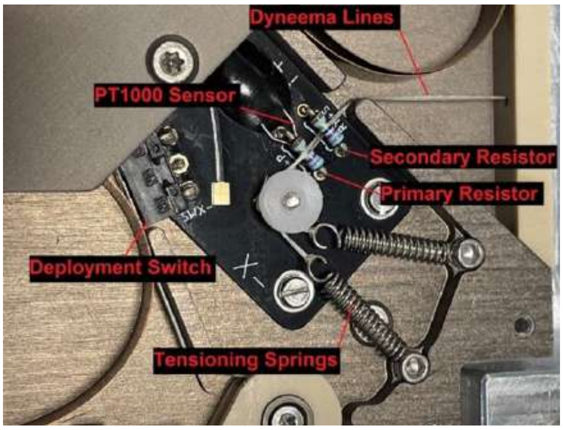

Figure 1. Overview of one HDRM present on the ADM.

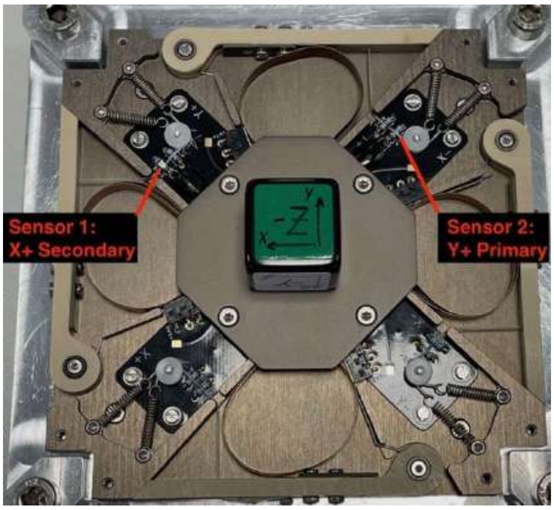

Figure 2. Top view of the ADM before TVAC test showing resistor sensor locations.

3. Test Setup and Test Profile

Before installation of the ADM in the chamber, deployment tests were carried out at ambient, first using the primary burn resistors and, after installation of new meltlines, using the secondary burn resistors. After a final reinstallation of the meltlines the module was installed in the vacuum chamber. During the entire test campaign, based on previous observations at ambient, a duration of 30 seconds was used for all burn tests.

Figure 3 shows the test setup inside the chamber. The primary method of heat transfer to the test item is conduction through a thermal plate mounted in the centre of the chamber. A thermal shroud also surrounds the test item for heat transfer via radiation. For the test, the module was mounted on an aluminum adapter plate. This adapter plate was then bolted to the thermal plate. Copper spacers were used between the adapter and the thermal plate to ensure good conduction while allowing space for the harnesses which were routed from the bottom of the module to pass-throughs on the side of the chamber.

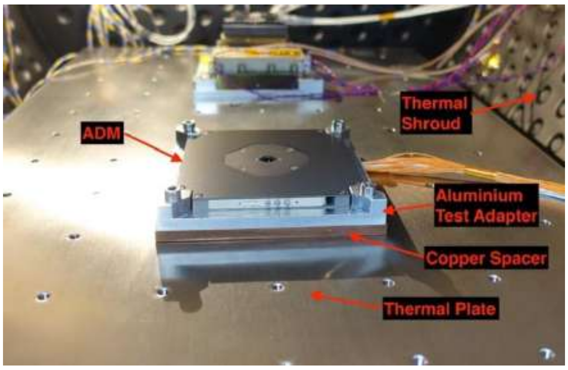

Figure 3. ADM mounted inside the chamber.

On the outside of the chamber the ADM was connected to custom built EGSE which allowed operation of the module and logging of voltages, currents and PT1000 temperatures.

After pump down of the chamber, the temperature profile followed for the test was dictated by the acceptance test of the EIRSAT-1 radio transceiver which took place at the same time. Figure 4 shows the thermal plate temperature and chamber pressure as measured throughout the test. The test consisted of four full cycles from cold to hot and then back to ambient temperature. Also shown in Figure 4 are the times at which burn tests were carried out in the chamber.

As refurbishment of the ADM is not possible without repressurising the chamber, it was only feasible to perform one burn test with meltines installed for each antenna element. It was decided to carry out these tests at the coldest part of the profile, after the first cold dwell period at -40C (burns 1-4 in Fig. 4). After these tests, several more burn tests were completed at different parts of the cycle to assess the response without meltlines and further stress the module. The most burn tests were carried out for the resistors with temperature sensors installed, i.e. the Y+ primary resistor and the X+ secondary resistor (with all secondary resistors operating together). In total 134 burns were carried out, 54 with secondary resistors and 80 with the primary resistors, 57 for Y+, 8 for Y-, 8 for X+, and 7 for X-.

4. Results

4.1. Deployment tests at ambient and after the first cold dwell in vacuum

Table 1 lists the results of deployment tests carried out at ambient before placing the ADM in the chamber and at the end of the first cold dwell in vacuum. During the ambient deployment tests all elements deployed successfully for both primary and secondary resistors. For the primary burn tests, the deployment times for the X- and Y+ elements are longer than the 3-4 seconds that have typically been seen during ambient testing of the module. This is not surprising however and is most likely due to the addition of the temperature sensors on the Y+ resistor and on the PCB directly underneath the X- resistor. The sensors and thermally conductive epoxy reduce the thermal isolation between the resistor bodies and the PCB meaning they are not as effective at cutting the line. Ideally, a non-contact temperature measurement would be used to measure the resistor temperature. However, this is not feasible in the vacuum chamber. For the secondary burn tests at ambient, again the X+ showed a longer than typical deployment time. Again, this is likely due to the addition of the temperature sensor directly on the resistor body.

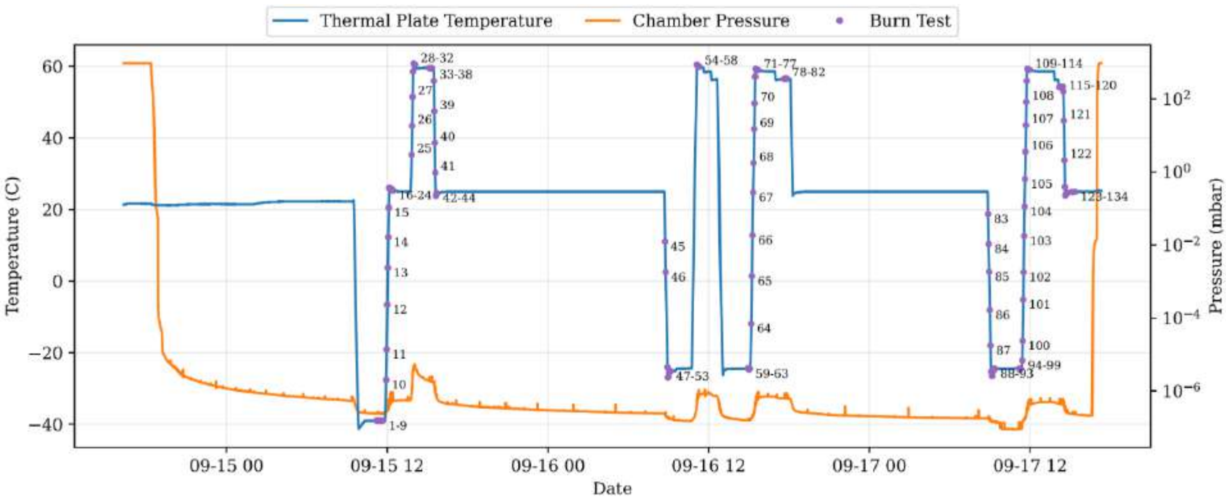

Figure 4. TVAC temperature and pressure profile showing times that burn test were carried out.

In vacuum the first two deployment tests were carried out using the Y+ and Y- primary resistors. Again, the resistor with the sensor installed (Y+) took longer to deploy at 22.8 seconds. The Y- element deployed after 9.9 seconds. The next burn test used the secondary resistors, with X- and X+ elements still stowed. During this test the X- element deployed at 20.1 seconds but the X+ remained stowed after the 30s burn had completed. Again, this is probably due to the reduced performance caused by adding the sensor. Finally, the X+ primary resistor was used to deploy the remaining element, taking 10.3 seconds.

Table 1. Deployment test results at ambient and after first vacuum cold dwell.

Burn Resistor	Average Current (A)	Switch Times (s)			
		Y+	Y-	X+	X-
Ambient					
Y+ Pri.	0.144	6.6	-	-	-
Y- Pri.	0.143	-	4.2	-	-
X+ Pri.	0.144	-	-	4.3	-
X- Pri.	0.144	-	-	-	5.3
Sec.	0.584	3.0	3.7	6.5	3.7
Vacuum First Cold Dwell					
Y+ Pri.	0.145	22.8	-	-	-
Y- Pri.	0.145	-	9.9	-	-
Sec.	0.581	-	-	-	20.1
X+ Pri.	0.145	-	-	10.3	-

4.2. Resistor temperature profiles in ambient and vacuum, with and without meltlines

Figure 5 shows the temperature of the Y+ primary resistor during burns at ambient and after the first cold dwell, both with and without meltlines in place. Here the effect of the dyneema lines on the temperature reached by the burn resistors is clear, seen as the difference between the dashed and solid lines. For the vacuum burn the breaking of the first meltline can be clearly seen, with a change in conduction of heat away from the resistor. Then, approximately 2.5 seconds later the breaking of the second line can be seen, coinciding with the deployment switch activation and again with a change in heat transfer characteristics from the resistor.

Figure 5 also shows a significant difference in performance in vacuum vs. ambient conditions. The rise in temperature of the body of the burn resistors after 30 seconds in vacuum (229C) is 50C greater than that achieved in ambient conditions (179C).

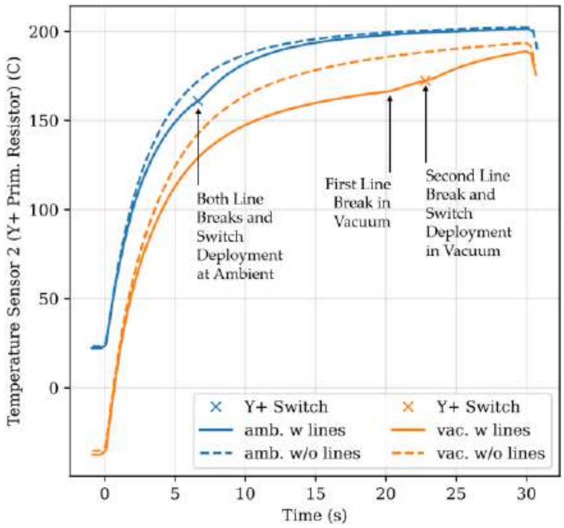

Figure 5. Resistor temperatures during burns in ambient and after vacuum cold dwell.

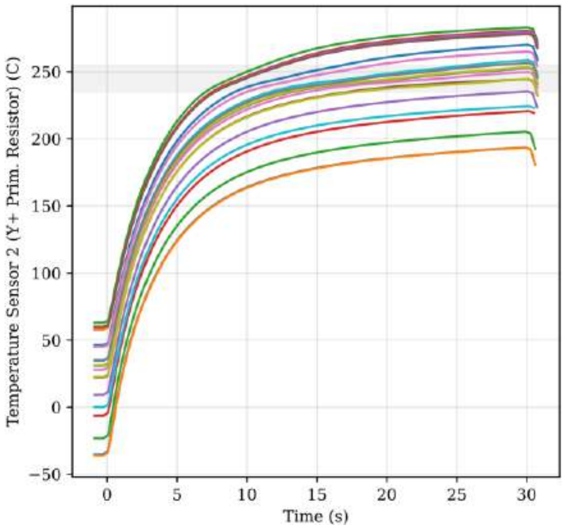

Figure 6. Y+ resistor temperatures during burns over a range of starting temperatures. The region where desoldering occurs is highlighted.

4.3. Performance at high temperatures

After removing the ADM from the chamber, the cover of the module was removed to inspect inside. It was noted that there was a small ball of solder that had adhered to the outer cover. In addition, it was noted that one of the resistors in this area had dropped to a lower height above the PCB surface. This would suggest that during burns at high temperature the resistors legs may get hot enough to reflow the solder joints connecting them to the PCB. The solder used has a melting point of approximately 183C. Figure 6 shows the temperature curves for the first 20 burn tests carried out using the Y+ primary resistor. Here we can clearly see a flattening of the curves when the temperature reaches approximately 250C. This suggests that when the body of the resistor reaches this

DOI: 10.5821/conference-9788419184405.079

temperature the legs are then hot enough to reflow the solder joints and the latent heat required for melting causes the observed flattening of the heating curve.

5. Discussion and Conclusions

During the TVAC test it was shown that this HDRM can operate successfully in vacuum at temperatures between -37C and +56C. The burn resistors were shown to be very robust to repeated operation over this range of temperatures without failure, with a total of 134 burn tests being carried out.

A major technical challenge for this type of HDRM, particularly if using off-the-shelf components is to design it to operate successfully over the full range of possible operating temperatures on orbit. At low temperatures the change in temperature of the resistor during a burn must be maximised so that it breaks the meltlines. To help with this the width of the PCB traces supplying current to the resistors should be as small as possible to maximize the thermal isolation of the resistor bodies while also being able carry the required current. At high temperatures the resistors must not get so hot that they breakdown, reflow the solder joints or damage the PCB or nearby components. In this test it was shown that the components themselves are very robust, but solder reflow is an issue. To avoid this a solder alloy with higher melting point should be used for the resistor joints. One such alloy, approved by ECSS is 10% tin 90% lead. Alternatively, the burn time could be adjusted, or power modulated depending on the ambient temperature, or the resistors could be switched off when notified by the switch of a successful deployment. However, all these solutions add complexity and possible points of failure for what is generally a mission critical mechanism.

During the test It was observed that the delta T achieved by the burn resistors in vacuum is 50C greater than that at ambient, due to the absence of convection. This must be considered early in the design stage as components that work well in ambient will likely face higher extremes of temperature in vacuum.

Finally, the effect of the meltlines in conducting heat away from the burn resistors cannot be neglected, as clearly seen in Fig. 5. Therefore, it is advantageous to use a line with the smallest diameter possible. In the testing phase, the correct number of meltlines should always be installed. A mechanism that operates successfully with a single line may not deploy when a second is installed.

Acknowledgements

The authors acknowledge all students who have contributed to the EIRSAT-1 project. EIRSAT-1 is supported by ESA's Education Office under the FYS! 2 programme. MD, DM, JT, RD and LS acknowledge support from the Irish Research Council under grants GOIPG/2018/2564, GOIPG/2014/453, GOIPG/2014/684, GOIPG/2019/2033 and GOIPG/2017/1525, respectively. GF acknowledges support from a scholarship associated with the UCD Ad Astra fellowship programme. DM, AU, JM and SMcB acknowledge support from Science Foundation Ireland (SFI) under grant 17/CDA/4723. SW acknowledges support from ESA under PRODEX contract number 400012071. JE and JR acknowledge scholarships from the UCD School of Physics. FM acknowledges support from the UCD School of Computer Science. LH acknowledges support from SFI under grant 19/FFP/6777 and support from EU H2020 AHEAD2020 project (grant agreement 871158). This study was supported by ESA's Science Programme under contract 4000104771/ 11/NL/CBi and by ESA's PRODEX Programme under contract number C 4000124425.

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From Soyuz-docking manoeuvres to microalgae cultivation: hands-on training for Master's students

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Abstract

A strong connection between research and teaching at a university is crucial to offer students a unique opportunity to put in practice the concepts taught in theoretical lectures. At the University of Stuttgart, several hands-on training courses have been offered for eight years within the module “Selected hands-on training for space”. Those are adapted to the current research at the Institute of Space Systems. During one semester, students participate in two of the offered courses and are evaluated through an exam or a report. Three ECTS for the space specialization in the aerospace engineering Master are granted after successful completion. The limited places offered are usually filled up in matter of hours and the students’ feedback has been very positive every year. The module includes up to five different courses, depending on the semester. The Life Support Systems seminar is focused on the cultivation of microalgae, linked to the institute’s ISS Experiment photobioreactor PBR@LSR. After learning the basic life support system concepts, the students build and conduct their own microalgae photobioreactor experiment. In the Missions Analysis practical seminar, based on the work of several PhD candidates, the participants learn and put in practice aspects of mission planning with the help of the Astos Solutions software as well as the SPICE toolkit. During the Rendezvous and Docking practical training, students learn about the operation and handling of a spacecraft. Besides theoretical lectures, guided sessions in the simulator allow to put into practice the handling of common complex procedures, audio-visual perception and motor skills. This seminar is linked to the research carried out in the SIMSKILL experiment. In the Earth Remote Sensing seminar, students learn how to handle payload data for Earth observation and their scientific evaluation. The Flying Laptop, a satellite fully built at the institute and launched in 2017, is used for this course. Finally, the research carried out in the field of electrolysers and fuel cells for space applications at the institute prompted the establishment of a training course. After deepening their knowledge on both electrolysers and fuel cells, the students prepare, carry out and evaluate various experiments. This paper presents the different training courses from our institute and their link to the current research.

Keywords

Earth-Observation, Fuel Cell, Hands-on training, Life Support System, Mission Analysis, Soyuz simulator

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Acronyms/Abbreviations

EL	*Electrolyser*
FC	*Fuel Cell*
IRS	*Institute of Space Systems*
LSS	*Life Support System*
PBR	*Photiobioreactor*

1. Introduction

At the Institute of Space Systems (IRS – *Institut für Raumfahrsysteme*) at the University of Stuttgart (Germany) research in several space topics is being conducted, with topics ranging from small satellites to space stations. This research allows to get aerospace students closer to real projects, for example involving them in Bachelor's or Master's Thesis. Besides that, the institute offers yearly a Hands-on Training module. Students enrol for a three ECTS module and participate in two hands-on training seminars. Over the last years five different trainings have been offered looking at Life Support Systems (LSS), mission analysis, rendezvous and docking manoeuvres, Earth observation and Fuel Cells (FC) and Electrolysers (EL). Each training seminar is organized independently, all including some theoretical lectures and practical sessions. The evaluation process is also linked to each hand-on training seminar, with a theoretical and practical exam, a report and/or a presentation.

This paper presents the seminars offered at IRS, looking at the current research, the training goals and development.

2. Hands-on Training on Life Support Systems

2.1. Current research at IRS

The working group "Life Support Systems" at the IRS has been investigating the use of biological components as part of the LSS, to produce oxygen and food for future human space flight missions. Due to their high harvest index and high growth rates, microalgae are interesting for these types of applications. The experiment PBR@LSR on the International Space Station, with the goal of demonstrating long-term stability of the cultivation under space conditions, has been one focus of the working group [1]. Current projects include the use of such systems in the context of planetary habitats, including in situ resource utilization. Besides that, the gained knowledge in this field is being transferred to terrestrial applications

2.2. Training Goals

The goal of the seminar Life Support Systems [2] is to provide students a broad overview of the activities of the research group and *a* first contact with the conduction of biological experiments. The students should learn about the production methods of relevant experiment hardware, setup of experiments and the collection and evaluation of data.

2.3. Training development

After a lecture introducing the state of the art and research on biological LSS, the seminar consists of three parts. First, the students are involved in the production of the illumination unit, by SMD-soldering. This illumination unit allows defining a certain illumination spectrum and an intensity profile to reproduce illumination conditions [3]. This allows students to simulate the solar spectrum and intensity on Mars for their experiments. The second part of the seminar consists on the setup of the experiment, Figure 1, programming the illumination unit to match the given spectrum and intensity profile. In phase three, the students collect data for growth rate and nitrate absorption and made calculations with the acquired data for the dimensioning of a PBR as part of a LSS. This process allows the students to get a full overview of how a dimensioning study would be developed, from experiment hardware production to the conduction and evaluation.

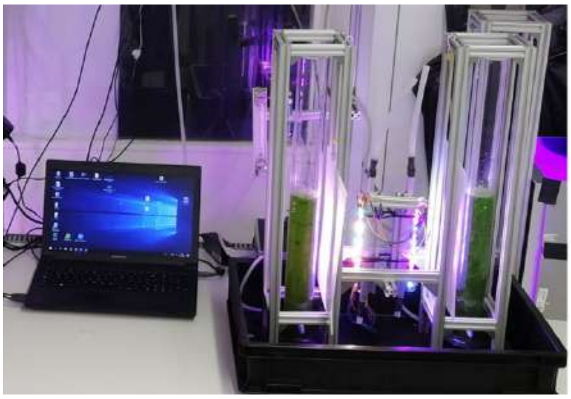

Figure 1: Test stand for the LSS seminar experiments

3. Hands-on Training on Mission Analysis

3.1. Current research at IRS

Multiple research groups at the IRS use the software ASTOS and SPICE. While some utilize SPICE data to explore the dust regime in the Saturnian system, others implement the university satellite within the SPICE framework to establish optical laser downlinks [4]. ASTOS simulations are for example used to prevent star tracker blinding. Using ASTOS, it is also possible to perform automated analysis for future spacecraft constellations in Earth vicinity and around Lagrange points, e.g. for potential sunshades around Sun-Earth Lagrange Point 1 [5].

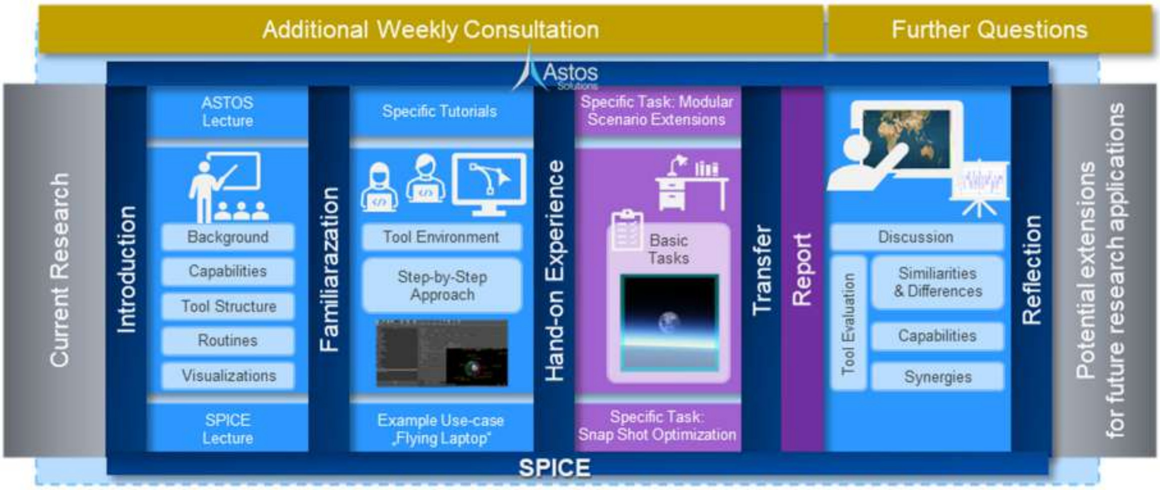

Figure 2. Overview of the Mission Analysis seminar

3.2. Training Goals

The goal of this seminar is to provide hands-on experience with those tools, with respect to typical mission statements. Students should be able to describe the basic functionalities of both programs and their logical frameworks. In addition, they should be able to explain the similarities and differences and justify their preferred tool for potential scenarios. Furthermore, based on their own experience they should be able to judge the user friendliness.

3.3. Training development

The seminar, Figure 2, starts with lectures describing both tools, including some background knowledge and their capabilities. Once the students are familiarized with the tools the hands-on training begins with tutorials. Within these, the students perform a step-by-step approach within the project environment to solve first SPICE / ASTOS tasks. This gained knowledge is then used to carry out the semester task. This is divided into four subtasks: three basic and a more complex one, leaving space for creativity. The phase-specific objective is the efficient interaction with the software tools. For trouble-shooting and further questions, the students can request support via mail or join the weekly consultation. The task processing including a final report of the results achieved is performed in pairs to simulate the future cooperative work environment within project teams and reviews. After report submission, a final meeting to discuss their impressions regarding the similarities, differences, opportunities, capabilities and further aspects of the tools is carried out. This meeting should support the students to reflect and evaluate the lessons learned during the seminar. While the selection of the specific tasks is based on current research at IRS the final team reports are used as baseline for innovative ideas and potential extensions for future research.

4. Hands-on Training on Rendezvous and Docking

4.1. Current research at IRS

During more than a decade a 1:1 scale version of the Soyuz Spacecraft's descent module has been used for the instruction of students at the IRS, Figure 3. Additionally, a mobile version of the simulator and a Virtual Reality concept are being used for both teaching and research. The technical development of such simulator has been supported by the continuous participation of students in both Bachelor's and Master's theses.

Within the framework of the Soyuz Simulator project, a series of research experiments have been run during the last years by developing portable versions of the bigger simulator. SIMSKILL in Antarctica [6], and SIMSKILL-RU [7] and SIMSKILL-VR [8] in the facilities of the IMBP in Moscow, Russia. The goal of this research is to understand how human performance is affected by surrounding stressors such as isolation, confinement and hypoxia (lower oxygen concentration). With the experience gained in such international projects, the seminar at the institute benefits from the developed technologies and training procedures.

4.2. Training Goals

The Soyuz Rendezvous and Docking seminar aims to provide students with both theoretical insight on the Soyuz spacecraft, and more generally on human spaceflight. The seminar starts with four different lectures, some of them taught by a Soyuz Astronaut. The main goal is then to learn how such a spacecraft is flown by getting familiarized with the vehicle's systems and flight behaviour.

DOI: 10.5821/conference-9788419184405.080

Figure 3. Student at the Soyuz Simulator at IRS

4.3. Training development

Students get acquainted with the internal systems of the Soyuz-TMA spacecraft, the mission phases to the ISS and back, the safety procedures to follow, among others. During the practical training, a series of approach and docking scenarios to the ISS are proposed. During the later weeks of the seminar, rendezvous and phasing are taught as well, a mission phase that requires also knowledge on orbital mechanics, being provided in parallel with a theoretical session.

At the end of the seminar, a final check flight and a theoretical test are performed, in order to check the knowledge and piloting performance acquired during the semester.

5. Hands-on Training on Earth Observation

5.1. Current research at IRS

The small satellite Flying Laptop, launched in July 2017, was developed and built by PhD, graduate and undergraduate students at IRS with assistance by industry and research institutions. The project goals include technology demonstration, earth observation and improving the education of students at the University of Stuttgart in the fields of satellite development, integration, test, and operations. The satellite houses a multispectral camera system, a panoramic camera and an AIS Receiver as payload sensors.

To use the payload data of the Flying Laptop, it has to be assembled, processed, stored and provided [9]. The processing includes the calibration and georeferencing of the image data as well as the decoding of the AIS messages. Using georeferencing, the data can be used to determine the satellites attitude to improve its pointing [10].

5.2. Training Goals

Earth observation, using satellites, is a vital part for environmental monitoring, infrastructure and agriculture. Therefore, the main goal of this seminar is that students learn about the capabilities of satellite data, including spatial and spectral information. In addition, students need to look into the boundary conditions of Earth observation, including satellites orbit, its pointing capabilities and downlink capacities. During the training, the students have to define their own observation application. This preferably includes data from the Flying Laptop satellite, but can also use different satellite systems and sensors. The data has to be retrieved and analysed with either self-defined algorithms or common tools like image processing and GIS software.

The grade for the seminar is given by evaluating the results of the students in a 10 to 20 pages report.

5.3. Training development

The Training includes three lectures. The first lecture gives an overview of the Flying Laptop Mission and its payloads. It also introduces boundary conditions, and camera systems. Previous seminar results as well as possible future applications are discussed. The second lecture has its focus on the satellite operations and image processing, looking particularly at sun synchronous orbit, different pointing modes and the automated processing pipeline of the Flying Laptop, among others. The third lecture includes an exercise on how to fetch data from the Flying Laptop satellite and how data is represented in Python. The concept of images being arrays and how to modify them with python code is shown. The metadata of satellite images is observed and evaluated.

The students are then assigned into teams of two and granted access to the Flying Laptop data. As a first step, the application feasible within one semester is defined in consultation with the supervisor. During the semester, the students are free to schedule meetings with the supervisor to discuss the progress, possible issues and obstacles.

Since each student team is defining their own application, the results are diverse. They range from image processing for the Flying Laptop data, to vegetation observation with the Flying Laptop images, to measurements with Sentinel 2 and Sentinel 5P, and ship tracking with the AIS receiver of Flying Laptop. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows an example of the results obtained by a group of students in 2018. The

DOI: 10.5821/conference-9788419184405.080

multispectral camera system of the Flying Laptop, with its green, red and near infrared channels, was used to create NDVI (Normalized Differential Vegetation Index) images. The scale is chosen to show the round, artificially irrigated fields in the desert of Abu Dhabi.

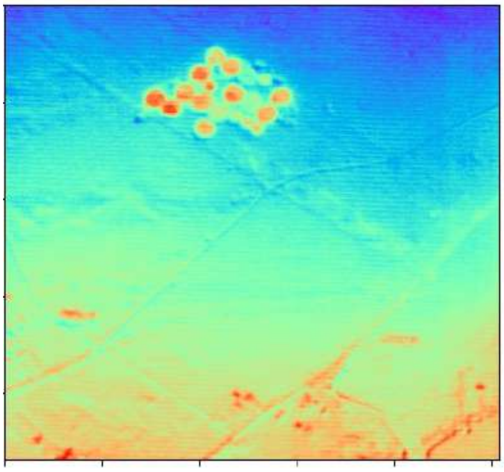

Figure 4: NDVI of fields in the desert of Abu Dhabi

The training has four main tasks: Earth observation (what satellite data can be used for and what the results imply), data processing (how to alter data and apply their own algorithms for their applications), work on a self-defined topic autonomously and self-determined in a team (promoting motivation and creativity) and the written report at the end of the training.

6. Hands-on Training on Fuel Cells and Electrolysis

6.1. Current research at IRS

At the IRS research of Fuel Cells and Electrolysis, looking both at the LSS and energy system has been conducted. The main focus has been on the integration and synergies for human space flight missions [11].

6.2. Training Goals

The hands-on training shall provide a detailed insight into space flight related electrochemical technologies. This kind of practical experience enables deeper understanding of the subject. Students shall learn underlaying principles and the operating principle of fuel cells (FCs) and electrolysers (ELs). Further goals are to demonstrate practical challenges and characterize FCs and ELs by experiment. Furthermore, students shall identify synergistic potentials between those technologies and LSS. In order to consolidate the different lessons learned, students shall individually work on exercises, which focus on the design and dimensioning of FC and EL in the scope of a LSS.

6.3. Training development

An introducing lecture teaches the electrochemical fundamentals and provide an overview on different types and categories depending on electrolyte and utilisation. Moreover, the operating principles are explained and students learn theoretically how to characterize FCs and ELs, and how to determine efficiencies and losses

The following hands-on training, Figure 5, is divided into 4 different workstations, two students team up and pass through each station. Students self-sufficiently set up the circuit and implement measurement technology. Two experiments are designed for the characterisation of a single cell proton exchange membrane electrolyser (PEM-EL). The first one covers determination of a polarisation curve, second one includes determination of energetic and faraday efficiencies. Thereby each group analyses a different operating point. Accordingly, two experiments are designed for the characterisation of a single cell PEMFC, which also include determination of polarisation curve, energetic and faraday efficiency.

Finally, the students write a report including experimental setup, results and analysis. The report also includes two design exercises.

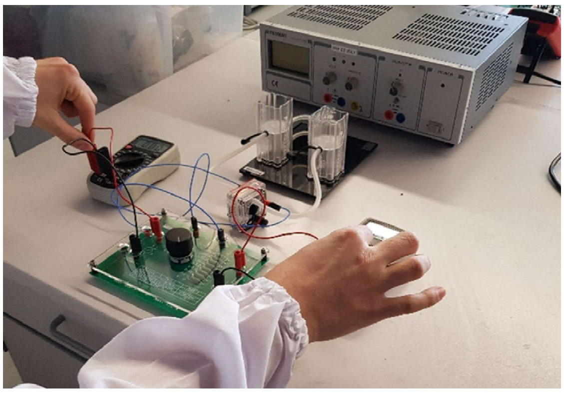

Figure 5. Students carrying out an experiment to determine polarization curve, energetic and faraday efficiency

7. Conclusions

At the Institute of Space Systems – University of Stuttgart research in several space fields has been carried out of decades. As a university institute, it is our goal to prepare the future aerospace engineers. Besides the theoretical courses, a hands-on training module has been offered for several years. This includes seminars in Life Support Systems, Mission Analysis, Rendezvous and Docking

DOI: 10.5821/conference-9788419184405.080

manoeuvres, Earth Observation and Electrolysis and Fuel Cells. This allows students to learn by doing and, at the same time, get closer to the research currently taking place at our institute.

The students are evaluated through practical exercises, reports or presentations. Team work is in most cases also a key element. With that, soft-skills play also an important role in this module.

The feedback from the students has been very positive over the years, encouraging us to continue offering this module every year. The number of offered places is limited and, unfortunately, some students are left out every year.

From the lecturers' point of view, this module offers us the opportunity to get a different point of view in our research, from the fresh view of highly motivated students, which in many cases, then decide to carry out their Master Thesis or further research with us.

Acknowledgements

The development of this Module would not have been possible with the help of all PhD candidates and students, who have contributed to the development of hardware, software and required material. Most of the seminars also required some financial support, which has been provided by the Faculty of Aerospace Engineering of the University of Stuttgart.

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ERMES: Design and preliminary simulations for an autonomous docking manoeuvre

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Abstract

In the last decades, small satellites have played an important role in space missions. Due to their reduced dimension and costs, they became affordable to smaller companies and research laboratories to conduct scientific experiments and technological demonstrations in space. In addition, the number of these satellites has considerably increased due to their wide use in technological, scientific and commercial domains. In this scenario, autonomous architectures, as well as miniaturized mechanical subsystems for small satellites, are continuously investigated.

Experimental Rendezvous in Microgravity Environment Study (ERMES) is a student project that focuses on the simulation of an autonomous docking manoeuvres between two CubeSats mock-ups equipped with miniaturized Guidance Navigation and Control systems and mechanical docking interfaces. ERMES aims to integrate different subsystems for autonomous docking, to increase the Technology Readiness Level and to study possible applications for in-orbit servicing. This paper deals with the design and development of the tests for autonomous docking manoeuvres between two CubeSats mock-ups to be performed in a reduced-gravity environment during a parabolic flight. A Target-Chaser configuration has been selected, where the Chaser is fully active and the Target is cooperative. The Chaser is equipped with a miniaturized cold gas propulsion system with eight thrusters to control its attitude and position; in contrast, the Target has a set of three reaction wheels to control only its attitude. The tested miniaturized mechanical docking interfaces employs a probe-drogue configuration. The most demanding aspect of the development phase will be the dedicated software for the proximity navigation. The reduced-gravity conditions will be achieved during a campaign of parabolic flights thanks to the participation to the European Space Agency "Fly Your Thesis!" programme 2022.

Keywords

Autonomous docking, CubeSats mock-ups, miniaturized systems, parabolic flight, proximity navigation software.

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Nomenclature

p_{sonic}	*Sonic pressure*
p_{total}	*Total pressure*
γ	*Heat capacity ratio of CO_2*
T	*Thrust*
A_{exit}	*Exit Area*

Acronyms/Abbreviations

EKF	*Extended Kalman Filter*
GNC	*Guidance Navigation and Control system*
IMU	*Inertial Measurement Unit*
PWM	*Pulse Width Modulation*
ROS	*Robot Operating System*

1. Introduction

In the last decades, nano and micro class satellites have revolutionized the space industry making the orbital environment accessible to an increasing number of entities, such as industries, research centres or universities, thanks to their manufacturing simplicity and reduce cost and mass. This new opportunity led to a spike of interest towards studies that investigates more reliable and efficient actuation systems, adaptable miniaturized interfaces and software for autonomous satellites.

This paper focuses on autonomous docking manoeuvres between CubeSat mock-ups to be performed in a reduced-gravity environment. Docking manoeuvres can be divided into three major phases: the first phase of fly-around needed to insert the spacecraft in an orbit around the target, an approaching phase to reach it and, finally, a phase of proximity navigation that ends with the actual docking. ERMES interest lies mostly on the last phase since proximity navigation manoeuvres are notoriously difficult and troublesome because mistakes during this phase could easily lead to mission failure. Generally, most docking manoeuvres are not fully automatized and require an astronaut to check the proper progress of the operation, however small satellite-based missions cannot afford human monitoring. Hence, they usually rely almost entirely on sensors and navigations software to properly manoeuvre autonomously. Therefore, efficient navigation and control software, as well as miniaturized subsystems for autonomous small satellites are of great interest.

2. Background

Due to the interest in this kind of application, few space demonstrations of autonomous docking manoeuvres have been performed. For example the Automated Transfer Vehicle (ATV [1]) carried out on multiple occasions rendezvous with the International Space Station (ISS); more recently, the Crew-2 Mission [2] by NASA and SpaceX performed an autonomous docking manoeuvre with the ISS. Regarding small satellites studies it can be cited: Synchronized Position Hold, Engage, Reorient, Experimental Satellites (SPHERES [3]) and Astrobee [4] aboard the ISS, consisting of a series of miniaturized satellites used to test flight formations, rendezvous and autonomy algorithms; the proposed CubeSat Proximity Operations Demonstration (CPOD [5]) mission, led by Tyvak Nano-Satellite Systems, that focused on a docking manoeuvre of two 3U CubeSats.

Finally, the University of Padova has a solid heritage on autonomous docking manoeuvres studies: the Flexible Electromagnetic Leash Docking system (FELDs [6]) studied an electromagnetic soft docking technology; Autonomous Rendezvous Control And Docking Experiment - Reflight 2 (ARCADE-R2 [7]) correctly performed three release operations and two docking procedures between 2-DOF vehicles; the Position and Attitude Control with Magnetic Navigation (PACMAN [8]) investigated the possibility of performing magnetic proximity navigation and attitude control for soft docking manoeuvre.

3. ESA Fly Your Thesis! programme

The *Fly Your Thesis! programme* is an opportunity granted by the European Space Agency's (ESA) Educational Office [9] to groups of university students from all over Europe, to conduct their experiments or technological demonstrations in controlled low-gravity conditions. These conditions are achieved on board of an Airbus A310 Zero-G, operated by Novespace, by performing a parabolic flight. This peculiar trajectory causes a drop of gravity level within the cabin nearing weightlessness that lasts for approximately 22 seconds per parabola. The campaign consists of a series of 3 flights of 30 parabolas each and takes place in Bordeaux.

4. ERMES concept

In this frame, the ERMES experiment aims to design and develop a test for an autonomous docking manoeuvre between two free-flying CubeSat mock-ups equipped with Guidance Navigation and Control (GNC) systems and miniaturized mechanical docking interfaces. This experiment will be performed on a parabolic flight since it has been selected for the ESA *Fly Your Thesis! programme* 2022.

In general, the ERMES experiment aims to prove the feasibility and versatility of autonomous docking manoeuvres between small satellites in view of future space applications and services, including large structures assembly, flight formations management and active space debris removal. Moreover, ERMES collects the heritage of previous projects of the University of Padova on autonomous systems for docking manoeuvre in order to increase even more the technology readiness level. Therefore, it presents itself as a further step towards a more complete on-orbit technological demonstration.

The two mock-ups involved in the manoeuvre (Fig.1) work in a Target-Chaser configuration, in which the Chaser actively performs the manoeuvre to reach the Target, that, in the meanwhile, acts cooperatively by contrasting unwanted attitude disturbances. Moreover, the manoeuvre will be performed autonomously but the mock-ups. The mock-ups will be released by a Release Structure composed of a holding mechanism to support the mock-ups prior to the start of the experiment and a slider to accelerate the Chaser towards the Target.

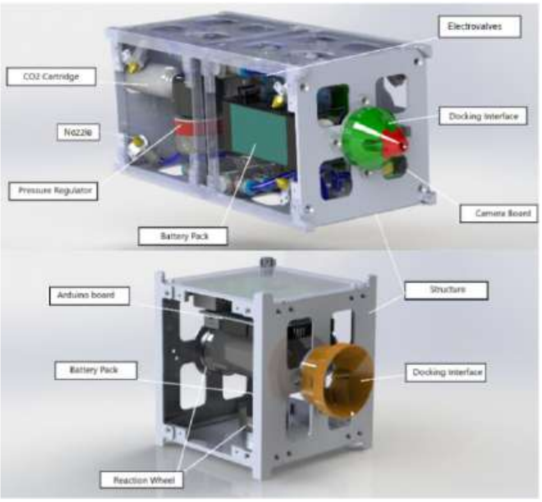

Figure 1. Chaser and Target mock-ups [1]

The Chaser is a 2U CubeSat mock-up (20x10x10cm) and is equipped with a cold gas propulsive system for the position and attitude control and a localization subsystem to recognize the Target. The dedicated proximity navigation software uses the information obtained by the localization subsystem to calculate the path to reach and dock the Target. The Target is a 1U CubeSat mock-up (10x10x10cm) equipped with reaction wheels for attitude control. The mock-ups are equipped with probe-drogue miniaturized docking interfaces [10], composed of an active probe on the Chaser and a passive drogue on the Target.

The connection between these two interfaces is obtained with a physical insertion of the two and then a mechanical interlock thanks to a servo motor that rotates the tip of the probe.

The experiment is composed of four main phases (reported in Fig.2):

1. Release phase: the mock-ups are released from their initial electromagnetic constraints into a free-flying condition.
2. Path planning phase: the Chaser localize the Target and compute the trajectory to reach it.
3. Proximity navigation phase: the Chaser approaches the Target by controlling its velocity and attitude, while the Target maintains the initial alignment.
4. Docking phase: the Chaser actuates the servo motor of the docking interface to lock the two mock-ups together.

After each manoeuvre, an experiment operator relocates both mock-ups for the next parabola.

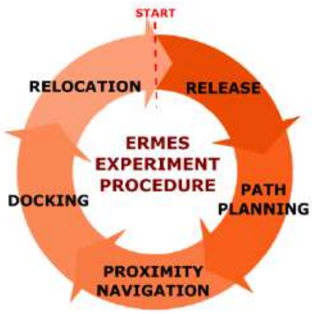

Figure 2. Experiment procedure [2]

5. GNC systems

Due to the complexity of the manoeuvre and the high level of autonomy that the mock-ups have, the main focus in the design and development of ERMES has been dedicated to the GNC systems. The GNC system of each mock-up is composed mainly by the two actuators subsystems and the dedicated software to perform the manoeuvre. Therefore, the following subsections are dedicated to these defining subjects.

5.1. Chaser - Actuators system

As mentioned in the previous section, the Chaser has to follow the trajectory, computed by the proximity navigation software, by actuating its thrusters. In particular, it is equipped with a propulsive system based on expendable CO_2 cartridges and characterized by a set of 8 actively controlled thrusters. The main components of the pneumatic system are: (1) a pressure regulator to set the working pressure at *2.5 bar*; (2) electrovalves, that are

DOI: 10.5821/conference-9788419184405.081

the actual actuators controlled by the on board computer system to vary the flow to the nozzles; (3) the nozzles to accelerate the flow. In particular, the nozzles are simply convergent, instead of a classic convergent-divergent configuration due to the necessity of avoiding supersonic flows since the experiment takes place at standard atmospheric pressure and not in a vacuum chamber. In fact, supersonic flows lead to shock waves, that could cause unwanted increase in pressure in the pneumatic system and, consequently, damages to the system or simply alter its performance. The choice of a convergent solution allows also to model the thrust output linearly with the respect to the pressure set on the regulator. In fact, for pressure higher than *1.8 bar*, the flow exits at a sonic state (Mach number equal to 1) and, therefore, the exit pressure is a function of only the total pressure set on the regulator (Eq.1). Consequently, the thrust is linear too (Eq.2).

$$p_{sonic} = p_{total} * \left({}^{2}/_{\gamma} + 1\right)^{\frac{\gamma}{\gamma-1}} \quad (1)$$

$$T = A_{exit} * p_{total} * \Gamma_{(\gamma)} \quad (2)$$

The thrusters are divided into two groups of four thrusters each that are positioned in two opposite faces; these groups are further divided into couples of thrusters pointing towards the same point (Fig.3). This tilted configuration allows control over both its attitude and position (6 Degree of Freedom). To move or rotate along a single axis four thrusters must be actuated together as shown in Table 1.

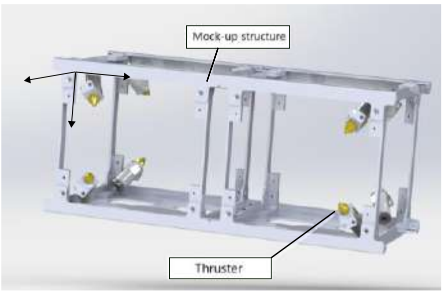

Figure 3. Thrusters configuration [3]

Table 1. Thrusters to be actuated (see Fig. 3) to control the different Degrees of Freedom [1]

	Translation		Rotation	
	+	-	+	-
x	1458	2367	3456	1278
y	1256	3478	1467	2358
z	5678	1234	2468	1357

The electrovalves are controlled with a 30 Hz Pulse Width Modulation (PWM) with 16 steps, that determines the duty cycle of the valve. It is important to highlight that the 16 steps are not related to a standard 4 bit PWM, but a fictitious 8 bit PWM with only 16 possible values instead of 256. The tests of the PWM control were based on a set of laboratory experiments. The pneumatic circuit consisted in a nozzle, an electrovalve, a pressure regulator and a CO_2 cartridge. The pressure regulator guaranteed a constant pressure in the pneumatic system. Thrust data were acquired with a load cell connected to the support plate of the nozzle. Initially, the data acquisition dealt with the 256 steps (8 bit) PWM so that the real trend could be plotted. As expected, the real trend is a sigmoid with the initial values around zero because for low value of duty cycle the electrovalve does not have the time needed to react to the signal and consequently completely open (Fig.4, first graph). Therefore, the number of steps available has been restricted in a way that makes it linear with the respect to the duty cycle values. This choice greatly simplifies the control of the actuators. The simplification lies in the shift from a real sigmoid trend to an ideal linear trend of the thrust. The next step was to find 16 out of 256 values of duty cycle that could approximate a linear trend of the thrust. Finally, this new fictitious 16 steps PWM has been tested by sending random step-like commands of duty cycle to the electrovalves. The resulting trend (Fig.4, second graph) well approximates the desired linearity.

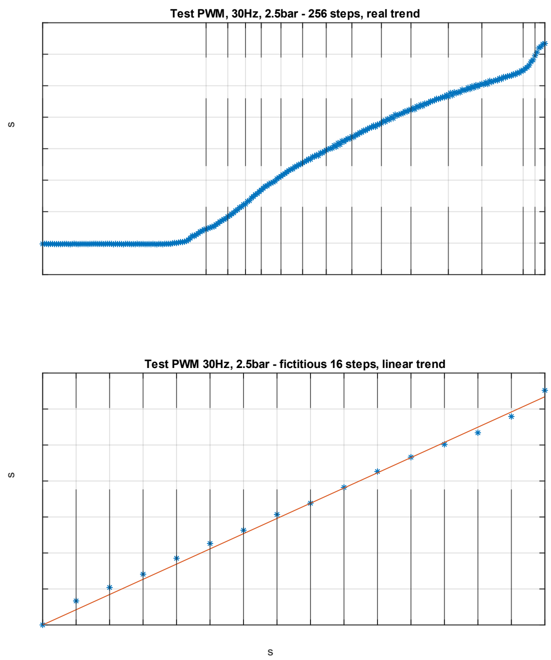

Figure 4. PWM linearization [4]

DOI: 10.5821/conference-9788419184405.081

5.2. Target - Actuators system

Differently to the Chaser, the Target has a simpler actuators system due to the fact that it has to control a lower number of Degree of Freedom (three rotations). It is composed of a set of three reaction wheels along three perpendicular axes (as shown in Fig.5). The reaction wheels are composed of a brushless DC motor and a flywheel to increase the moment of inertia.

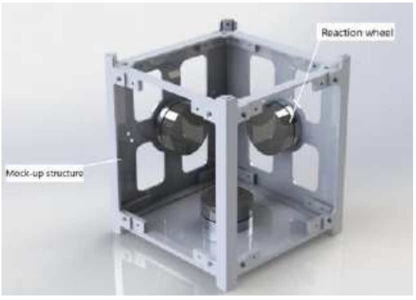

Figure 5. Reaction wheels configuration [5]

Reaction wheels are widely used for attitude control because of their manufacturing and control simplicity. They react by contrasting unwanted disturbances to maintain the angular momentum constant and fixed, but they can be used also to perform attitude manoeuvre. In ERMES both these features can be implemented, in fact the Target can maintain its orientation with the respect to the initial alignment or by pointing towards a specific point during all the manoeuvres. These two different behaviours can be compared to find the best approach in order to successfully dock.

5.3. Proximity Navigation software

The Proximity navigation software is based on three main levels (as shown in Fig.6). It runs thanks to an on-board computer system mounted on the Chaser, that is composed of an Arduino and a Raspberry board as main units and employs a set of sensors for data acquisition. The main sensors are Inertial Measurement Units (IMU), proximity sensors and a camera for the localization system. The on-board computer system includes also a current monitoring module and a sensor to trigger the locking mechanism of the docking interface. Between the two mock-ups, only the Chaser needs to recognize the other and compute the path needed to dock, therefore the Target is equipped with a simpler on-board computer system, that comprehends IMUs and an Arduino board.

The Low Level deals with the control of the actuators and it runs on the Arduino boards. In the Chaser, it receives step-like commands of variation of acceleration along a certain axis from the medium level and actuates properly the thrusters. In particular, it is composed of 6 independent closed-loops Single Input Single Output (SISO) dedicated to a single Degree of Freedom each. The feedback is guaranteed by the IMUs, from which the low-level extracts information about the linear and angular accelerations. As mentioned, the input is a step-like command of acceleration, while the output is the duty cycle of the valve needed to actuate the command. In the Target, the control system is based on a closed-loop control system of the reaction wheels. The output of the control is the velocity of the three actuators to contrast the torques read by the IMUs, which represent once again the feedback of the system.

The Medium Level deals with the recognition of the Target, path calculation and command submission (via UART communication). It runs on the Raspberry board, which has been delivered with an Ubuntu 20.04 Server installation and the Robot Operating System (ROS) Noetic framework [11] [12]. The localization system is based on an AprilTag Detection [13] [14] [15] for the visual perception, then the data acquired from the camera are used to have information regarding the distance and twist of the Chaser with the respect to the Target (that represent the only valid reference point). In particular, the twist is calculated by deriving the pose provided by the computer vision algorithms. The whole software implements two Extended Kalman Filter (EKF), one to fuse sensors that have continuous read (like the IMU) and one to fuse all sensors (IMU and computer vision-based localization). This system, although it is standard, gives us a particular advantage: it allows to differentiate the relative movement between Target and Chaser, discerning if it is caused by a movement of the Target or a movement of the Chaser. Moreover, the estimation is continuous and, for small intervals of time, has a negligible error. The Raspberry can execute 2 types of trajectories: one that adjusts one axis at a time, and another that tries to optimize the quadratic problem of finding a trajectory that requires the minimum amount of fuel. After calculating the trajectory, it sends the relative commands to send o the lower level.

Finally, the High Level is the control level for the experiment operators, in fact it runs on a laptop. It does not interfere with path

DOI: 10.5821/conference-9788419184405.081

computation or data handling; it is needed just to start the manoeuvre by sending the command to initiate the releasing phase.

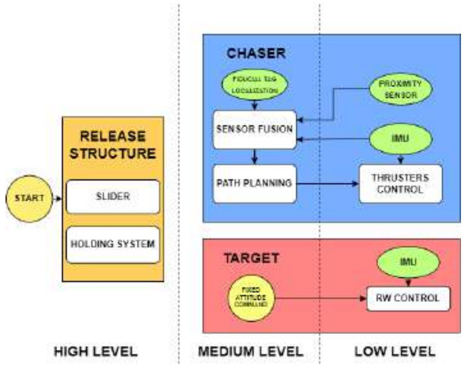

Figure 6. Software architecture [6]

6. Conclusions

ERMES focuses on autonomous docking manoeuvres with miniaturized systems; it investigates not only design solutions and components but also possible software architectures for high reliable autonomous systems. Moreover, it delas with discussing the efficiency and robustness of the software approach in relation to the actual manoeuvres during the parabolic flights. In this paper the design of the main subsystems of the experiment is presented. However, the interest is the integration of all the systems and the simulations of the manoeuvre, initially in the laboratory and then during the campaign. The simulations in the laboratory will be performed on a low-friction table and will concern the validation of two-dimensional docking manoeuvres so that the critical points can be evaluated and eventually corrected in view of the final test in a reduced-gravity environment during the flight campaign.

Acknowledgements

The authors wish to thank the ESA Education Office, that supports the ERMES project as part of the Fly Your Thesis! Programme 2022, and Novespace that owns the Airbus A310 Zero G and operates the flights.

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A story about how the novel ROSPIN Academy programme is bringing space education to the Romanian youth in the pandemic context

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Abstract

Continuous education is the foundation of a sustainable society and ecosystem, and this paper relates the story of one of the most ambitious educational programmes for University students from Romania. The country acceded to the European Space Agency's Convention in 2011, but does not have a dedicated undergraduate programme for space education, although the local space industry is growing and is demanding more skilled professionals. In this context, the Romanian Space Initiative has been organizing the ROSPIN Academy educational programme since the spring of 2021. Currently, each Edition of the Academy has 3 Levels, coordinated with the least busy University periods: Level 1 is an introduction to the space sector (autumn 2021), Level 2 consists of a technical overview of the lifecycle of space missions (spring 2022), and Level 3 offers hands-on experience with industry (summer 2022). Although the curriculum's core is spacecraft engineering, it aims to reflect the sector's interdisciplinarity, so topics such as astronomy, space sustainability and policy are also covered. The Lessons are delivered in English by national and international speakers from industry and academia, ranging from young graduates to experienced professionals. Participants can interact directly with them, in a context that promotes the idea that space is not only for rocket scientists. The participants' interpersonal skills are also trained through exercises and games about space topics, which require them to work together in teams. The accepted participants of the Academy are selected based on their motivation and thinking, relevant knowledge and compatibility with the Academy learning concept. Currently, more than 400 applicants have been accepted in the past or current Editions of ROSPIN Academy. Last but not least, the national outreach achieved through this programme is a key defining value. ROSPIN Academy is present at national level, across industries, and mixes undergraduates and graduates, with focus on the former. This is demonstrated by the evolution of the distribution of the accepted participants, in terms of city, year and field of studies. Due to the organisation's efforts to promote the second Edition nationwide with the support of professors from the biggest STEM Universities, this distribution has clearly evolved. Edition 2 shows a more diversified pool of participants compared to Edition 1, which mostly had active participants with aerospace background from Bucharest. As a result, ROSPIN Academy is uniting the local space communities while educating the next generation of space engineers.

Keywords

Community, Interdisciplinarity, Modern Space Education, Technical and Interpersonal Skills

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Acronyms/Abbreviations

CV	*Curriculum Vitae*
EO	*Earth Observations*
ESA	*European Space Agency*
ESPI	*European Space Policy Institute*
EU	*European Union*
NASA	*National Aeronautics and Space Administration*
NGO	*Non-Governmental Organization*
ROSPIN	*Romanian Space Initiative*
SSEA	*Symposium on Space Educational Activities*
STEM	*Science, Technology, Engineering, and Mathematics*
UPB	*University Politehnica of Bucharest*

1. Introduction

The global space economy is steadily growing, reaching a total of $371 billion in 2020, with the satellite industry having a $271 billion share. At the same time, the commercial and non-profit communications satellite market share has grown from 28% of the satellite industry in 2018 to 48% in 2020, demonstrating a tendency towards a commercially led space industry. In line with the industry growth, the number of spacecraft launched per year has increased from around 500 in 2019 to over 1800 in 2021 [1]. This has been fuelled by the 200 kg class satellite constellations becoming the norm in the industry (SpaceX and OneWeb) [2]. Moreover, there is a sustained effort towards nanosat to microsat scale constellations (like Planet and Spire Global), which is leading to a range of current and future platforms in the 3U-12U size scale for Earth Observation, Internet of Things and Communication [3].

The global space economy growth and the commercialisation of the space market is also reflected at European level, increasing the need of qualified professionals to work in the industry. The EU budget allocated to space activities has increased from €5 billion for the 2007-2013 period to €14.8 billion for the 2021-2027 period. The European space industry is the second largest in the world with 231.000 professionals for an industry worth between €53 - €62 billion. A third of the world's satellites are manufactured in Europe and the EU companies have increased their turnover from €90 billion in 2011 to €161 Billion in 2018. The upstream sector, focused on launchers, generates €8.8 billion and accounts for 6% of the global space industry in terms of job creation (around 43.000 jobs). The downstream market is also increasing as the number of employees has risen by 17% in the past year to 11.600 [4-5]. Overall, ESA estimates that for every Euro spent on space there has been 6 Euros benefit to society as well as job creation [6]. Having high quality and easily accessible space education in Europe is essential to supplying this growing market with a trained workforce as is also highlighted in the ESA Agenda 2025 [7].

A study done by the European Space Policy Institute (ESPI) indicates that all EU, ESA and European Associated Member States have at least one educational programme that has a space-related focus [8]. However, the majority of these programmes are focused in Western Europe (e.g. UK, France, Spain, Italy, Germany and the Netherlands) and they are usually specializations at a Masters or PhD level. As a result, Bachelors programmes represent only 16% of the courses at European level [8], making early access to space education difficult across the continent. This is where a programme like ROSPIN Academy can help deliver space knowledge to Bachelors level audiences, thus leading to an earlier specialization in relevant areas for this industry.

At a national level, Romania has less than 10 space-related programmes, with the main body of courses being offered by the Aerospace Engineering Faculty of the University Politehnica of Bucharest (UPB). However, none of the Bachelors specializations are related to space sciences, with the focus being on aeronautics [9]. At Masters there is a single relevant course on Systems Engineering, taught in Romanian, while at European Level 93% of the Masters level space courses are in English. Overall, the space education currently offered in Romania is limited and lacks diversity due to the limitations of the native language. On the other hand, the local space industry has been growing steadily, especially since Romania joined ESA in 2011. There are now several multinational companies in Romania, producing space software (e.g. Thales, GMV, Deimos) and hardware (e.g. High Performance Structures, Saab), as well as several research institutes (e.g. COMOTI, INCAS) involved in ESA funded projects. However, the vast majority of the graduates joining the national space industry are not formally educated in this field, due to a lack of access to relevant programmes. This is the gap that the Romanian Space Initiative (ROSPIN) is trying to bridge with the educational programme discussed in this paper, namely ROSPIN Academy.

DOI: 10.5821/conference-9788419184405.082

2. The Romanian Space Initiative

The Romanian Space Initiative is a young Non-Governmental Organization (NGO) that came to life thanks to passionate people that converged towards one goal – bringing space closer to the Romanian youth. As such, the ROSPIN vision is to create a united community of individuals with similar aspirations regarding the space sector. To achieve this, ROSPIN is very active in its mission to develop the Romanian Space Ecosystem through various activities, in line with the organization's 3 pillars:

- Pillar #1 – educational programmes
- Pillar #2 – hands-on technical projects
- Pillar #3 – community events

Overall, the ROSPIN team presently counts ~ 70 students and professionals, who are either organizing or participating in ROSPIN projects and activities. In order to succeed in creating a powerful community within a technologically complex and internationally collaborative environment such as the space sector, the ROSPIN culture is strongly rooted in core values such as teamwork, diversity and inclusiveness. Individual fulfilment is another core value, since the volunteer team members need to feel empowered to achieve their personal goals, while also learning and growing within the organization. Ethical behaviour is also central, as well as transparent communication to foster trust in leadership, trust in teams and trust in individuals. Also, pro-actively seeking innovation, adaptability and creativity are other core values. Last but not least, sustainability also has an important role to develop the organization and to ensure the community is educated to venture out in the space sector with an approach that does not jeopardising the future with today's actions.

3. The ROSPIN Academy concept

3.1. Origin and proof of concept

The concept for the educational programme known as ROSPIN Academy (under pillar #1) was born at the end of 2020, in the COVID-19 pandemic. In fact, this emerged as a response to a clearly identified need within ROSPIN's first project (chronologically speaking) – a technical team that aims to develop the first educational CubeSat in Romania (under pillar #2). When endeavouring to expand this team, a significant number of candidates showed substantial interest for such a space project, but lacked the knowledge required to meaningfully contribute.

To address this need, the ROSPIN leadership developed ROSPIN Academy, to make space attractive to Romanian University students, to offer them a context to understand the sector's complexity, depth and level of international collaboration, as well as to prepare them to join this sector. The Academy is based on a series of online Lessons that focus on spacecraft engineering, but some of them also cover higher-level, interdisciplinary topics. Through this, the participants understand the motivations and concerns of the various stakeholders in this growing sector, while also developing their knowledge and professional skills.

The first Academy Edition was delivered in the spring of 2021 with Lessons taking place twice a week, over a 3 months period. It served as a testing ground to see how such a novel programme is received by undergraduate and postgraduate students from Romania. Edition 1 enabled the ROSPIN team to learn valuable lessons, related to the optimum duration and timing of the Academy, the selection process of the participants, the communication and sharing of materials with them, the development of their interpersonal and networking skills, and the communication with the volunteer Speakers.

3.2. Current architecture and curriculum

After Edition 1, the comprehensive curriculum was restructured in 3 Levels of increasing difficulty and technical depth. These Levels are coordinated with the least busy University periods and allow for an annual recurrence, as shown below for the past and current year:

- Edition 1 (spring of 2021)
- Edition 2, Level 1: An introduction to the space sector (autumn of 2021)
- Edition 2, Level 2: Lifecycle of a space mission (spring of 2022)
- Edition 2, Level 3: Practical experience with industry (summer of 2022)
- Edition 3, Level 1 (autumn of 2022)

Level 1 serves as an introduction to various perspectives, covering higher-level topics such as astronomy, the evolution of the space sector (past, present and future), space education and careers, space policy and law, space sustainability, and human spaceflight.

Level 2 continues with specialised spacecraft engineering topics (the core of the Academy), following the lifecycle of space missions: feasibility studies, mission design and systems engineering, orbital mechanics and mission analysis, the various spacecraft subsystems and their design, manufacture, assembly, integration and testing, launch, and operations.

The Lessons within the first two Levels are delivered entirely online and they are based on the restructuring of the original curriculum.

DOI: 10.5821/conference-9788419184405.082

Then Level 3 (proof of concept in 2022) will be designed for the most astute participants and it will take place in person as a 1-week intensive workshop. It will be organised in partnership with relevant stakeholders from the national sector, giving the participating teams the challenge to design, present and defend a space mission in front of a professional jury, hence putting in practice the knowledge and skills acquired in the previous Levels.

3.2.1. Interpersonal skills

In addition to acquiring knowledge by attending the Lessons, the participants also get to interact with each other and practice their interpersonal skills in the process, e.g. communication, critical thinking, debating, networking, etc. This is achieved through various exercises and games (i.e. Energisers) that are based on space topics or scenarios, for example a survival exercise in a scenario of a crew being stranded on the Moon, and having limited resources and tools. The participants are split into smaller groups (usually 5 – 6 per group) and have to work in teams for these Energisers, which are included in the Level 1 and 2 Lessons. The benefits of participating in these Energisers are expected to be reflected through productive teamwork in Level 3. Furthermore, it is likely that Level 3 will include dedicated training to further develop their relevant interpersonal skills, in addition to improving their technical expertise through this practical, hands-on experience.

3.2.2. Diversity of Speakers

A main contribution to the value of ROSPIN Academy is the network of national and international Speakers, ranging from young graduates to world-renowned experts in their fields, reflecting the internationally collaborative and diverse character of the space sector itself. Participants can interact directly with them, in a context that promotes the idea that space is not only for rocket scientists. All the Lessons are delivered in English, training them directly in a necessary language for joining this sector. Table 1 presents the number and diversity of volunteer Speakers who delivered Lessons within the Academy, for each Edition and Level that has been organised. It is also noted that the total number of Speakers from Edition 1 is comparable to that from the 2 Levels of Edition 2, highlighting the effect of restructuring the curriculum, without changing the content that is covered from one Edition to the next.

Table 1. Diversity of ROSPIN Academy Speakers, from one Edition to the next [1]

	National Speakers working in Romania	**National Speakers working abroad**	**International Speakers working abroad**
Edition 1	16	7	8
Edition 2, Level 1	11	2	4
Edition 2, Level 2	3	9	3

The Speakers come in a volunteer capacity, not as direct representatives of their current or past employers. However, it is worth noting these have been professionals from GMV, Thales, ROMSPACE (i.e. national industry), ESA, Deimos, GMV, CGI, Airbus, ClearSpace, Blue Origin (i.e. international industry), and the Universities of Southampton, Stuttgart, Delft and Washington (i.e. academia).

A similar diversity is also envisioned for Level 3, which will aim at gathering professionals from both industry and academia.

3.2.3. Complementary ROSPIN activities

ROSPIN Academy acts as a launch pad for its target group, since the Alumni can then also get involved in other projects and activities of the organization, e.g. technical projects such as the CubeSat team or the Earth Observation (EO) Data team (under pillar #2). Under pillar #3, a notable opportunity will be the Romanian Space Forum (proof of concept in 2022), which will provide an end-to-end experience for the participants, putting them in direct contact with Romanian space stakeholders. Community events are also taking place monthly, fostering networking opportunities. Last but not least, the national effort of ROSPIN is enabled by its Ambassadors, who are Academy Alumni. Their long term goal is to allow ROSPIN to migrate from a single organization model to a group of local space communities with their own dedicated projects and events.

DOI: 10.5821/conference-9788419184405.082

4. Results & discussion

4.1. Target group and eligibility

The direct ROSPIN Academy beneficiaries are the accepted participants, so the programme's success is evaluated from this perspective. The target group are undergraduate University students, although some postgraduate and PhD students are also accepted, as long as the majority of accepted participants is represented by undergraduates. This target has the aim of reaching an audience at an early development stage in their careers, to inspire them to consider building a career in space.

Accepted participants from Edition 1 have not been considered for Levels 1 and 2 of Edition 2, since the curriculum's content has remained substantially the same, and so the availability of slots is maximised for those who have not had this opportunity before. However, those with Certificates of Participation from Edition 1 will be considered for Level 3 of Edition 2, as this will occur for the first time in 2022.

Furthermore, students from both STEM and non-STEM Universities have been accepted to the introductory Level 1, whereas only students from STEM Universities have been considered for Levels 2 and 3. Also, candidates do not need to have participated in Level 1 to be considered for Level 2, but this is advisable. Similarly as before, Edition 2 participants will require a Certificate of Participation at least from Level 2, to be considered for Level 3.

4.2. Selection process and earning Certificates of Participation

Based on the lessons learned in Edition 1, the ROSPIN team has refined the application and selection process of the participants. Currently, an applicant does not need to provide a CV or a cover letter, but instead has to submit a comprehensive application form. The selection is based on evaluating 3 strengths of the application: their motivation & thinking, their relevant knowledge, and their compatibility with the Academy learning concept.

Until now, more than 400 applicants have been accepted in the past or current Editions and Levels, and hence have been given an opportunity to learn more about the space sector and spacecraft engineering.

Currently, Certificates of Participation are awarded to the most dedicated participants, solely based on their attendance. These Certificates are provided only to participants who attended at least half of the Lessons for a given Edition or Level.

4.3. Increasing national outreach

Another defining value for ROSPIN Academy is the national outreach achieved through the accepted participants, which directly contributes to ROSPIN's overall mission and vision. After dedicated efforts to promote Edition 2 nationwide, with the support of professors from the biggest STEM Universities across the country, the national distribution of accepted participants has seen a clear growth in Edition 2 compared to Edition 1. This is also reflected through the associated acceptance rate of participants:

- ~ 95% for Edition 1, by accepting 144 participants
- 50% for Level 1 (Edition 2), accepting 175 participants from 340+ individual applications
- 75% for Level 2 (Edition 2), accepting 135 participants from 175+ individual applications

Overall statistics are shown in Figures 1a, 1b and 1c, about the distribution of more than 400 accepted participants in ROSPIN Academy.

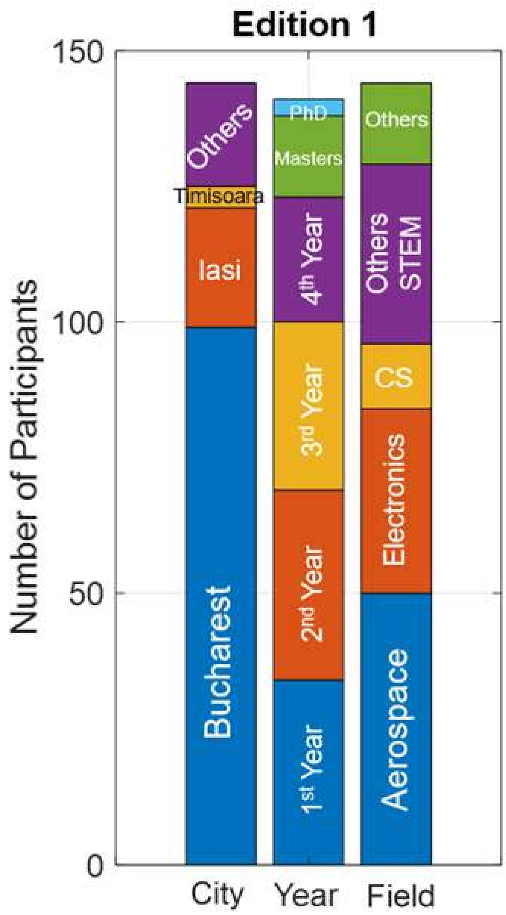

Figure 1a. Distribution of accepted participants in Edition 1

DOI: 10.5821/conference-9788419184405.082

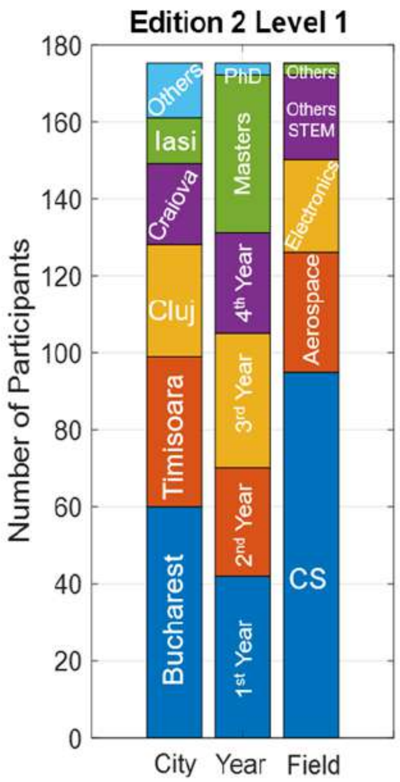

Figure 1b. Distribution of accepted participants in Edition 2 – Level 1

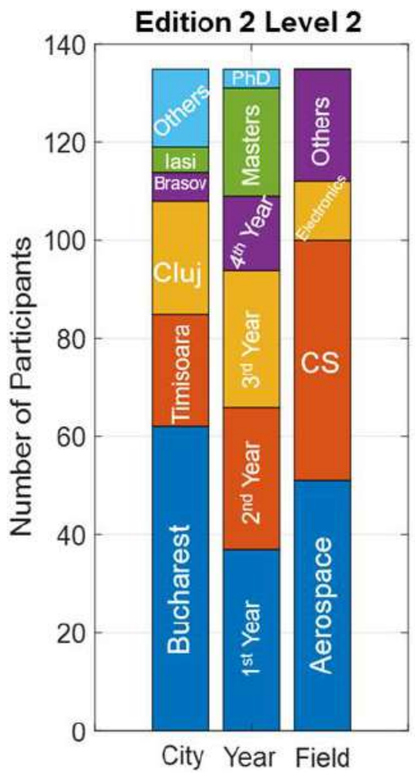

Figure 1c. Distribution of accepted participants in Edition 2 – Level 2

5. Conclusions

Continuous education is the foundation of any sustainable society, and this paper described one of the most ambitious educational programmes in Romania. ROSPIN Academy has been offering high quality space education since early 2021, and the accepted participants have an end-to-end educational journey. The ROSPIN team has grown alongside them, and the programme has grown substantially in record time. In the future, the Academy will continue to take place recurrently. It will also keep fostering relationships with stakeholders, improve the participants' engagement, enable even more national outreach, and improve the knowledge checking of its participants. Also, in 2022 a novel workshop will be integrated in the Academy concept through Level 3, continuing to prove the value of this programme in the context of a growing space sector. The continuation of ROSPIN Academy will also keep raising space awareness in Romania and continue to expand opportunities, in line with ROSPIN's mission and vision.

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TEASPOON: a once in a lifetime opportunity to Sedna

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Abstract

In the challenge of unveiling the enigmas that still surround the origin and early evolution of the Solar System, the study of trans-Neptunian objects plays a crucial role. For this purpose, Sedna is probably the most intriguing candidate for a space mission. A better understanding of its highly elliptical orbit could improve our knowledge of the evolution of the Solar System and could potentially lead to the discovery of an unknown planet. Moreover, the planetoid is expected to host a significant amount of tholins and probably a subsurface ocean of liquid water, making the analysis of its composition extremely interesting. In 2076, Sedna will reach its minimum distance of 76 AU from the Sun. This is a scientific opportunity that will not happen again in the next 11400 years.

Exploiting this instance, TransnEptuniAn Sedna PrObe for Outer exploratioN (TEASPOON) is a mission proposal to send a probe to Sedna, featuring a payload suite to perform an optical characterization, study the particle environment and conduct a radio-science experiment. Moreover, the long travel will be an opportunity to explore the Kuiper Belt looking for observations or, hopefully, discover new objects. The harsh environment, characterized by objects with unknown trajectories, requires Collision Avoidance strategies, while long-term radiation exposition demands electronics shielding and the preference for rad-hard components. More generally, the 77 AU distance and 30 years duration of the mission makes the design even more demanding. Therefore, solving those challenges would inaugurate a new generation of space missions to the edges of the Solar System and beyond.

This proposal has been developed in the framework of a Space Mission Analysis and Design course by a team of students at the master level in Space Engineering at Politecnico di Milano. A concurrent engineering approach has been followed, leading the study through its phase 0/A. This enabled them to practice in actual working conditions of a space agency's mission study, and underlined the importance of this kind of experience at a Master's level course.

Keywords
Concurrent engineering, mission proposal, Sedna, Solar System exploration, Trans-Neptunian Objects

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Acronyms/Abbreviations

ADCS	*Attitude Determination and Control System*
EPS	*Electrical Power System*
OBDH	*On Board Data Handling*
PS	*Propulsion System*
RTG	*Radioisotope Thermoelectric Generator*
STR	*Structure*
TCS	*Thermal Control System*
TMTC	*Telecommunication and Telecommand System*

1. Introduction

The objective of this paper is to present a proposal of an interplanetary science mission, developed entirely by ten Master's level students. The study was carried on in the context of the *Space Mission Analysis and Design* course of the MSc in Space Engineering of Politecnico di Milano, with a total duration of 6 months. The target of the study was to develop a mission to advance the knowledge and exploration of the Trans-Neptunian Objects, with the following given high-level requirements:

- Observation data of the composition and shape shall be obtained with at least $O(10^2)\ m$ in resolution.
- The system shall be capable to detect moons, if present.
- The spacecraft class should be $< 400\ kg$.
- Launch shall not occur earlier than 2027.

A Concurrent Design approach was followed, with each student holding the responsibility of one area of design. The entire project was developed adhering to ESA's ECSS guidelines and margin philosophy, to better simulate the experience of working at a real Space Mission proposal at ESA.

2. Scientific objectives

The Kuiper Belt is a region of space extending beyond the orbit of Neptune, whose mysteries are still to be unraveled. It collects a huge number of minor bodies and dwarf planets offering an intriguing look into the formation of the Solar System. Most of these bodies are composed of frozen volatiles and an organic compound called *tholin,* but a much better physical characterisation is deemed necessary. To date, the New Horizons mission to Pluto is the only one that targeted a Kuiper Belt object, but the interest towards this region is getting more and more traction.

2.1. Why Sedna?

A preliminary screening is performed to select the mission target. Smaller objects are discarded, and further relevance is given to the hypothetical surface composition and the presence of natural satellites. Lastly, feasibility of the proposal is accounted for. The outcome of this survey is the selected target: Sedna. It is a large planetoid, very enigmatic as neither its mass nor dimensions have been measured with an acceptable accuracy [1]. Models of internal heating via radioactive decay suggest that Sedna might be supporting a subsurface ocean of liquid water [2], its surface homogeneously coated by tholin [3], and its apparently long rotation period could be justified by the presence of unidentified natural satellites [4]. Thus, the scientific interest for this planetoid is unobjectionable.

Its main attractive feature is the extremely elongated orbit: with an eccentricity $e = 0.849$, it has an estimated perihelion of $76\ AU$ and an aphelion of $937\ AU$. A visual representation of its orbit is presented in Figure 1.

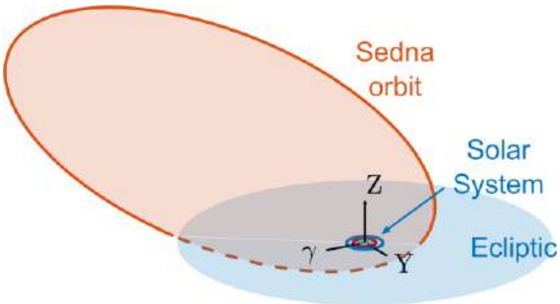

Figure 1. Sedna orbit

Such an eccentric and extreme orbit implies a tremendously long orbital period of about 11400 years, the second longest one of any known objects in the Solar System.

Due to its formation by accretion of smaller bodies, Sedna's initial orbit is assumed to have been almost circular. Therefore, the gravitational interaction with another body must have tugged it into its current singular orbit. Many theories have been proposed, but perhaps the most fascinating one is the presence of an unseen planet beyond the Kuiper Belt, the cryptic Planet X [5]. As of 2020, Sedna was at approximately $85\ AU$ from the Sun and will reach its perihelion around 2076. Thus, the window of time available to prepare an explorative mission towards this peculiar body is exceedingly narrow and cannot be missed out. This scientific opportunity is unique

DOI: 10.5821/conference-9788419184405.083

to better understand the Solar System evolution and investigate a planetoid that will not be available to human reach for thousands of years.

2.2. A rewarding challenge

Besides its scientific importance, the manifold complexity represented by planning and operation adds up to the reasons that make such a mission of absolute interest. Following the successes by *Voyager* and *New Horizons*, time is ripe for further raising the bar.
A mission to the boundaries of the Solar System would practice the capability of managing a decades-long effort and push the technological development towards safer and more reliable solutions, all at once: the expedition would turn into a rehearsal which paves the way for the future of interplanetary missions. Paramount importance should be given to all the aspects related to robustness and integrity, considering the long-lasting journey and the presence of hazardous elements (threat of collisions and radiation exposure among the others).

2.3. Payloads and experiments

A payload suite is selected to comply with the scientific objectives outlined in §2.1. The full list, together with their usage, is shown in Table 1.

Table 1. Payload suite

Payload	Usage/objective
Pan Camera	Imaging of Sedna (surface topography, planet radius).
Near Infrared Spectrometer	Composition of Sedna's atmosphere and surface.
Energetic Particle Spectrometer	Characterisation of interplanetary and interstellar media; composition of Sedna's atmosphere.
Dust Flux Monitor	Analysis of the dust flux in the interstellar medium, Kuiper Belt and Sedna's proximity.
Solar Wind Instrument	Interaction between Solar Wind and Sedna's atmosphere; characterisation of the Heliopause (extended mission).
Telescope	Imaging of Sedna; survey of the Kuiper Belt (discovery of new objects); assessment of collision avoidance manoeuvres.
Radio-science Experiment	Search for Sedna's atmosphere (occultation); gravimetric analysis.

3. Mission Design

3.1. Mission timeline

The mission analysis foresees the launch on 12/05/2033, followed by gravity assist around Jupiter on 05/09/2034, and the closest approach to Sedna on 24/06/2059, with a total duration of 26 years and the possibility to further extend it, if applicable. As the scientific operations at Sedna end, the spacecraft will transmit all the data to Earth over the next 1.5 years. The timeline and the trajectory are shown in Figure 5 and Figure 2, respectively.

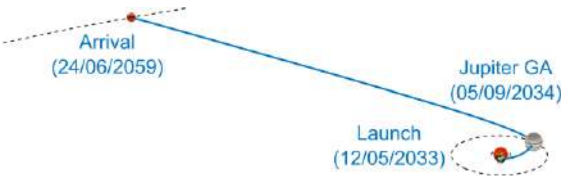

Figure 2. Baseline trajectory

3.2. TEASPOON configuration

The configuration obtained through the process up to phase A is presented in Figure 3 and Figure 4. From Figure 3, the 3-metres-diameter High Gain Antenna can be noticed, which has been designed to communicate with Earth up to $77\ AU$ and beyond (reducing the data rate).
The power source for the mission is represented by the RTG, placed at the opposite face with respect to the payloads, to reduce radiations; moreover, the tank between RTG and payloads mitigates the radiation and thermal fluxes whilst the fuel is kept warm.
Figure 3 introduces the concept of MLI and louvres for thermal control.

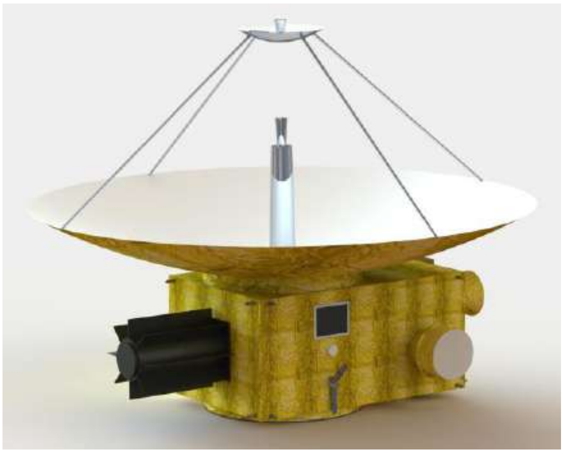

Figure 3. TEASPOON external configuration

The ADCS thrusters are placed at the corners of the lateral surfaces, while reaction wheels allow fine pointing. Attitude determination is

DOI: 10.5821/conference-9788419184405.083

carried out by means of two star trackers. The orbital manoeuvres are performed, instead, by 4 thrusters aligned with the spacecraft centre of mass. Within the structural cylinder, a spherical hydrazine-based fuel tank is characterised by a blow-down pressurising system.
The On-Board Data Handling components are collocated in the payload section, due to both limited radiation from the RTG and space efficiency.
A structural analysis has been performed to assess the feasibility of such a configuration, which has the most critical elements in the RTG weight, its cantilevered position and payload section distribution.

Figure 4. TEASPOON internal configuration

3.3. Mass Budget and Mass Breakdown

The TEASPOON mass budget, including total dry & total wet mass at launch, is computed following the ESA margin policy [6]. Each subsystem accounts for Design Maturity Mass Margin and then the System Level Mass Margin (equivalent to 20% of the nominal dry mass – $47\ kg$ in this analysis) is included. The details about the total mass budget and its breakdown are provided in Table 2 and Table 3.

Table 2. Mass Breakdown

	Dry mass (w/o margin)	Margin		Total	
	[kg]	%	[kg]	[kg]	%
STR	29.30	10	2.93	32.2	13.71
EPS	33.18	7.3	2.42	35.6	15.15
OBDH	6.20	5	0.31	6.5	2.77
TMTC	53.57	10	5.4	58.9	25.07
ADCS	32.36	5.1	1.64	34.0	14.48
TCS	4.50	25	1.13	5.6	2.39
PS	33.94	5	1.7	35.6	15.16
Payload	25.20	5	1.26	26.5	11.26
Nominal dry				**235.0 kg**	

The harness mass is estimated to be the 5% of the nominal dry (equivalent to $11.7\ kg$). It is worth to notice that the total wet mass is below the constraint of $400\ kg$. Finally, the total mass at launch is computed by considering also the selected apogee kick engine ($2137.0\ kg$ [7]), the Launch Vehicle Adapter and Payload Separation Ring system ($84.3\ kg$ [8]).

Table 3. TEASPOON Mass budget

Total dry [kg]	Fluids [kg]	Total wet [kg]	Total launch [kg]
293.8	57.5	351.2	2572.5

3.4. Power Budget

Accounting for the ESA margin policy [6], the power consumption of each subsystem is retrieved as the output of the subsystem's preliminary sizing and reported in Table 4.

Table 4. TEASPOON Power Budget

Subsystems	Power [W]	Margin [%]	Margined [W]
Payload	4.1	5	4.3
TMTC	51.3	10	56.4
ADCS	25.8	5	27.1
PS	15.9	5	16.7
OBDH	20	5	21
TCS	15	25	18.8
EPS	10.3	10	11.3

Finally, combining these values with the estimated activity time and levels, the power consumption of each mode is computed and illustrated in Table 5.

Table 5. Spacecraft Modes Power Budget

Power/Modes	Average* [W]	Maximum* [W]
Commissioning	63.1	75.5
Check	61.6	143.8
Observation	105.1	164.8
Cruise	75.2	164.8
Hibernation	47.3	164.8
Safe	68.6	143.8
Encounter	128.9	164.8
Scan	71.4	91.5

*20% ESA system-level margin included.

DOI: 10.5821/conference-9788419184405.083

3.5. Link Design

The measure of link reliability is naturally declined on a parameter called link margin. The huge distance reached during the Sedna flyby directly entails the difficulty to maintain the link margin larger than the $3\ dB$ margin indicated by ESA. In fact, the data rate must be drastically reduced to guarantee a safe connection: this fact obliges to make a trade-off between the data rate, the volume of the scientific data to collect, the time needed to damp all data on ground and the transmitted power request. The selected solution is reported in Table 6.

Table 6. Sedna's scientific data downlink

Link Margin [dB]	4.14
Downlink data rate [bps]	475
Total downlink time [years]	1.48
Total Volume of data [MB]	2640
Power TX [W]	60

3.6. Cost estimation

The mission costs were estimated with the NASA PCEC tool and are reported in Table 7.

Table 7. Cost estimation

Area	Cost [M €]
Spacecraft*	280.30
Launch	133.84
Mission operations	367.54
Other	74.96
Total	**856.64**

*Integration, assembly, and tests included.

4. Discussion of critical aspects

Several criticalities affect the mission design, leading to innovative solutions aiming at matching the scientific requirements.

Target distance is a major driving criterion, affecting crucially the telecommunication and power generation subsystems. In fact, a fundamental phase of the whole mission is the data downlink after Sedna encounter: missing this task would automatically mean to fail the main scientific objectives. Despite the favourable orbital position of Sedna, the encounter will still take place at the enormous distance of more than $77\ AU$. This issue has been overcome suggesting the adoption of the Deep Space Network (on ground) and of 3m-diameter High Gain Antenna on-board which highly impacts on the overall mass and configuration design. Just as reference, New Horizons exploited an antenna dish of $2.1\ m$. This ruled out all the examined alternative configurations and acted as the key driver for the selected one. Moreover, since the signal delay becomes more and more significant during the cruise, a high degree of autonomy in spacecraft operations is required. Regarding the power generation, the driving criterion is the distance with respect to the Sun. The adoption of an RTG is thus mandatory.

Mission Duration gives rise to additional criticalities. Since the reliability is a key requisite of this mission, all critical components shall be capable to work for more than 26 years: this is often not possible, hence redundancy is the major strategy to be followed. The downside is a considerable increment of mass. Moreover, also the ground segment is affected by such a long mission duration: training of new personnel and maintaining the motivation of the staff for the whole duration of the mission are issues that should not be taken lightly. The generational shift is leading the selection of adaptive systems that can be tuned based on current technologies developed during the mission execution. This is addressed with a software architecture that employs proper abstraction layers within an object-oriented framework.

Short residence time. The trajectory shown in Figure 2 imposes a considerable relative velocity at the encounter between Sedna and the spacecraft, requiring the collection of a significant amount of scientific data in a narrow time window (~ 40 min). The identified approach consists in a simultaneous acquisition from multiple payloads and a consequent precise planning of the on-board operations, to be executed in a fully autonomous manner. In the proposed design, the key features allowing satisfactory performances are the payload configuration (see §3.2), the 3-axis stabilised attitude control for an accurate closed-loop tracking and the OBDH designed for sustaining a large data flow from the instruments while guaranteeing autonomous operability.

Collision risk. During the long cruise in the harsh environment of the Kuiper Belt, several objects could jeopardize the mission's safety. Three classes of threats have been identified and a mitigation strategy has been proposed for each:

- Dust particles ($< 1\ mm$): possible degradation of exposed surfaces. All the instruments shall include a protective shutter. MLI erosion shall be considered.

DOI: 10.5821/conference-9788419184405.083

- Small objects ($1\,mm \div 1\,m$): cannot be detected but an impact could cause severe performance degradation. The structure shall be designed to withstand possible minor impacts, shielding properly critical components.
- Larger bodies ($> 1\,m$): can be detected up to the resolution threshold of the instruments. A collision would cause a catastrophic failure. Hence, an autonomous collision avoidance system has been proposed for the mission. Exploiting the spinning motion of the spacecraft, a continuous mapping is performed whenever a higher density of objects is expected. Propellant has been allocated for possible Collision Avoidance Manoeuvres.

Radiation exposure is another threat stemming from the environmental conditions of the mission. The accumulated total ionising dose and the hazard of single events effects during the Jupiter fly-by as well as the Deep Space travel, demands specifical solutions as the shielding of sensitive components, the adoption of rad-hard equipment, the implementation of Error correcting code.

5. Conclusions

TEASPOON is an incredibly ambitious mission, due to the extreme mission environment and its challenging objectives. Nevertheless, this work has clearly stated the main criticalities to address and how the proposed design is intended to tackle them. The result is a feasible and consistent proposal which fulfils the scientific objectives while respecting mass, power, link and management constraints.
However, to increase the chances of full success, further work needs to be done on what remain the most critical challenges. It is indeed considered necessary to improve the resistance to radiation, the reliability of the components and the collision avoidance system. The remoteness of the launch window must be exploited for the technological improvement of the implemented solutions and even more importantly, for extensive and prolonged testing campaigns.
Although the huge efforts and investments to be put in place, mission success would allow not only to greatly improve our knowledge of the Solar System, but also to carry out one of the most ambitious technological demonstrations ever attempted in space, opening the door to future interstellar missions.

Acknowledgements

This work was carried out under the supervision of Prof. Michèle Lavagna and Astra Team in the context of *Space Mission Analysis & Design* course at Politecnico di Milano.

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Figure 5 Mission Timeline

Development of a multi-payload 2U CubeSat: the Alba project

Federico Basana[1], *Alexandru Andrei Avram* [2], *Francesco Fontanot*[2], *Luca Lion*[3], *Alessandro Francesconi*[2]

Abstract
Alba CubeSat UniPD is a student team of University of Padova with the aim to participate to the ESA Fly Your Satellite! (FYS!) programme and to launch for the first time at University of Padova a CubeSat made by students.

The proposed mission has three independent objectives: (1) to collect in-situ measurements of the sub-mm space debris environment in LEO, (2) to study the micro-vibration environment on the satellite throughout different mission phases, (3) to do precise orbit determination through laser ranging and evaluate procedures for fast satellite Pointing, Acquisition and Tracking (PAT) from ground. The proposed technological experiments aim to obtain data that will enrich the current knowledge of the space environment and will provide precious information useful for the further development of some research projects currently performed at University of Padova.

In order to reach the objectives, in these years the activities of the teams aimed to develop a 2U CubeSat equipped with three payloads. The first payload is an impact sensor that will be placed on one of the outer faces of the satellite and will be able to count the number of debris impacting the spacecraft thus being able to measure the energy/momentum transferred to the satellite. The second one is a Commercial Off The Shelf (COTS) sensor that measures the micro-vibrations experienced by payloads in a CubeSat in different mission phases. The third one consists in a number of COTS Corner Cube Retroreflectors that will be placed onboard the satellite. Thanks to this, Satellite Laser Ranging (SLR) will be done to collect data on the satellite range and range rate using a facility currently under development at University.

This paper presents the mission objectives and motivations. In addition, the mission phases and the preliminary design of the CubeSat reached during the activities of the project are shown. Particular attention is given to the payloads which are the most challenging aspect of this project.

Keywords
CubeSat, Impact sensor, Micro-vibrations, Laser Ranging

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Acronyms/Abbreviations

ADCS	*Attitude Determination and Control Subsystem*
CCR	*Corner Cube Reflector*
COTS	*Components Off The Shelf*
EPS	*Electric Power Subsystem*
FOV	*Field Of View*
FYS!	*Fly Your Satellite!*
GNSS	*Global Navigation Satellite System*
LEO	*Low Earth Orbit*
LEOP	*Launch and Early Orbit Phase*
OBC	*On-Board Computer*
PAT	*Pointing, Acquisition and Tracking*
POD	*Precise Orbit Determination*
SLR	*Satellite Laser Ranging*
TCS	*Thermal Control Subsystem*
TT&C	*Telemetry, Tracking and Control*

1. Introduction

In the last decade, the space industry has increased its interest in the development of small spacecraft mission based on the CubeSat standard. The possibility to employ readily available and inexpensive Components Off The Shelf (COTS) has the effect of decreasing the system cost and complexity in comparison to traditional satellites [1].

CubeSats were initially envisioned as educational or technology demonstration platforms that could be developed and launched in a short amount of time [2]. However, in the recent years more advanced CubeSat missions have been developed and launched such as: SunStorm, which aims to measure X-Ray fluxes [3], and RadCube, which has the objective to measure in-situ the space radiation and magnetic field environment [4].

The activity of Alba CubeSat takes place in this framework. Alba CubeSat UniPD is a student team from University of Padova, which aims to develop and launch a 2U CubeSat by participating to the ESA Fly Your Satellite! (FYS!) project. The objective is to obtain data that will enrich the current knowledge of the space environment and will provide precious information useful for the further development of some research projects currently performed at our University. These projects are in the fields of small satellites technologies, with focus on (1) space debris, (2) highly-stable pointing mechanisms, and (3) Pointing, Acquisition and Tracking (PAT) of small satellites with laser payloads.

2. Mission Objectives

The proposed mission has three objectives: (1) collect in-situ measures of the sub-mm space debris environment, (2) study the micro-vibration environment on the satellite and (3) do orbit determination through laser ranging. These objectives and their motivations are presented in the following sections.

2.1. Collect in-situ measure of sub-mm space debris environment

The small debris population cannot be observed from ground and available models require validation through in-situ measurements [5,6]. To this aim, several missions and payloads have been proposed, e.g. the ESA "Debris inOrbit Evaluator" (DEBIE I, DEBIE II) [7], the NASA "Space Debris Sensor" onboard the ISS [8], the "in-situ micro-debris measurement system" from JAXA [6], the piezoelectric sensor developed by University of Texas at Austin onboard the Armadillo CubeSat [9], and the solar panel-based impact detector SOLID [10]. To reach this first objective the team plans to develop an impact sensor that will be placed on the outer faces of the satellite, those not covered by solar panels.

2.2. Measure micro-vibrations on board

Micro-vibrations on spacecraft represent an issue for payloads requiring high pointing accuracy and/or stability over time [11], and they might represent a particular concern for CubeSats and small satellites that normally are not equipped with very-high performance attitude control subsystems. Furthermore, simulating real orbital disturbances is difficult on ground [12, 13], and hence collecting reliable measures of the possible vibrations spectra in realistic operational scenarios is a significant research activity. Micro-vibrations in space have been measured in few missions such as SAMS-II and AMAMS by NASA [15, 16]. However, to our best knowledge there is a lack of information about micro-vibrations on small satellites and there is also the need of correlating such vibrations with typical mission

DOI: 10.5821/conference-9788419184405.084

events (e.g. activation of actuators, thermal cycling, debris impacts, etc.) [17]. This will help to improve the pointing accuracy and stability of future high-performance payloads for small satellites. To reach this second objective, we aim to measure vibrations with COTS sensors, such as accelerometers, and correlate the measurements with scheduled as well as unpredicted mission events.

2.3. Orbit determination through laser ranging

Satellite Laser Ranging (SLR) has been used in many important scientific missions for precision orbit determination (e.g. GOCE [18] and Galileo [19]). Several examples of CubeSat using this technique can be found such as Nice Cube [20], BeoCube [21] and CUBETH [22].

In order to reach this objective, a number of COTS Corner Cube Retroreflectors (CCR) will be placed onboard the satellite and SLR will be done to collect data on the satellite range and range rate. To this aim, we will consider the opportunity of using a new facility under development at our university for testing laser communication with LEO satellites. This facility is based on a telescope with automated azimuth/elevation control, a beacon laser and a receiver section with active focusing of the laser spot. Alba CubeSat satellite will be used as a real target for testing several PAT procedures.

3. Mission description

Three main mission phases have been foreseen at the current project design state. These are the followings:

1. Launch and Early Orbit Phase (LEOP)
2. Operations
3. Disposal

The LEOP is characterized by three different modes: (1) launch mode, (2) detumble mode and (3) coarse Nadir Pointing mode. In launch mode, all non-essential systems will be turned off, and the main objective is to remain alive until the satellite deployment. During the detumble mode all non-essential systems are still offline and the main objective is to reduce the rotational rate down to a certain threshold. This mode is accessed immediately after the deployment of the satellite and in the case of an emergency. A robust ADCS is used to accomplish this phase, with the aid of actuators and sensors like magneto-torquers and sun-sensors. The coarse Nadir Pointing mode constitutes the first actual operational mode. Here a low precision Nadir Pointing attitude is obtained, and the first link with mission control is established.

The operations phase is the core of the satellite schedule. Here all the subsystems and payloads are turned on. In the current design state, the sub-modes of the operations phase still not completely defined. Nevertheless, two modes have been already defined: (1) idle mode and (2) safe mode. The idle mode is activated if no operations are scheduled. The objectives of this mode are to maintain the satellite operative and keep the battery charged. In the current design a nadir pointing attitude is maintained for this mode, but a sun pointing attitude is still being considered. The safe mode is part of the constant monitoring of the satellite conditions, and it is activated whenever one alert condition is triggered. The alerts consist in non-nominal or unexpected events like:

- No ground contact for a certain amount of time;
- Off-nominal telemetry;
- Low battery voltage.

Once one of the alerts is triggered, the satellite, completely autonomously, runs a status check and assessed its condition. This mode is maintained until the satellite conditions are nominal again and a command is received from mission control.

The last planned mission phase is the disposal phase. This mode is activated once the satellite's expected lifetime is over. Once this phase is reached all switches are opened and the batteries are completely drained. The satellite follows a passivation procedure and loses any control or operative ability. This mode states the end of the mission and culminates with the satellite's passive de-orbit.

4. CubeSat design

The team is following the concurrent engineering method to reach the critical design of the CubeSat. The key features of the method are the constant and intensive communications between all members, and the spiral process of design which tries to reach the best solution. The concurrent approach has been studied in deep through the ESA hands-on experience called "CubeSat Concurrent Engineering Workshop".

The design process of the CubeSat has been driven by the payloads. The subsystems that compose the CubeSat were chosen and developed starting from the payloads requirements in terms of mass, volume, required power, required pointing accuracy and thermal range. Considering these requirements, the team decided to develop a 2U CubeSat platform. The functional description of the satellite is shown in Figure 1. The architecture of the satellite includes the needed subsystems to ensure the functionality of the payloads, i.e.:

1. TT&C: Telemetry, Tracking and Control System
2. EPS: Electric Power System
3. ADCS: Attitude Determination Control System
4. OBC: On-Board Computer
5. TCS: Thermal Control System

In addition, other critical aspects of the mission have to be taken into consideration, i.e. the mission analysis and the ground segment. In the following sections presents the payloads and the subsystems.

4.1. Payloads

The design philosophy that has been followed during the development of the CubeSat is to extensively use Commercial Off The Shelf (COTS) components. In this fashion, a robust and reliable design can be reached in a simpler way rather than implementing *ad hoc* components. The only exception to this philosophy is the space debris impact sensor which is being developed by the team.

The impact sensor combines several technologies to count the number and, possibly, to measure the energy/momentum transferred to the satellite by impacts with small debris (sub-mm size). The debris detector concept, which is currently under investigation, will be made by a

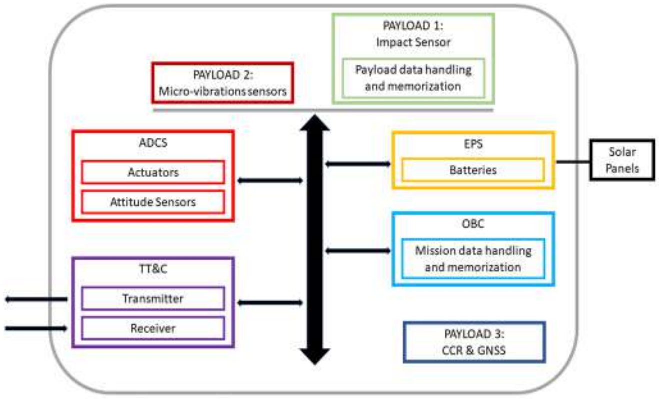

Figure 1: CubeSat functional description

multitude of thin, conductive strips (material: copper) which are made of a fine pitch (pitch: ~ 100 um) laid on a thin film of nonconductive material (thickness: ~ 12.5 um, material: polyimide). When a particle with an effective diameter larger than the strips collides against the sensor film and penetrates it, one or more stripes are severed and become nonconductive. Hence, an impact can be detected by monitoring the conductivity of the stripes. The sensor external area will be approximately 9 cm x 18 cm and will face the positive direction of the satellite velocity in order to maximize the probability of detection.

For what concerns the measurements of the micro-vibrations on board the satellite, accurate COTS triaxial accelerometers will be used. The challenge related with this payload is to distinguish micro-vibrations from measurement noise. For this purpose, low-pass filters will be used in the measurement chain to decouple the measurement noise from micro-vibrations.

Precise Orbit Determination (POD) will be achieved through SLR. In fact, the CubeSat will host CCRs that will be placed on the face pointing nadir. For the time being an array of 5 CCRs of 12.7 mm in diameter has been implemented in a quatrefoil formation: one CCR in the middle with the face parallel with the satellite and the other four forming a cross with a vertical mounting angle of 50°. This design aims to improve the Field Of View (FOV) projection on the ground allowing greater visibility from the laser station and longer contact duration. The analysis of the data recovered by the returned signal will grant the possibility to determine the orbital parameters with greater precision than the standard navigation tools such as a GNSS receiver. The

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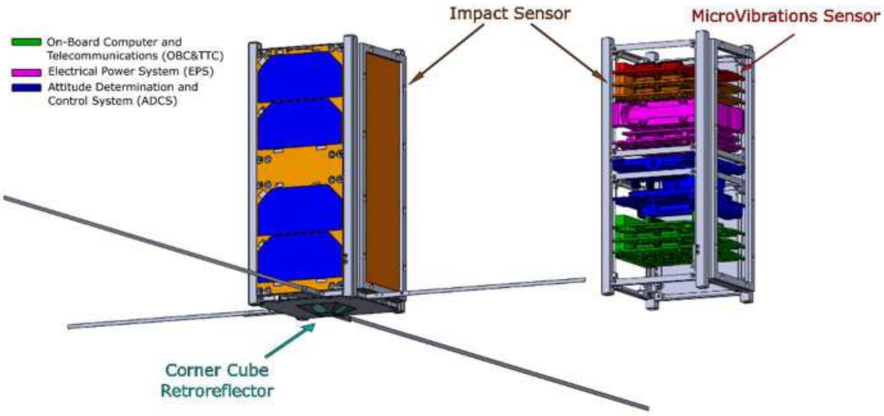

Figure 2: CubeSat preliminary design

design of the CCR array is still preliminary and could be modified in the future iterations.

4.2. Subsystems

For the time being the project is in the preliminary design review stages, hence the COTS components that have been considered for the subsystems may be changed in future.

The ADCS is the only subsystem responsible for the attitude determination and control of the satellite. The attitude is determined by means of sun sensors and magnetometers and maintained by means of reaction wheels and magnetorquers. In particular, 3 magnetorquers, along with the 3 magnetometers and the sun sensors, have to detumble the satellite during the detumble mode and compensate the environmental torques during the whole duration of the mission. The ADCS is intended to be placed as close as possible to the centre of mass of the satellite, to facilitate its operations. The power required by the system is generated by solar panels which are mounted on every face of the CubeSat with the exception of the faces that host the impact sensor and the CCRs respectively. The generated power is stored in batteries to guarantee the power to the system during eclipses. The data on board the satellite is managed by the OBC, which consists in a Pumpkin Motherboard Module 2 and a BeagleBone. The telemetry and data are transmitted to the ground segment by means of a UHF/VHF antenna and a VHF uplink/UHF downlink transceiver. Particular attention is given to the thermal control of the satellite: thermal sensors are placed in the proximity of the components which are more sensitive to thermal variations, i.e. batteries, payloads and on-board computer. In addition, specific thermal paths are designed in order to keep the satellite into the required thermal range. Figure 2 shows the preliminary design of the CubeSat obtained after several iterations in the preliminary design phase.

5. Conclusions

In this paper, the Alba CubeSat UniPD mission objectives are presented. The objectives are: (1) collect in-situ measures of the space debris environment, (2) study the micro-vibration environment on the satellite and (3) do orbit determination through laser ranging. Additionally, a brief description of the mission phases is provided. In order to reach the three mission objectives, three payloads have been developed: an impact sensor, a micro-vibration sensor and a structure of CCRs. Among these, only the impact sensor required to be developed *ad hoc* while the other two are COTS. Furthermore, a preliminary design of the 2U CubeSat is shown. In the future work, new iterations of the design will be executed in order to reach the optimal configuration of the system.

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DOI: 10.5821/conference-9788419184405.084

From BEXUS to HEMERA: The application of lessons learned on the development and manufacturing of stratospheric payloads at S5Lab

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Abstract

In the last years the S5Lab (Sapienza Space Systems and Space Surveillance Laboratory) from Sapienza University of Rome has given to the students the opportunity to gather knowledge on stratospheric payloads by supporting the design and development of two experiments selected for the participation in the REXUS/BEXUS educational Programme, managed by three european space institutions. The insights and lessons learned gathered during the participations in the REXUS/BEXUS educational programme gave the possibility to the student to take part in the development of a third experiment in the frame of the professional research programme HEMERA and complete it successfully. STRATONAV (STRATOspheric NAVigation experiment) was a stratospheric experiment based on Software Defined Radios (SDRs) technology whose aim was the testing of the VOR (VHF Omnidirectional Range) navigation system, evaluating its performance above the standard service volume, which was launched on BEXUS 22 in October 2016. TARDIS (Tracking and Attitude Radio-based Determination In Stratosphere) was developed as a follow up of STRATONAV between 2018 and 2019. Similarly to its predecessor TARDIS was a stratospheric experiment aimed at exploiting the VOR signal, with the aid of SDRs, to perform in-flight attitude and position determination, and was launched on BEXUS 28 in October 2019. After the launch of TARDIS, a team composed both by former STRATONAV and TARDIS students was formed for the development of a third stratospheric experiment going by the name of STRAINS (Stratospheric Tracking Innovative Systems), conceived by Sapienza University of Rome and ALTEC and supported by ASI. STRAINS main objective was the proof of concept of the possibility of achieving the Time Difference of Arrival (TDOA) and the Frequency Difference of Arrival (FDOA) for navigation purposes with the aid of SDRs. The experiment was developed between 2020 and 2021 exploiting the lessons learned from the former team members of the two BEXUS campaigns and was launched on board of the Hemera H2020 stratospheric balloon in September 2021 from Esrange Space Center, Kiruna, Sweden. After a brief description of the stratospheric payloads design and manufacturing, the paper will present the major lessons learned from the previous stratospheric experiments, STRATONAV and TARDIS, and their application to the development and manufacturing of the latest launched stratospheric experiment STRAINS, as well as their educational return to the students involved in the projects.

Keywords

Stratosphere; lessons learned; Students; REXUS/BEXUS; HEMERA

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Acronyms/Abbreviations

ASI	*Italian Space Agency*
CNES	*French Aerospace Studies Center*
DLR	*German Aerospace Center*
ECTS	*European Credit Transfer and Accumulation System*
ESA	*European Space Agency*
GNSS	*Global Navigation Satellite System*
LEO	*Low Earth Orbit*
REXUS/BEXUS	*Rocket- and Balloon-borne Experiments for University Students*
ROMULUS	*Radio-Occultation Monitoring Unit for LEO and Upper Stratosphere*
S5Lab	*Sapienza Space Systems and Space Surveillance Laboratory*
SDR	*Software Defined Radio*
SNSA	*Swedish National Space Agency*
STRAINS	*Stratospheric Tracking Innovative Systems*
STRATONAV	*Stratospheric Navigation Experiment*
TARDIS	*Tracking and Attitude Radio-based Determination In Stratosphere*

1. Introduction

The Sapienza Space Systems and Space Surveillance Laboratory (S5Lab) at Sapienza University of Rome is developing a variety of stratospheric experiments with the research group's participation into international research and student programmes for stratospheric experiment launches [1], [2]. In particular, since 2016, two student experiments (STRATONAV and TARDIS) have been launched through the REXUS/BEXUS Programme, managed by SNSA, DLR and ESA, and one experiment (STRAINS, supported by the Italian Space Agency, ASI) has been launched with the HEMERA H2020 balloon launch infrastructure, coordinated by the French Space Studies Center (CNES). A third BEXUS experiment has been selected in late 2021 for a flight opportunity in the next cycle.

All the experiments share the lessons learned from the experiment design, development and operations and this heritage is generally handed over among the groups of participating students, PhDs and researchers.

The experiments share the mission idea which is always related to navigation and the wide usage of Software Defined Radio (SDR) technology for signal recording, processing and exploitation for navigational purposes.

This paper deals with the lessons learned from the development of stratospheric experiments at S5Lab. After a brief presentation of all the projects carried out for stratospheric and high altitude experimentation, the main lessons learned are in-detail described. The future perspectives and opportunity are finally presented in the conclusions.

2. Stratospheric experiments

S5Lab has developed in the last six years the following projects designed for stratospheric balloons:

- STRATONAV (Stratospheric Navigation Experiment, [3]), selected for cycle 9 of the REXUS/BEXUS Programme and flown in October 2016 from the Esrange Space Center in Kiruna, Sweden. The experiment was aimed at verifying the VHF Omnidirectional Range aeronautical navigation systems above its standard service volume for future high altitude, stratospheric and suborbital navigation;
- TARDIS (Tracking and Attitude Radio-based Determination In Stratosphere [4]), selected for cycle 12 of the same Programme and flown in October 2019 from Esrange. The payload was aimed at continuing the investigation begun by STRATONAV, by exploiting the VOR system to allow positioning and attitude determination (gondola yaw angle) via real-time Digital Signal Processing (DSP) in stratospheric flight;
- STRAINS (Stratospheric Tracking Innovative Systems [5], [6]), selected for the 2020 HEMERA balloon campaign from Esrange Space Center. The flight was then delayed of one year for the COVID-19 outbreak in Europe. The payload has been launched in September 2021 from Esrange. The experiment was aimed at verifying innovative tracking systems (based on multi-lateration or on balloon path prediction through single site angular

DOI: 10.5821/conference-9788419184405.085

and Doppler measurements) for future usage on stratospheric and suborbital aviation;

A new experiment, named ROMULUS (Radio Occultation Monitoring Unit for LEO and Upper Stratosphere) has been selected for cycle 14 of the REXUS/BEXUS Programme, involving the same technologies used for navigational experiments towards Global Navigation Satellite Systems (GNSS) Radio-Occultation monitoring for weather prediction models while in high altitude flight. The experiment will be flying on the next BEXUS balloon campaign between 2022 and 2023.

All the payloads, including the STRAINS experiment for the HEMERA Programme, have been developed and carried out with an extensive involvement of University students. In particular, while STRATONAV and TARDIS were involving only students in the realization of the payloads, as per mission of the REXUS/BEXUS Programme, the mission developed for HEMERA was carried out by a core team of both researchers and students, with many former participants of the previous two BEXUS experiments.

Figure 1: STRATONAV team members involved in the 2016 BEXUS launch campaign, October 2016.

Figure 2: TARDIS team members at the 2019 BEXUS launch campaign, October 2019.

Figure 3: STRAINS team members at the 2021 HEMERA launch campaign, September 2021.

Figure 4: ROMULUS team in Rome, November 2021.

DOI: 10.5821/conference-9788419184405.085

3. Main lessons learned

The main lessons learned are reported hereunder.

3.1. *Software Defined Radio-based payloads*

All the described experiments are based on SDR technologies for their payloads. SDRs are devices able to perform Radio-Frequency operations, including reception, recording, decoding or modulation and transmission of data through software, allowing a significantly enhanced flexibility on experimental payloads design.

The S5Lab research group involvement into SDR-related activities with STRATONAV marked the first encounter with this technology, which, in the first experiment, was only used to perform radio spectrum recordings to be analyzed at ground after experiment recovery. In the following years, TARDIS has allowed in-flight signal processing of the received signals, while STRAINS has granted the first example of SDR-based transmission in flight for its mission purposes.

The nature itself of the stratospheric missions and the tasks delegated to SDRs are already suggesting a huge evolution in the complexity of the produced codes and functionalities. While recording the spectrum is a basic function that allows to postpone the data analysis and to perform it with high-performance ground-based computers, the implementation of a transmitting chain on-board an in-flight platform needs to carefully address all the issues related to payload safety and frequency stability. The three developed missions have allowed to cope with those and to go forward with the next mission related to data acquisition for GNSS radio-occultation investigation with SDRs.

SDRs are devices that can be extremely difficult to code, develop, test and operate in the actual operational environment, especially when students are involved with leading roles in the development. The main lessons learned from these developments are to start to train the students as early as possible on basic SDR tasks, which can become part of their background before their involvement in the actual mission. In this case, this has led to the opportunity for the S5Lab researchers and students to develop a SDR course which is given at Sapienza with 1 recognized ECTS. Another lesson learned is related to the availability of similar hardware at the lab and with the objective difficulty of parts procurement in these years: differentiating the typologies of SDR to buy throughout the years has allowed, especially during the development of STRAINS, to develop code on similar (same brand or same typology) SDRs before the actual arrival of the flight SDRs in Rome. In the case of STRAINS, this has saved the team from being forced to increment the workload in the last months before flight, since the flight SDRs were tested with already made code at the arrival, instead of coding and testing after the boards arrival. Having spare models of all the SDR typologies available at the laboratory can definitely save time and allow preliminary testing of code and routines on SDR.

3.2. *Interface requirements with launch system and testing facilities*

The development of three experiments to be launched from the same space base has allowed to gain some sort of confidence with the launch system and its main requirements. Although the three experiments were developed in the framework of two different Programmes (REXUS/BEXUS and HEMERA), the launch system was in the end similar and the general requirements could be considered the same.

In particular, the main difference between the interfaces of STRATONAV and TARDIS (and in the future, of ROMULUS) and the ones related to STRAINS are in the power systems: BEXUS experiments are connected to an external power system through a 28.8V power line with a passthrough power socket, while HEMERA experiments have to generate the power internally and they can at most use Electric Ground Support Equipment for power generation during on-ground testing.

Despite some minor differences in the mechanical interfaces of the experiment box and external appendages, the mechanical and data interfaces were similar in both programmes and allowed to consolidate a baseline design for stratospheric experiments lifting off from the Esrange Space Center. Such experiments are based on an experiment box, whose size is limited by the maximum cross section of the thermal vacuum facility at Sapienza University of Rome, and an external appendage (e.g. a pole) fastened through a stiff system machined in aluminium. The fastening system of STRAINS was the same part used for STRATONAV with some minor fixes to adapt to the new pole design. Frangible appendages have always been chosen for all the systems, allowing not to include the risk of damaging the experiment carrier system (i.e. the gondola). Having this baseline really helped in speeding up the design and development processes especially with STRAINS, which profited from the experience of team members previously involved in the BEXUS experiments and also reused some flown parts when possible. The baseline design that has been set up through these lessons learned is now part of the laboratory heritage and it is often used with the new students (e.g. with the new BEXUS team ROMULUS), while they are allowed to change the design to fit their requirements during the development cycle of the Programme.

3.3. Number of students per team, women inclusion and recruitment practices

The number of students participating in the stratospheric missions of S5Lab changed throughout the years. With STRATONAV, a core team of six members with three support members was considered. With TARDIS, eleven students were involved in the mission, while STRAINS involved approximately 18 people in the whole development process. As visible, the rising complexity of the mission concepts allowed the involvement of more students in the projects. As far as the inclusion and gender equality are concerned, the women share of the team members increased from approximately 15% with STRATONAV to around 30% in the last two projects, namely STRAINS and the new BEXUS team ROMULUS. Although the percentage is still quite low, this reflects the number of women studying aerospace engineering at Sapienza, with an overall good result that can be improved in the next projects.

Although the “correct” number of team members is difficult to evaluate, it must be noted that recruitment of students has passed from objective difficulties in finding new people with the first stratospheric projects to a large number of students requiring participation into the laboratory teams, including stratospheric projects. This was mainly caused by the outreach programme of the first BEXUS mission and of the other projects which allowed to bring new students to the laboratory as interested in participating in similar experiences.

As of now, the recruitment practice is generally based on an internal selection process: students are often divided in teams (two teams for each of the last BEXUS participations) and a challenge is assigned to the students. The winning team gains the chance to participate in the call for proposals and, if needed, to recruit new students from the losing team. The losing team students are allowed to participate in other activities of the laboratory if they want to. This approach has allowed to select the most motivated students for the actual proposal production, to begin team building practices before the actual proposal development and to start verifying the internal hierarchy of each team well ahead the project start. The approach obviously requires a high number of volunteers (roughly two or three times the actual final number of team members) for being operative.

As far as the optimal number of team members is concerned, “usual” BEXUS teams at S5Lab have around 10 participants, which, on the authors’ vision, satisfies the high workload demand for the project yet allowing all the team members to have a decisional role on one or more aspects of the project. Additionally, the actual space in the laboratory dedicated to such activities needs to be taken into account in the process.

4. Conclusions

The Sapienza Space Systems and Space Surveillance Laboratory (S5Lab) has developed since 2015 three stratospheric experiments through the REXUS/BEXUS and HEMERA Programmes. The three experiments have flown from the Esrange Space Center in Kiruna, Sweden in 2016 (STRATONAV), 2019 (TARDIS) and 2021 (STRAINS). A fourth team named ROMULUS has been selected for the new cycle of the REXUS/BEXUS Programme in late 2021 and will fly from Kiruna at the next available opportunity offered by the supporting agencies.

The heritage in stratospheric experiments development at S5Lab has allowed to develop many lessons learned that have helped the later experiment design processes. For example, all these experiments are using SDR technologies as main payload. The complexity of the SDR tasks has increased through the years, passing from recording the spectrum on a receiving-only SDR to establish a communication link through SDRs in downlink from the balloon to remote areas in Sweden. The students’ knowledge on SDR programming has been enhanced by establishing a basic SDR course at the University, which allows to recruit interested students before the projects start.

Launching many times with the same launch infrastructure at the same launch base has allowed to build a certain heritage in the experiment design and a baseline design for all the experiments that share most part of the interfaces. The main difference between the two projects that are involved are related to the electrical interfaces and in the power system, which is external for BEXUS (through a standardized socket) and internal for HEMERA. The remaining interfaces have been generalized and, where possible, part designs have been re-used and adapted for STRAINS from previous experiments.

The recruitment of students has passed from certain difficulties in finding new team members with the first BEXUS experiment, to recruiting two teams that compete through a challenge to give birth to the actual core team of the new proposal. This has been granted through an outreach programme dedicated to the Sapienza aerospace engineering students, that are now in general more aware of such opportunities at the early stages of their academic career. As far as inclusion is concerned, women team members have increased from about 15% with the first experiment to around 30% with the later experiments. Although the percentage does not reflect an actual gender equality, this number equals the share of women students in aerospace engineering at the faculty and is demonstrating an enhanced diversity in the teams.

Acknowledgements

STRATONAV, TARDIS and ROMULUS are or have been participating in the REXUS/BEXUS Programme in different cycles. The REXUS/BEXUS programme is realized under a bilateral Agency Agreement between the German Aerospace Center (DLR) and the Swedish National Space Agency (SNSA). The Swedish share of the payload has been made available to students from other European countries through the collaboration with the European Space Agency (ESA). Experts from DLR, SSC, ZARM and ESA provide technical support to the student teams throughout the project.

The STRAINS project development is supported by ASI (Italian Space Agency) through the agreement “Accordo Attuativo 2019-33-HH.0” among ASI, INAF, IAPS, INGV, DIAEE-Sapienza and IFN-CNR. The STRAINS experiment has been selected for the HEMERA H2020 Balloon Launch Infrastructure and has been launched from Esrange Space Center on 11 September 2021, thanks to a launch opportunity offered by the HEMERA Programme. The authors gratefully acknowledge the whole HEMERA team for coordinating the balloon launches and for providing the launch opportunity for the STRAINS experiment.

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Asociación Aeroespacial Cosmos: educational impact and returns of a three-year-old student aerospace association

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Abstract

Cosmos Aerospace Association is a leading engineering students' group, located in the Universidad Rey Juan Carlos (URJC) in Madrid, Spain. Providing a one-of-a-kind opportunity to all varieties of students for both personal and engineering growth, it is one of the few active aerospace student associations in Spain. Within this work, we introduce the achievements, influence and lessons learned from our association in these years. We focus on its educational impact in the environment of the university: not only from the perspective of aerospace-related degrees but also in the promotion of STEM careers on students of all ages.

Conceived by undergraduate aerospace students and supported by professors and university staff, Cosmos was born to provide a creative and learning environment in the promotion of our passion for space and science in general. Bringing together students with similar mindsets, it has become a symbiotic platform in which all university actors share their efforts and join forces to enhance the university experience both from a curricular and extracurricular perspective.

The association is divided into three main areas: Administration and Legal, Construction, and Education. Each of these areas branch with Projects and smaller teams both transversal and vertically. Under the Construction branch, both aeromodelling, satellite and rocketry projects are found and developed. An autonomous VTOL vehicle and a solid combustion rocket are being designed with internal and external funding. Special mention goes to the design and construction of CosmoSat-1, our very first CubeSat mission, which is now starting to take off. The Education area involves the organization of cultural and educational activities, from coding seminars, hackathons to film forums or Women in STEM days, all of them transversal to the aerospace industry. In this regard, our most ambitious project to date has been SpaceCon URJC: a space-themed conference by and for university students, bringing together professionals from aerospace companies, space agencies, and research groups in a month-long virtual conference. Over a series of presentations and interviews, students can get a glimpse of a variety of possible careers in everything from satellite manufacturing, orbital mechanics, space debris, and everything in between. With an initial run in 2020, SpaceCon has been repeated in 2021 with great success.

In short, COSMOS, while promoting a passionate interest for Space, has become a common meeting point for students and professors outside the fixed and fitted courses, where creativity can boom and grow.

Keywords

Aeromodelling, Rocketry, Sci-Comm, Spacecraft-ing, SpaceCon, Student association

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Acronyms/Abbreviations

GISAT	*Grupo de Investigación Consolidado en Sistemas Aeroespaciales y Transporte*
STEM	*Science, Technology, Engineering and Mathematics*
URJC	*Universidad Rey Juan Carlos*

1. Introduction

Cosmos Aerospace Association is an initiative by and for students. Focused on space and aeronautical activities, it is an opportunity for undergraduate students launching their careers to collaborate, learn, and get closer to the Aerospace Academia and Industry with educational, cultural, and engineering activities. While the association was born only four years ago, diffusion and growth have been remarkable, with important contributions to the University community and social life. It has also increased contact between the University and the Industry, enhancing and promoting synergies to the advantage of all interested stakeholders. This paper develops the trajectory made from the inception of the association to its current state, exploring its structure, main activities and projects, as well as its educational and professional impact for all the involved agents.

This work is structured as follows: Section II explores the background and rationale behind the association and its origins, together with its structure and the symbiotic environment it provides. Section III develops the main projects, activities and work, and a brief overview of day-to-day functioning of the association. Section IV focuses on the educational impact of Cosmos, from a student and professor's perspective. Section V summarizes the experiences, results and lessons learned, analysing both its successes and failures. Finally, future plans and ideas and projects are introduced.

2. Background

Cosmos Aerospace Association, or Cosmos for short, was created to build and expand on the inertia of the recently created degrees on Aerospace Engineering of the Universidad Rey Juan Carlos. With the kick-off of three newly designed aerospace degrees, motivated students, researchers and young professors congregated within the same institution, with funds enough and passion projects to be developed. This led to individual and collective projects in the first years: talks which both introduced new technologies in the Aerospace Industry and presented the workaday life of an engineer, seminars featuring women in STEM, and participation in European Engineering competitions and projects [1].

These first attempts showed the need for a better organization and more student involvement, highlighting a hunger in the University for engineering associations—the existing associations were focused on social or political movements. More technical activities were limited to classrooms and laboratories.

In this scenario Cosmos was born among a small group of students (with the support of their professors), looking to work together on common interests and explore past the limits that any fixed academic curriculum has. A wide variety of possibilities were established since the beginning, from model rocketry and international competitions to educational activities and study groups. Significantly, an emphasis was made on promoting the participation of women and other marginalized groups in STEM fields. The social impact was also important, bringing together a group of people excited about space exploration, flying, and learning, from all over the University.

To the founding members it was clear that a structured and diverse association was necessary. Although the aims were ambitious and vague at the start, as is to be expected, over time three main areas were identified, as presented in the introduction: Legal, Construction and Education. The vision for the association was clear: by the students, for the students. The aim is to learn, grow as better professionals and partake in activities that promote technical aspects and to grow as people.

This three-area division was thought not as a vertical and self-contained but as a way of concentrate the efforts of all the members in focalized activities. An emphasis has been placed on being by the students, for the students, with timelines adapted to the course loads and schedules of the university and working to give access to a wide variety of experiences and opportunities. In addition, as will be seen in the following sections, many of the activities have an audience beyond Cosmos members--making an impact on the university, as well as secondary schools and different levels of education.

The internal structure of the association is divided into two main layers: the board of directors and the organic teams. A horizontal structure is promoted across and along the two, as these two layers only serve to functionally divide internally the different activities and workload to be completed. The decision-making process is always handled by all the members.

The board of directors is composed by elected members and takes care of the correct development of the association as well as handling current and future issues and projects. It oversees legal, financial, management, and bureaucracy, and guides the association. Finally, one of its crucial activities is the filtering of the proposed projects and to prepare their resource allocation that will be approved by the assembly of members. The board, together with extra helping members that support their activities, is what is defined as Legal Area.

As for the activities, the second layer is composed of all of Cosmos' members, divided into two main clearly defined areas: Education and Construction. Within this, there are workgroups focused on individual projects or activities. Each team is headed by one or two leads (usually, project manager and technical officer), who coordinate with other teams and serve as a guiding voice for all the activities carried out within the team. This stratification is highly inspired by the working organization in the aerospace industry, and it is expected to evolve under the system engineering philosophy.

The Education Area has the widest variety of activities, and these tend to be more short-term, general and with a smaller group behind each. The aim of the group is to promote general scientific interest among members, with special focus on the aerospace world, while also divulging and introducing non-STEM people into the very same topics. Related to this team, a Research Group was founded within Education to have a first-hand experience of an academic career at an amateur level, in close collaboration with the Aerospace Research Group of the URJC, GISAT.

The Construction Area is where the passion projects are made possible. They are mainly developed in stages over time, iteratively. Construction is divided into two main teams, working separately in the development of aeronautical and satellite vehicles, projects to be described further below.

The four-year lifetime of Cosmos has brought to life (and laid to rest) many projects across many fields of knowledge and interests, to greater or smaller success, but always enriching and experience full. While these projects have traditionally been born and held within both Education and Construction, in many cases their multidisciplinary nature have bridged all the association's functional and structural barriers, promoting teamwork and collaboration among associates.

These two areas are, since their formation, intertwined. The industrial, academic and research contacts made by the educational team throughout the talks and activities are then feedbacked towards construction. Not only to promote new ideas, strategies, and ways of organization but also to stablish funding, resources, and engineering bounds within them. As a result, passion projects with original ideas from students are shared with industrial agents and researchers, creating a perfect breeding ground for innovation.

3. Cosmos' principal projects

3.1. Education Team: main projects overview

For the Education team, one of the first and most successful activities has been the organization of a series of lectures from young professionals in the field of Aerospace Engineering over the span of several years. These talks, started by professors and members of the GISAT, were professionalized and structured, passing for disperse sessions mostly guided and filtered by company interests to topic-oriented conferences and seminars with technical, professional, and human perspectives. Over time, Cosmos, together with the professors and researchers of the university, has hosted lectures on cutting-edge space applications: origami structures, small satellites, space weather, modern technologies for propulsion, and much more.

Also, a series of Crash Courses have been recursively held and offered by members, with the aim of helping students from our faculty who struggled with tools useful for their studies, such as LaTeX, Matlab, Catia, Julia, and Python. Although they started being presential, they were easily passed to online lectures with the pandemic, being now imparted mostly in hybrid format to allow as many students as possible to attend. To impart these courses, an extra effort was made to include experts in these tools as part of the lectures, being an example the Aeropython association [2] or Catia experts from the aerospace industry.

A very popular activity was the organization of visits to companies and sites of interest: ESAC, Airbus, Thales Alenia Space, and others.

Another focused of the Education team has been on visits to secondary schools, mentoring programs, and participation in university orientation fairs have allowed Cosmos to impact the lives of future engineers, especially providing visibility of women in STEM fields.

DOI: 10.5821/conference-9788419184405.086

Also, along this line, several panels have been organized for International Women's Day, discussing topics that impact STEM fields and women working in aerospace.

One of the more ambitious projects is the organization of study groups for the more difficult subjects within the aerospace curriculum. In Cosmos' groups, veteran students helped younger members as amateur professors with the most requested curriculum subjects. This was a space dedicated to problem-solving and helping those who need a little more help to grasp the difficult concepts. This created an environment where the students worked together to better understand the subjects and helped each other to learn. It also helped students isolated during the Covid pandemic to get to know others.

The Education group also has a strong focus on culture and society. Film club activities for aerospace movies in the university were popular, even among non-STEM students, before sanitary measures made them impossible. The podcast, debate forum, YouTube channel, and magazine have been explored to potentially reach both associate and non-associate interested students, also developing non-technical skills of those team members usually more focused on engineering. Such formats have accommodated everything from philosophical discussions to monthly reviews of relevant aerospace ephemerides.

Among all these, the most significant educational project to date is the SpaceCon congress. Already held twice, since 2020, the SpaceCon project aims to offer students a closer insight into the space industry and space-focused academia, bringing in cutting-edge research lecturers and industry stakeholders, space agencies, as well as amateur and professional associations, in a congress-like format, with dedicated sessions for top areas within the aerospace sector. The success of this initiative has constructed invaluable bridges between the URJC and the professional space communities, resulting in fruitful collaborations between the two, while promoting management, organizational, and other soft skills among the hosting Cosmos members.

3.2. Aeromodelling Team: main projects overview

The aeromodelling branch of Construction has focused for the past years on a series of flying wings, named after “HC-1”. This project allowed students to put into practice theoretical background by conceptualizing, designing and making the entire vehicle from scratch.

In addition, the current flagship program in the aeromodelling team is D.I.A.N.A. This program is composed of four projects: Fixed Wing 0, Fixed Wing 1, GNC and VTOL0. The goal of Fixed Wing 0 is to manufacture open-source model aeroplanes by applying and experimenting with project management different methodologies, such as Agile. Fixed Wing 1 is a modular 3D printing model aeroplane in which the aerodynamic configuration and performance of the vehicle is interchangeable. The objective of the project members is to become proficient pilots and trainers, leveraging the model aeroplane capability to adapt to the pilot's skills, together with developing a conceptual tester for clients, who can customize the model aeroplane behaviour. The GNC project aims to develop the autonomous flight and stability algorithms and software for both an UAS multirotor and UAS fixed wing, to be embedded in future team vehicles independently of their aerodynamic configuration. Finally, the VTOL0 is an unmanned aerial, electrical vertical take-off landing system, whose application is to analyse natural disasters and to search for lost people autonomously.

In addition, the team has also launched dedicated flying simulator courses, taught by Cosmos PPL(A)-accredited associates. They have been a great opportunity for him to share his experiences and allowed students to get a first-hand experience of pilot training.

Yet another fun but still remarkable activity of 2021 was a large-scale handmade kite-flying competition, organized in collaboration with the local government to involve secondary-school (including special education students) as well as university students. After the success of the competition, it will be celebrated again in 2022, with the aim of flying more than 50 handmade kites. While the technical load of this project is smaller when compared to previous ones, the aim of it is to promote social interest into the aerospace practice, together with strengthening local bindings and social community activities.

3.3. Satellite Team: main projects overview

An important part of Cosmos development has been the development of several NewSpace-related projects, getting students hands-on real engineering technological challenges which will face sooner or later. In particular, the Satellite team was created back in 2019, where several Cosmos members developed the Attitude Determination and Control Subsystem of

FOSSASAT-2 mission, from the open-source FOSSA Systems association.

The second main project of the Satellite team is COSMOSAT-1, a CubeSat that is being developed together with the British company B2Space with their “Fly your CubeSat” program. It consists of the design, construction and subsequent launch of the CubeSat during one academic semester. The COSMOSAT’s systems will initially be tested during a stratospheric balloon flight as a first iteration this 2022, reaching conditions very close to space, as preparation for its main objective and mission: a microwave In-Orbit Demonstration for energy collection and transport. This project has been well received by the academic staff, as well as the directorial team at the university, and this is complemented by high participation and organization of those Cosmos members which are involved in the project. Students from different degrees are getting involved in this project and supplying much multidisciplinary expertise. The CubeSat is also eye-catching to collaborations in the industry and at the university.

The project is very exciting, working directly on something that will fly in space. Additionally, the wide range of skills needed to design all the subsystems in a CubeSat are an excellent place to apply things learnt in the classroom and gain practical experience. The collaboration with B2Space has allowed the members to develop skills in project management, approaching it as a serious engineering project following the steps currently seen in the industry.

4. Educational interest and perspective

Independently of the success of the different activities accomplished throughout these years, their educational and social impact cannot be neglected. Cosmos offers a platform where students can apply theoretical knowledge acquired in class in real engineering projects, introducing members to the daily life of their future careers. In addition, given the wide variety of activities and their nature, other non-technical skills are promoted on the daily basis of the association, such as project management, teamwork, oral expression, interests for other cultures, social interaction and engagement… In these two past years, the latter have become increasingly important, at times in which the sanitary situation has made bonding nearly impossible among new university students. In this context, Cosmos has provided a social support network in which members are able to get to know each other, something vital within the academic process.

From the university perspective, the appearance of the Cosmos association meant a changing point on how to interact with our students and how to define innovative and improvement strategies. As stated in the background section, the appearance of the aerospace degrees at the URJC meant not only new highly motivated students in our institution but also the beginning of the academic career of a group of young professors. Most of us, repatriated from international institutions, saw these new degrees as an opportunity of teaching in a renewed and updated way.

Finding such a clear synergy with the Cosmos Association allowed us to join forces with them and to set common goal for the improvement of their education, as well as their human quality of our students. In particular, the Aerospace research group, GISAT works together with Cosmos as a pilar on improvement to attract industrial, technical and human talent and resources to the orbit of the university.

The benefits from the Education branch are clear: they reach where professors cannot in the classroom and laboratories. Not only by organizing seminars or study groups, but also by bringing external professionals to complete the industrial point of view sometimes missing in the Academia. Additionally, these educational activities translate into an active involvement of the speakers from the talks or lecturers of the seminars with the Aerospace Area of the URJC, allowing for industrial collaborations (research projects), academic ones (fundings and technical support for the Cosmos Activities) and even the addition of new associate professors that allow for active knowledge transfers.

However, the most important result for the university, and particularly for the Aerospace Area, that Cosmos has brought is the materialization of the curricular learning in terms of real projects. It has been more than proven that although the theoretical background is and will be always needed, the learning-by-projects approach is crucial for STEM students. And although this kind of learning can be forced in the different courses of the university, exams and gradings always remove the-fun-of-it. Cosmos and its construction branch provide an opportunity to gamify the academic process. Supervised by their professors and guided (and hopefully, sometimes funded) by the industry agents involved with the university, the projects become tangible solutions where a full set of soft and hard skills is learnt: from systems

DOI: 10.5821/conference-9788419184405.086

engineering to the applications of the equations and simulations from their courses.

For all the above, having a strong, organized, and proactive organization of students is a key element to the education of better engineers and, consequently, a better industry in the future.

5. Results and lessons learned

The impact of Cosmos has been far greater than was imagined when the idea was first born. The students who take on an active role in Cosmos have a structure to support their ideas and projects--as has been described above, there is a broad area of impact! Additionally, those students who are new to the university or to student groups have found it a welcoming place where they can participate in a variety of activities before they find what suits them best. Additionally, and more rarely for STEM associations, Cosmos has a large impact on the student body as a whole--especially on STEM students who are not members

Collaboration with companies and organisations has also increased visibility of the university within the industry, promoting a symbiosis that will impact the careers of students for years to come.

However, not everything has been smooth flying. A variety of challenges have been faced within the association, especially in participation, coordination, and leading roles. Currently, over 200 students have passed through Cosmos with differing levels of participation. While some members spend many hours a week on Cosmos activities, others chip in smaller chunks of time when they can spare them. This has not been considered a problem--the ultimate goal is for Cosmos to serve as a backup to the ideas and especially the needs of the students. However, there are often problems with members who commit to projects and then are unresponsive when it comes to participating, resulting in overload and tension for leading members.

The other recurring issue faced in Cosmos has been filling the more organizational roles. While the construction projects are impressive, and the educational activities rewarding and entertaining, the association could not function if not for the secretaries, treasurers, presidents, and directors. The roles carried out by these members are seen as less attractive or entertaining. It has, as a result, been harder to fill these positions, and moments of transition have led to organizational disarray.

6. Conclusions

After nearly four years of experience, the resulting association is one where the senior or graduated students can collaborate with new students, continuing work on existing projects, and maintaining a space supportive of many kinds of exploration and learning. One of the main goals inside Cosmos is to inspire and increase the interest between the students in space and STEM activities, engage them in the aerospace world and encourage them to leave a mark in science. In addition to the successful results and projects completed up to this day, the experience of the past four years has shown valuable lessons from which to learn and advance towards such ultimate goals.

As for the future of the association, it is intended to continue with current projects and keep learning from the mistakes, forging new alliances with the aerospace industry and other associations with the same interest as Cosmos. The Education team is still growing, coming up with new activities every day. In 2022, they will be participating more actively in several events focused on younger students. There are plans for conferences with even more international collaboration soon. The Aeromodelling team is currently embarked on many ambitious projects which will see it through the end of this year and into the next. Inside the Construction team, it is planned to develop a rocketry team, in which the students will be able to get in touch with rocket science.

Overall, Cosmos has grown to the point where more ambitious projects have become feasible, and this will lead to more collaborations with industry and international agents. Students pass through on short timescales, but our hope is that the association will remain a constant and will welcome many future generations of students to the URJC.

Acknowledgements

Authors wish to acknowledge the GISAT group and the ETSIT at URJC for their support through these four years of Cosmos life.

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Collaborative Space Design project: A student's experience

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Abstract

The student members of the Collaborative Space (systems) Design (CSD) project discuss its implementation and highlight its concepts. The CSD project is an elective course at the MSc Space Flight programme at the Delft University of Technology, Faculty of Aerospace Engineering, where students exercise the design process of a space mission, spacecraft or a major spacecraft subsystem in a team setting, along with several important external stakeholders. Focus was given to the application of concurrent engineering and systems engineering techniques. Interaction between the students and the external stakeholders was also extremely valued. Two teams participated, one designing a liquid oxygen electric pump and one a CubeSat asteroid observer mission. In this work the students report their experience, highlighting how they approached the different phases of the design process. Positives and negatives of the course are also presented, together with some feedback on potential modifications to future editions of the course.

Keywords

Engineering, Space, Education, Design Project

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Acronyms/Abbreviations

All used acronyms and abbreviations used in the following paper are listed in alphabetical order, as follows:

CAO	*CubeSat Asteroid Observer*
CSDP	*Collaborative Space Systems Design Project*
DARE	*Delft Aerospace Rocket Engineering*
ECTS	*European Credit Transfer System*
EP	*Electrical Pump*
ESA	*European Space Agency*
LOX	*Liquid Oxygen*
RPM	*Revolution Per Minute*

1. Introduction

This paper wants to highlight the experience, from a student point of view, of a method, performed, during the academic year 2020/2021, in the first edition of the Collaborative Space Systems Project Design (CSD) course of the MSc program at TU Delft Aerospace Engineering faculty. It is based on concurrent engineering, which is a work methodology that emphasizes the simultaneous performance of different tasks, within the group. This course offers students the unique possibility to get engineering design experience through engineering design projects within the space engineering field.

In the CSD course, focus lies on simulating a potential future realistic career situation, where a design project is executed for a certain customer. The primary goal is to acquire concurrent design skills and abilities in a teamwork setting, while also taking into account system engineering aspects like stakeholders, requirements, planning and costs among others.

The experience this course offers is very different from the rest of the courses given in the MSc program. While the whole theoretical knowledge is meant to be already obtained by the student himself from previous courses and their theoretical lectures, the practical knowledge is to be acquired, practicing what has been taught earlier. It is not only meant as manually build something, but also, and especially, differently from all the other courses, in terms of both being in contact with stakeholders and clients interested in the project and working, within a team, on multiple aspects of space engineering.

Two student project teams were given an assignment by their respective customers. Main interactions with the customer at the beginning of the project were several iterations on product requirements and constraints. Later these were followed by design reviews. In the end a design deliverable and report were supplied. Each team had their own supervising professor, providing feedback content-wise and coaching on concurrent design processes. In one of the two projects, the customer and supervisor coincided, and the professor had to simulate two different roles. In the other case, professors were just supervisors, while a company was the true customer.

Within the two teams, expectations were the learning of how to design a complex dynamic mechanical system as part of a rocket engine experiencing the full design process on the one hand, and on the other one, acquiring engineering skills on how to design a space mission from scratch.

The following paper is organized in such a way that it introduces the student experience of this new Collaborative Space Systems Project Design course with its general organization and then explains, in chapter 2, the design phases adopted by both teams such as problem introduction meeting with clients, problem exploration and literature study, the generation of requirements, the concept creation and trade off, and the design reviews. Furthermore, there are the recommendations for future steps, in chapter 3 that should be followed to make the best out of this innovative and promising new educational method. In chapter 4, a few things have been reported also with regards to the changes done for the course in this new academic year. Conclusions, with a very brief summary, are then reported in chapter 5.

2. Design Phases

This section will describe the course organization structure and given tools, to then proceed further into the different design phases of the two projects.

2.1. Organization and Tools

The course setup has already shortly been discussed in the introduction. The two teams were given a design problem by a customer, who in the end expected a solution and certain design deliverables. Supervision was done by professors and internal supervisors which provided technical feedback on engineering quality, work approach and engineering support.

Next to the professors, the teams also had a SCRUM supervisor. SCRUM is a framework for project management in a complex environment or team [1]. Team members divide their work into smaller parts called sprints, often two weeks in length or shorter. At the end of each sprint, completed work is shared with all stakeholders, and then the sprint is reflected for improvements in the next one.

Along with SCRUM, another given tool was CDP4. This engineering tool is meant to support and facilitate multidisciplinary design teams in complex concurrent design challenges [2]. The tool is primarily used to keep track of design variables and their correlations for all team members. Design requirements and constraints are monitored to maintain compliance with changing variables in the design process. Variables can be connected with other design programs like SolidWorks. Updated variables in the process are then linked back to CDP4 and can be shared online with other team members, after which the variables in their design programs are automatically updated. This program is also used by ESA and other institutes in their multidisciplinary projects.

Furthermore, the Collaborative Design Lab (CDL) was facilitated as working environment on the Aerospace faculty. This lab is equipped with all needs for such concurrent design projects like the one undertaken by the teams. The lab includes a large audio system room with many working spaces, several interactive whiteboards, equipped with Starleaf software, projectors, cameras and microphones that also facilitate online meetings. A visual representation of the course organization and tools can be seen in Figure 1.

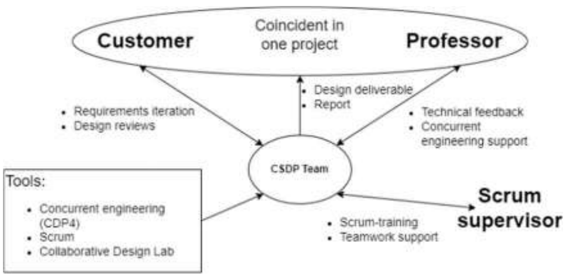

Figure 1. CSDP course structure

2.2. Problem introduction

A kick-off session was held for both the CSDP teams to introduce the students to their projects, to provide them useful tools to be used as a support to their work (like SCRUM and CDP4), and mostly important to present them to their customers.

The first team, formed by four students, was chosen to perform a preliminary design of an electrically driven centrifugal liquid oxygen (LOX) pump for Project Sparrow's Firebolt engine, developed by Delft Aerospace Rocket Engineering (DARE) [3]. The aim of Project Sparrow (DARE's flagship project) is to produce a liquid bipropellant rocket engine 'Firebolt' capable of delivering 14 kN of thrust, running on liquid oxygen (LOX) as oxidiser and ethanol as fuel.

The actual customer for the EP project was a member of DARE who was closely following the team and planning weekly meetings to keep track of the progress made. The students were mostly interacting with this person, with less frequent meetings with the complete DARE Firebolt team to discuss important points of the design phases. Along with the customer, the students were also introduced to an internal supervisor from TU Delft, whose role was to guide and advice the group on the design choices. Meetings with the supervisor were more frequent (also twice a week when necessary) and more informal than the meetings with the customer.

The second team of four students was chosen to design a CubeSat asteroid observer mission. Asteroids are of great interest to the scientific community. Thus, the design of a relatively cheap and quick (in terms of development time) mission to a near-Earth asteroid would open many opportunities to scientists and allow engineers to test state-of-art instruments in the space environment.

The solution to such a challenge is a CubeSat mission. A team of four students was tasked to design a CubeSat mission with the appropriate payload for observing a near-Earth asteroid. The main challenge of the mission was that the CubeSat had to be a standalone spacecraft in deep space. There are not many examples of CubeSats used for deep space missions. The large distance between a spacecraft and Earth combined with the limited capacity of a CubeSat put significant constraints on the mission design.

This project did not have an actual customer. The main stakeholder of the project was TU Delft. Every week the progress was presented to three TU Delft professors and experts who would provide the feedback and guidance for the next steps. These people represented the customer and were the team's supervisors simultaneously.

DOI: 10.5821/conference-9788419184405.087

2.3. Problem Exploration/Literature Study

The first part of the project consisted of an exploratory phase in which the teams gained information in the respective fields. For the electric pump team, this meant researching pump systems while for the asteroid observer team this was mostly a target selection. Although it was a positive experience to explore fields that were relatively new to both teams, this research phase took more time than initially expected. This resulted in a decrease of available time for the remaining design phases of the project.

From the literature study, primary and secondary science questions were established. This was an opportunity for the students to come up with their own research objectives, whereas in other projects these are generally provided at the beginning. Because the project covers multidisciplinary topics, different roles and responsibilities were allocated early in the process. For example, the asteroid team had a science officer, a systems engineer (originally scrum master) and a project manager who kept track of the project timeline. The next steps were to convert the research questions/objectives into requirements.

2.4. Requirement Generation

The requirements were a mix between stakeholder requirements and requirements set by the team itself. For the design phase of the project, each team member was responsible for the design of one or multiple subsystems. This division took place before the set-up of the requirements so that each team member came up with the subsystem requirements for their respective discipline. These requirements were then reviewed by the other team members, before they were presented to the stakeholders.

This already shows the constant communication between the team members themselves and with the stakeholders. To facilitate this communication between team members, the collaborative design software CDP4 was used. Via this software, team members could update the requirements and design parameters of the various subsystems and other team members could access these relatively easily, as previously mentioned.

2.5. Concept Creation

The next step was to generate multiple design concepts. The generated concepts lacked in detail, as teams concentrated only on feasibility and the potential to satisfy requirements.

The EP team utilized mainly empirical correlations found in literature to outline the main characteristics (Figure 2) of a centrifugal pump that could satisfy the flow, pressure and efficiency requirements set by the clients, DARE.

CDP4 was used at the beginning of the design phase, but after a few sessions, the asteroid team decided not to use the software anymore. As team members were still learning how to use the software, this often caused delays that were not compatible with the tight schedule. Also, as each team consisted of just four members and preliminary designs were considered, a simpler tool like Excel was deemed sufficient. After the concepts were developed, it was time to compare them and make a selection.

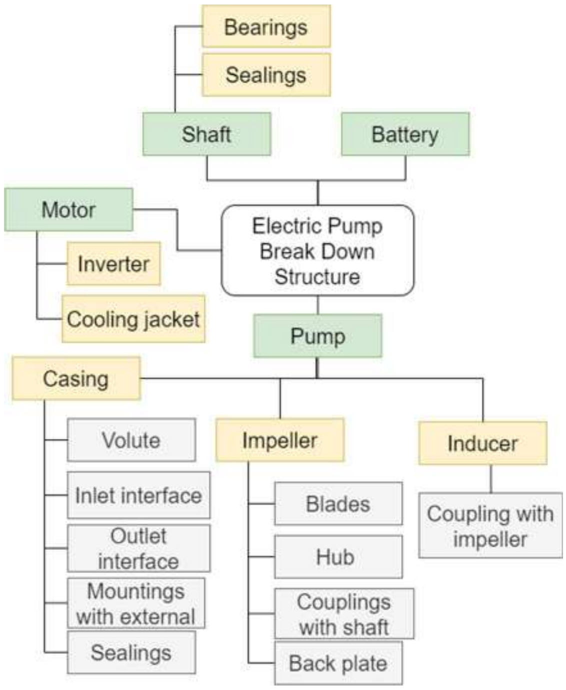

Figure 2. Electric Pump system architecture. Utilized in requirement flow-down and subsequently in concept generation.

2.6. Concept Trade-Off

For the Electric Pump group, two pump concepts were considered during the preliminary design, these being the conventional centrifugal pump, and the Barske pump. The latter, also called partial emission pump, has semi-open or open impellers and prove to be specifically useful in applications where high head is needed in combination with a relatively low revolution per minute (RPM). Conventional radial pumps, on the other hand, have curved, shrouded impellers, they are able to achieve relatively high efficiencies, and they are widely used in many different applications.

The trade-off for the pump selection has been done through a feasibility study: the power required for the functioning of each type of pump has been compared to the currently available electric motors on the market for these applications. The conventional centrifugal pump has been identified as the best option for the Firebolt engine, mainly because of the problems that arose with compatibility between pump efficiency and available motor powers. A comparison table has been created, a part of which regarding the motors' data can be seen in Table 1. However, as stated before, Barske pump gave promising outputs, which will be worth considering in case a wider and better selection of motors is found.

Table 1. Section of the comparison table used for the trade-off phase by the EP group. Uncertainty was determined by the utilization of empirical correlations and literature analysis.

	Barske	Conventional Centrifugal	Units
Power and efficiency			
Hydraulic power	18.39		[kW]
Brake horse power	Best 46	Best 27.04	[kW]
	Worst 52.5	Worst 31.7	
Efficiency	0.35 - 0.40	0.58 - 0.68	[-]
Motor			
Maximum continuous power	**36**		**[kW]**
Max RPM	50'000		[RPM]
Cooling needed	YES		[-]
Shaft diameter	10		[mm]
Motor diameter	60		[mm]
Motor length	142		[mm]

As for the asteroid observer mission, one of the main goals was to find an asteroid that is of interest for scientific community as well as that fits into mission constraints. Five asteroids were selected for the final comparison. These are 4660 Nereus, 21 Lutetia, 16 Psyche, 1989 ML, 2008 EV5.

The trade-off for target selection has been conducted based on four criteria: feasibility, innovative knowledge that an asteroid can bring, uniqueness of the mission, and cost. This can be seen in Table .

As seen from the trade-off table, the winner is 4660 Nereus which is very accessible due to its regular and very close Earth flybys. Also, scientists find it interesting due to its past which may shed light on comet evolution.

Table 2. Target selection for the CubeSat Asteroid Observer mission.

	Feasibility	Innovative knowledge	Mission unique	Cost
4660 Nereus	High (very close and accessible target, small Δv required)	Might have been a comet in the past.	No-one ever visited it.	Low
21 Lutetia	Low (due to the thick layer of regolith covering the surface)	Might have been a planet core.	Rosetta flew by the asteroid.	Medium
16 Psyche	Medium (too big to orbit)	Might be a remnant of a planet core.	There is already a mission planned to visit it.	Medium
1989 ML	High (easily accessible asteroid)	Interesting for mining	No-one ever visited it.	Low
2008 EV5	High (favourable orbital properties, small Δv required)	Potential hazardous object for Earth.	No-one ever visited it.	Medium

Legend:

Green	Excellent, exceeds requirements.
Orange	Might reach requirements with some modifications.
Red	Unacceptable.

2.7. *Design Reviews*

After the preliminary design phase, a mid-term review meeting was held approximately halfway through the project. Here the student teams presented their work to the customer and to the supervisor. Moreover, the groups were given the possibility to also contact external experts in the field to get feedback on the work done and suggestions for the next steps. This was done to keep the experience as close as possible to reality and at the same time to give the students a good opportunity to show their project to potential future investors and/or recruiters.

Similarly, a final design review was held at the end of the course. Both teams were invited to attend each other's final review so to provide feedback to their colleagues from a student point of view.

For the EP group, several members in the DARE society who were not actively participating in the Firebolt project were also invited to join the reviews to give their insight, as well as professors from TU Delft, invited by the supervisor.

For the CubeSat Asteroid Observer (CAO) group, the midterm review meeting was visited by the group members and supervisors only, while the final review was joined by other professors from Space Flight department of TU Delft.

3. Recommendations for future editions

In this chapter the authors suggest which possible modifications and additions can be applied to the course to solve the issues previously highlighted.

3.1. Subject Selection

It must be noted that if the chosen design challenge requires a very large amount of literature research from the students, little time might be left to dedicate to the other design phases. On the other hand, research and self-learning are important skills that should be included in the course. Similarly, is dealing with the uncertainty caused by incomplete knowledge. Thus, a balance should be struck when choosing the design challenge.

3.2. Supervision Involvement Levels

A higher level of supervision reduces the educational advantages generated by having the student team operate autonomously. However, the authors feel that, if a complex design subject causes the team to get stranded due to lack of knowledge, especially during the problem exploration phase, a high level of supervision can help compensate the deficiencies and still lead to a positive educational outcome.

3.3. Increased Number of Participants and Diversification of Skillsets

A bigger student team would make team coordination techniques, such as stand-up meetings, more relevant and put a bigger focus on concurrent engineering. In addition, the inclusion of students from different academic paths provides the chance to teach real-life team coordination skills, such as collaboration with colleagues with different knowledge and, as far as the team manager is concerned, assigning task in way that positively exploits the individual strengths of each member.

4. Second edition of the Course

At the time of writing, the second edition of the course has already started, during the academic year 2021/2022. Some modifications have been applied. An additional educational credit was assigned to the course, bringing it to 5 European Credits Transform System (ECTS). The hours associated with this additional credit have been dedicated to workshops on the engineering design process and on further education on the SCRUM method.

5. Conclusions

An innovative course concept that challenges a student team to solve a design problem is presented, with a particular focus on the point of view of the participating students. After an introduction on the structure of the course, the students' experience during the different phases of the design process is recounted. This is followed by suggestions given by the students on how the course could be modified in the future, together with an account of the modifications already applied to the 2022 edition of the course.

Acknowledgements

The most important acknowledgment goes to Delft University of Technology for providing us with the best infrastructure, self-improving and successful environment that a group of Master Students could ask for. Together with the University itself, there is the entire DARE team who supported us and the project, and the professors, and more specifically: Barry Zandbergen, Stephanie Cazaux, Alessandra Menicucci, Sebastiaan de Vet, Vidhya Pallichadath, the CDP4 assistant Ranjan Subhash Gaur, and the SCRUM instructor Gitte van Helden. Without them, none of the projects would have been possible.

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Domi Inter Astra (DIA) Moon Base: an interdisciplinary approach for cooperation to build a near-future Moonbase and how to use it as an educational tool

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Abstract

Permanent human settlements outside of low-earth orbit face technical and psycho-social challenges for the crew members and programmatic risks around funding and operating these missions, without clear public support and international involvement. A concept for the construction and operation of a lunar settlement named "Domi Inter Astra" (DIA), near the Shackleton Crater, was developed to understand the feasibility of a near-term permanent settlement crewed by international researchers and tourists. This project was created by a team under the Space Generation Advisory Council's auspices and a follow-on to our First Place design in the Moon Base Design Contest by The Moon Society. Technologies for infrastructure, life-support, environment control, and robotics were selected using high-level trade studies to balance resource requirements, safety, reliability, operability, and maintainability of the base over a long (20+ year) operating life with 10-30 inhabitants. Technology roadmaps were developed for gaps in existing technologies, considering opportunities with ISRU and methods of closing the environment control and life support system loops. A wider range of human factors pertaining to the social environment onboard the base is discussed to ensure long-term stability. Architectural design choices were made, keeping these factors in mind while also considering technical and economic viability. Large-scale space exploration projects must mitigate both public interest and funding risks throughout their life cycle. Economic roadmaps are introduced to diversify revenue streams throughout the settlement's design, deployment, and operation. Funding opportunities that evolve with the base design and functionality over time are identified for long-term economic sustainability. A polycentric model for international collaboration is explored to promote interest from current space-leading countries while providing opportunities for emerging space nations. The DIA lunar settlement case study showcases the interrelation between engineering, economics, architecture, science, social and management scopes. It highlights the interdisciplinary approach and inclusivity in the field of space sciences. This case study can help international and public-private partnerships to develop human space exploration capabilities further. The current DIA base plan could be used in many ways for educational activities, for any level of students and professionals. Two types of activities could be design and analysis based and mini analogue missions. Students could devise and perform small experiments that relate to the base's day-to-day activities as well as resources required, for example growing microgreens and plants in different conditions, geology surveys, 3D printing different objects and many such mini-projects. Graduate students and professionals could work on CAD modelling for structures, improving the architectural plan and the statistical analysis for the economical model.

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DOI: 10.5821/conference-9788419184405.088

Keywords

Extra-terrestrial settlements, Moon Exploration, Human spaceflight

Acronyms/Abbreviations

CAD	*Computer-Aided Design*
DIA	*Domi Inter Astra*
ECLSS	*Environment Control & Life Support Systems*
SEDS	*Students for Exploration and Development of Space*
SGAC	*Space Generation Advisory Council*
STEAM	*Science Technology Engineering Arts Mathematics*

1. Introduction to DIA

Domi Inter Astra (DIA, Latin for home among the stars) is a project that participated in the Moon Society's 2021 Moon Base Design Competition. This multidisciplinary and multicultural team was formed through the Space Generation Advisory Council (SGAC). After winning the competition, the team decided to share the project with the wider public to show them the wonder and excitement of space exploration. DIA's diverse team comprises 50 members from over ten countries, now working on writing an outreach book analysing lunar base building through the lenses of STEAM (Science, Technology, Engineering, Art, Mathematics). The entire lunar base is explored through the story of a young girl, Antariksha, from India, who is an integral member of the base. The combination of the creative aspects with technology highlights the values that DIA stands for: safety, collaboration, exploration, curiosity, and equality. The book is divided into three parts and starts by analysing the challenges that in 2022 do not allow us to start the construction of a Moon Base. The second part highlights how the base will overcome these challenges and establish itself before describing the operations and life on the base for the first ten years. The final part describes what the base will look like in 50 years and showcases future relations between Earth, the Moon and Mars. Once the book is published, the team will develop educational materials ranging from theory explanations to practical exercises and experiments related to the book's content. The current DIA base plan could be used in many ways for educational activities, both for school level and research-level professionals.

Figure 1. DIA Authors Technical Backgrounds

2. Thematic Areas of DIA

This section highlights the departments that play a key role in DIA.

2.1 Space Law, Politics and Policy

The DIA Moon Base is conceived in the spirit of international space projects like the ISS [1-3]. SGAC's Effective and Adaptive Governance for a Lunar Ecosystem (EAGLE) Manifesto will be followed to create a Lunar Governance Charter for peaceful and sustainable lunar exploration [5]. In this spirit, there is no claim of sovereignty, and space exploration is recognized as a benefit for all humankind [4]. DIA will rely on a polycentric governance system, where different structures and both public and private institutions will participate in rule creation in multiple and overlapping layers [6-7]. This will allow for an agile sustainable, accessible and intergenerational mindset. Decentralization and collaboration will be designed into the system. Decision-making will happen through a tiered system that ensures voting will be proportional to the investment made while ensuring no single block has excessive influence on voting (as seen in Figure 2).
An important area that should be addressed is the possible gap between social sciences and space exploration. Key professional fields like that of astropolitics [8], astrosociology [9] and the already burgeoning Space Law sector will need to be further developed going into the future. In order to initiate, operate and enhance activities in the competing jurisdictions of space and lunar exploration, significant capacity for establishing Space Law and Policy will be needed [10-11].

The UN Committee on Peaceful Uses of Outer Space (COPUOS) has explored the need to develop a specific corpus for Space Education to anticipate the needs of professionals that can build governance and regulatory systems [12]. The DIA base's extreme conditions can act as an excellent proving ground for these fields in the coming decades. Ideathons and moot court exercises could be a non-traditional way to educate lawyers and political scientists and introduce basic knowledge to technical specialists [13].

2.2 *Management*

The base management structure will be divided into Lunar and Earth segments, with the former taking care of day-to-day operations and the latter taking care of the broader project aspects (as seen in Figure 3). A rotating Managing Director will oversee both. In the spirit of decentralization and agility, a Lunar Base Operations Head is appointed on-board, equivalent to the commander on US/Russian spaceflight missions [14]. An overlapping shift rotation system will maintain continuous operation and monitoring while promoting crew interaction and unity.
There is a lot of scope for having roleplay situations, with semi-analogue astronaut exercises to help identify challenges involved and strategies that could be utilized.

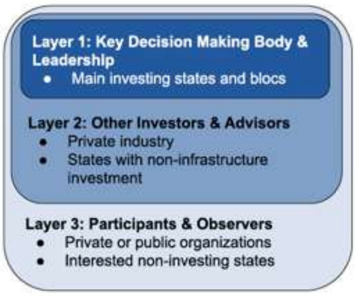

Figure 2. Polycentric Governance model of DIA

Figure 3 . DIA Base Management divided between Earth and Lunar Segments

2.3 *Society and Culture*

DIA honours multiculturalism and inclusivity by its very spirit and intends to have these act as core tenets of the base it will establish. The remote and challenging lunar environment means the base's culture will be key to ensuring its long-term survival. To that end, it is essential to establish a strong code of ethics and conduct and a culture of mutual trust and cooperation. Activities that could be done in this area could be surveys on cultural attitudes to space travel and exploration, audits of studies on work in remote and harsh environments, diversity studies (focusing on gender, race, disabilities and other markers), analogue astronaut experiments, as well as generating proposals for intercultural recreational activities.

2.4 *Health*

We hope to address inequity in information access via a comprehensive and accurate data set accessible to all on the Moonbase, regardless of gender, sexual orientation or identity. There are many extra considerations regarding the health of female astronauts in space [15]. The female menstrual cycle in space does not change in volume or character and does not impact a woman's ability to perform as an astronaut. A woman's fertility is not considered to be impacted by space. However, the ethical and practical considerations of having a child in space constrain research in this area. The unknown effects of space radiation and microgravity are risks simply too great to justify research in this area. [16]

2.5 *Economics*

A key aspect that will need to be addressed for the moon base will be the economic challenges with settling a remote outpost. At a high-level key question regarding the project's financing when it comes to its research, development, establishment and initial operation. Revenue generation is another aspect that can be tackled, with new models and sources of revenue that can be unearthed to help support the operation of the base. For example, lunar tourism is anticipated to be a key revenue source. However, ensuring sustainability and not overcommitting limited base resources will be a huge challenge.
Additionally, more specific challenges like evaluating the need for an internal economic system and establishing a system to enable commercial participation could be studied.

DOI: 10.5821/conference-9788419184405.088

2.6 Architecture

The base architecture will take into key consideration the psychological as well as the material and operational needs of its residents. Over the long-term, space missions' provisions must be made not only for key life-support and mission-critical operations but also for mental well-being. Modularity is also a key aspect of the design to allow crew members to adapt and modify based on their own learning and experiences. Building upon terrestrial architectural knowledge, the lunar base will need a new class of architecture to take on the unique lunar conditions.

Not only do all these challenges lie at the intersection of multiple STEAM fields, but they could also be readily utilized as challenge topics for an ideathon or collective brainstorming exercises [17].

2.7 Technical Development and Engineering

This area forms the core competency that will dictate the success or failure of the DIA project. It will address diverse challenges like selecting and establishing a settlement site, ensuring that key services and resources are reliably provided, and ensuring smooth and robust operations. The key subsystems identified and their key aspects are highlighted in Table 1.

Table 1. Engineering: Key Aspects

Subsystems	Key aspects
Settlement Location	Geographical location, Surface Mapping
Base Construction	Radiation Shielding
Power	Power Distribution, Audit and Conservation
Environment Control & Life Support	Temperature, Climate Control, Dust Ingress
Surface Transportation	Long/Short-range Transportation
In-Situ Resource Utilization (ISRU)	Mining, Extraction, Manufacture
Waste Management	Circular Economy
Operation & Control	Maintenance, Software
Safety Hazards	Regulatory framework

Something common to all the areas identified in Table 1, is the need to go beyond a basic technical understanding. Expertise must be built to a stage that allows for scalability, sustainability and robustness in the solutions proposed, all with the mindset of enabling further utility and expansion to unlock lunar colonization.

2.9 Innovation Principles:

The inquisitive nature of resolving these challenges in new scenarios have led scientists and individuals to grow new ideas. These concepts rely on meeting the needs of expeditions at low costs and resources-expeditions often have poor infrastructure, insufficient workers, and challenging environments. In these constraints, individuals often craft innovative solutions to make the best of every situation [18]. Transdisciplinary innovations from other fields such as social anthropology can serve as conceptual guides for innovation, alongside learning from translational research [19].

3. Educational Deliverables

Having introduced the key knowledge areas, the following section will explore the educational outcomes and deliverables that could be derived and implemented.

3.1 Collaborative Learning Activities

DIA intends to educate participants on the identified themes and their associated challenges through collaborative activity platforms. These can take the form of moot court sessions, brainstorming workshops, ideathons, role-play situations and mock debates [20]. These can play a valuable role in strengthening core knowledge areas, introducing adjacent knowledge fields, strengthening soft skills and practical problem-solving. Some example activities can be seen in Table 2.

Table 2. Collaborative Activity Examples

Topic	Activities
Fire Safety Design Challenge	- Requirement Generation - Risk/Constraint Identification - Storyboarding/Digital Mock-ups - Solution Brainstorming - Design/CAD Modelling - Concept Evaluation
Resource Utilization	- Stakeholder Identification - Motivation Setting

DOI: 10.5821/conference-9788419184405.088

	- Role Play Debates
Mock Crisis Response	- Learning Review - Plenary Sessions
Lunar Transport Challenge	- Traffic Estimation Study - Technology Audit -
Natural Design Challenge	- Biomimetic Principles Primer - Constraints Identification - Design Ideation

3.2 Open Learning Platform

A curriculum can be designed around the key technological and scientific knowledge required to enable effective lunar base design. The curriculum will utilize a pedagogical framework that relies on project-based tasks that can cater to all the VARK learning preference styles, with integrated assessment points to provide regular and constructive feedback. An online, open-source Learning Management System (LMS) can be used to not only provide access to learning material and resources but allow learners to practice autodidactism, giving them the license to motivate, regulate and evaluate their own learning.

3.4 Potential External Collaborators

DIA aims to partner with the largest student-led organization, Students for the Exploration and Development of Space (SEDS), SGAC, WoAA etc. The DIA moon base can serve as a common theme with various tracks that the students can take up; for example, there could be a logo design competition that focuses on spatial skills whilst the design of the base focuses on logical thinking. The main aim would be to explore the multiple intelligences, ensuring no child is left behind and develop various domains for the next generation in space that promote inclusivity, collaboration and advancing humanity through the peaceful uses of outer space.

4. Conclusion and Future Scope

The Domi Inter Astra project showcases the planning, development and operational directives of a Lunar base from a holistic and multi-thematic perspective. The project touches upon scientific research and engineering technologies employed , as well as the economic and management structure intertwined with architectural design aspects and societal significance of the human feature.

The study approach undertaken to develop this project has inspired a novel directive to research and analytical skills, which we have attempted to impart into students from the productive distributaries of this project. Real-life applications for the theories discussed in the project can aid a student's understanding by involving concepts from various subjects in tandem. This study showcased how the future book could be integrated into classes to educate the students of scientific, economic or engineering principles/theories by showing the real-life applications of those principles/theories. This is also done by worksheets and experiments that go together with the book. Additionally, the potential collaborators from NPO, NGOs, government organizations and universities could propagate STEAM for space technology. We aim to develop the integration of academia in space sector developments. The space-oriented companies are providing education as societal activity. A view from students and young professionals of space education. The continuous adaptation of the space education system to the evolution of sector needs The internationalization of space education train and attract world talents.

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Finestres al cel

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Abstract
We present an astronomy educational project intended for 16-year-old high school students that has been successfully deployed for 7 years under the Youth and Science Program of the Catalunya La Pedrera Foundation. The Youth and Science Program aims to encourage talented students to pursue careers in science and technology and a future as researchers. It consists of a two-week crash course covering all major topics in astronomy: stellar evolution, black holes, galaxy formation and evolution, cosmology, simulations, and gravitational waves, among many others. The classes focus on the relevant concepts in each of the aforementioned fields but without a detailed description of the math formalism or the most advanced concepts in modern physics, this to develop the students' intuition and interest in the wonders of the Universe without overwhelming them. Theoretical sessions are complemented with a set of practical sessions that help students to consolidate the concepts. All theory and practical sessions in this project are being compiled in an outreach book addressed not only to the students of this project but also to the entire amateur astronomy community.

Keywords
Astronomy course, High school, Observations, Practical sessions

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1. Introduction

Humans have looked up to the night sky since very early times. Indeed, the ancient Greek society already had a common widespread knowledge about the sky. Proof of this is the usage of constellations in the Iliad or the Odyssey to illustrate the directions of the hero's travels. More recently, in modern society, iconic figures such as Carl Sagan and Stephen Hawking have also instilled a widespread interest in astronomy. This has been supported by an extensive set of science fiction literature and filmography. Examples of the later are *Contact* or, more recently, *Interestellar* or *Don't Look Up*.

Nowadays, this interest in astronomy continues to grow, remarkably among young people [1,2]. As a direct consequence, we have seen the emergence of several outreach accounts in the social media with millions of subscribers that discuss science in general and astronomy in particular. Examples of such accounts are Quantumfracture (2.88M subscribers) or C de Ciencia (1.45 M subscribers). This growing interest is accompanied by a political will to disseminate the knowledge acquired by researchers, who are encouraged to increase their outreach activities. Indeed, most research grants now give merits to outreach activities (e.g., ERC programs[5]).

However, knowledge does not always flow from scientists to the general public but sometimes it flows both ways. This is known as citizen science and is widespread in astronomy. Leading the citizen science is the Zooniverse project[6] which originated from the GalaxyZoo project of the Sloan Digital Sky Survey Collaboration [3,4] and has now many publications[7]. Astronomy is particularly well suited for citizen science as there are numerous amateur societies whose members often have high-grade astronomical equipment (telescopes, CCD cameras, ...). Professional-Amateur Collaborations are encouraged by entities such as the Spanish Astronomical Society[8]. Amongst other activities they have the award Premio Javier Gorosabel de Colaboración ProAm en Astrofísica[9].

Despite all this, very little astronomy is taught as general education (elementary and high school), and young people often have to look for it elsewhere. For example, the Catalan curriculum [5] only includes one unit about "The Universe and the Solar System", in 1st of ESO (12-year-olds). This is within the "Biology and Geology" subject, often taught by by teachers withoun an background in astronomy and astrophysicss. Other than that, only the students that choose to study a scientific the scientific path at high school get to learn about Newton laws of gravity. Our project, Finestres al Cel, intends to cover this gap.

This paper is organized as follows. In section 2 we present the Youth and Science program, the framework we have used to deploy our project. The project itself is later presented in section 3, followed by a discussion on our ideas for the evolution of this project (section 4). Finally, we conclude in section 5.

2. Youth and Science program

Youth and Science is a program of excellence intended for 4th ESO students, which aims at fostering scientific and technological vocations among young people. For three years, selected students have the opportunity to experience research firsthand, both locally and internationally.

Figure 1. Long and short exposure composite of an observing night in MónNatura Pirineus. This shot was taken in the first observing night of the 2018 stay, in which the students are getting in contact with a telescope for the first time. The main telescope's dome is partially hidden behind a tree. Credit: V. M. de la Cita

During the first year, fifty selected students have the opportunity to have a unique experience and participate in a science research project at

[5] https://erc.europa.eu/
[6] https://www.zooniverse.org/
[7] https://www.zooniverse.org/about/publications
[8] https://www.sea-astronomia.es/
[9] https://www.sea-astronomia.es/premio-javier-gorosabel

MónNatura Pirineus[10] (figure 1). Each year the program offers five projects in different areas of science (physics, biology, chemistry...) designed by a team of expert scientists. 50 boys and girls from all over Catalonia are chosen in each edition to participate in this summer scientific camp. A total of ten students per project are chosen.

The Youth and Science Program does not end with the scientific stays at MónNatura Pirineus but continues for another two years with the research center stays and the international research stays. The goal of these two phases is to continue exposing students to science through a stay either at a research center or with an international science program.

The purpose of the second phase is for each student to join a research team in a scientific laboratory where they can work hand by hand with researchers and in international research groups. This phase also includes a unique option of international research stays with places reserved at prestigious science programs for students in the Youth and Science Program (such as the Research Science Institute at the Massachusetts Institute of Technology).

In order to participate in the second phase of the program, students have to write a scholarly article in the first quarter of the academic year immediately following the end of the first phase. The quality of this article will be a determining factor in securing a place in the next phase of the program.

In the final phase of the program, students should work on their own to find a research project to conduct during the summer after their 2nd year of baccalaureate. The purpose of this phase is for the students themselves to look for a research project on which to work that matches their preferences and scientific interests.

This program has been running yearly since 2008, and it is currently a reference in Catalonia, and students, teachers and schools alike look up to get involved with it, given its proven importance in developing young scientific careers. Due to its extensive trajectory, the number of former participants is large and they have created a network to keep in contact and build scientific relations, known as La Pedrera Science Academy Fellows[11].

3. The project: Finestres al cel

Finestres al cel (FCel) has been selected for seven years to be the astronomy and astrophysics project in the Youth and Science program. We, the authors of this paper, have led the FCel project since it started back in 2015. When we presented the first version of FCel we all were still Ph.D. students and the project was just a proof of concept. It worked well and got good reviews from the participants and the organizer; thus, the project was selected for a second year. From this second year onwards, we took advantage of both the insight we got from the previous versions and our increasing skills on teaching astronomy in the University or other educational centres to improve the project. An example of this increasing teaching skills by the leaders of the project is that two of us got the master of teacher formation (for middle and high school), and one of us is currently a science teacher in a high school.

As we mentioned before, this has been a successful project that in the last six years helped more than 60 students to find out if astronomy may become their vocation. One of the success' keys of the project is that we, the leaders, have an extensive, complementary and diverse background in the astrophysics fields and also a broad experience in outreach and educational activities in Spain and abroad.

After six years of feedback from the students, the organizers of the program, and from our own experiences, the project has evolved greatly. Unexpected difficulties and situations with the weather conditions that limited our practical lessons, and also with the material to be used, helped us to build a solid project with many alternative activities and lectures. The current version includes a large variety of activities, both in-class and practical exercises, that make use of many materials that are in general easy to get by amateur astronomy organization and high-schools. As a consequence, the program not only allows students to get a complete view of the current astronomical research but also to continue small research projects on their own.

Furthermore, the project is always under revision and change. In particular, we continuously update the activities to include unexpected and unique astronomical events

[10] https://monnaturapirineus.com/

[11] https://www.fundaciocatalunya-lapedrera.com/en/pedrera-science-academy-fellows

that become hot-topics in the public media. For instance, when the project started the gravitational wave astrophysics was only a theoretical idea; this changed after the first direct observation of gravitational waves in 2016 [6], when this became new field of experimental astrophysics. We are currently teaching this new field in our lectures as one of the important sources of information about the evolution of the universe, and we also invite experts on the subject to help us with teaching the details on this subject.

Aside of revising the project yearly, the project is very flexible to adapt for unexpected events. For example, the eleven year solar cycle forces us to include or remove from our program activities related with solar activity depending on the Sun's evolution. Other examples include the discovery of new comets or of observable supernovae.

Finally, in the last years we also incorporated new instrumentation we use to allow students learn about new fields in astrophysics, this is the case of the analysis of stellar spectra using a spectrograph (see figure 2).

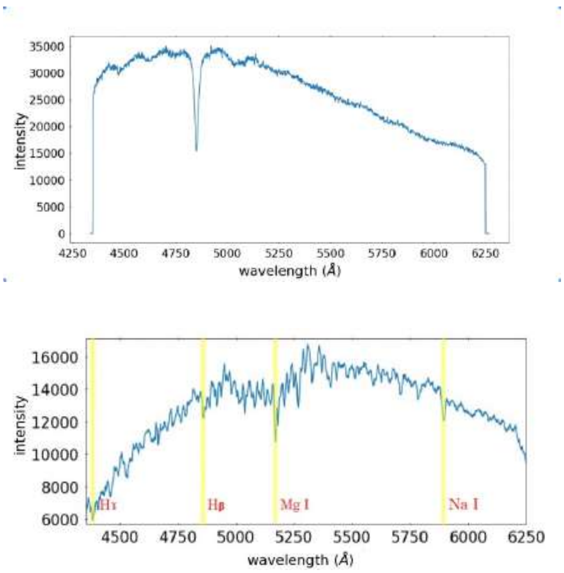

Figure 2. Two examples of spectra captured by the students with the program equipment. The spectrum in the top panel corresponds to Vega, an A-type star with few absorption lines. The spectrum in the bottom panel corresponds to Arcturus, a bright K-type star, much richer in absorption lines. The students highlighted the absorption lines that were able to identify. Credit: Joves i Ciència 2021

With respect to the educational plan within FCel, we moved from a traditional system to a new and modern educative model that is projects based. This was possible thanks to our new skills and the resources we gained when studying the education master and working in high-schools. In this new project, that is an evolution of FCel, we choose the object M13 as the central element of the whole educative event. M13 is a globular cluster visible from the Pyrenees' dark skies in summer that due to its complex nature immediately brings on questions related to many fields in astrophysics.

For instance, M13 allows us to talk about how can we make basic observations of single stars, how the galaxies form and evolve, and how simulations can help us to better understand the formation of stellar groups, among many others. Following the project-based educative model, we adapt our activities to the interests of our students while conducting them all the way through the many topics in the modern astrophysics.

4. Discussion

4.1. Reaching a wider audience

The success of our project in the last six years has encouraged us to expand the potential impact of our work to a wider audience. Our main goal now is to satisfy the need for knowledge about astrophysics that part of our society can have, in particular, high-school students and amateur astronomers. Therefore, we will create and publish a reference book based on the content of the FCel project.

It will include both theoretical and practical content, well beyond the typical outreach books: we want it to be an initial astrophysics course. It will also contain rigorous and up-to-date content on a wide range of astrophysics topics, including discussions on the newest hot-topics in research. In this book we aim to communicate with a plain language and emphasizing the points at which the scientific community is still working to understand.

Regarding the practical exercises, these will exemplify the concepts covered in the theoretical part and will be presented in plain language and with precise instructions for reproduction. Most of them will be reproducible using materials available in many centers of secondary and higher education, and that are easily owned by amateur astronomers. They may be used in the future as basis for work in high school science classes or high school research works. Moreover, the book will also include more specific topics and practices that require more specialized instrumentation.

These will be of interest to students with an advanced level in science and can encourage them to contact with amateur astronomy centers and associations to access their instruments. They will do the same for the amateur astrophysics' community, which often lacks of ideas to take full advantage of the instruments they have. This book will also encourage collaborations between professional and amateur astronomers.

In conclusion, this material will allow the readers to think about questions such as "Is the universe infinite? Is there life on other planets? How do stars form?", mainly providing tools and objective information so that they can respond themselves.

To our knowledge, there is currently no such book available. Thus, as mentioned above, we aim at filling the gap between outreach materials for the general public (usually very superficial in content), and astrophysics text books (usually too advanced).

4.2. An outreach book on general astrophysics

In the last years we worked in a summary of the FCel theoretical and practical exercises, and this has become the skeleton of the book. Summarizing, its structure will be the following:

- **First part:** Modern astrophysics from the solar system to the Universe's large scale from a theoretical point of view. We initiate this part with by introducing the basic concepts in astrophysics and observational astronomy that are necessary to understand both the theory and the proposed practices. This includes the coordinate systems and transformations, the types of telescopes and the detectors. After this very first introduction we explain concepts that are related with the structure, formation and evolution of stars and black holes. Later we move to the formation of planetary systems, in particular the Solar system, but also to a more general view of planetary systems in other stars, i.e., exoplanets, and we also show how can we detect them. The exoplanets topic allows us to introduce and talk about another recent field in astrophysics that is the astrobiology. In the next sections we focus on the wide field of formation and evolution of galaxies and of the Universe itself (cosmology). In relation with the extreme environments that accompany the first instants of the universe and also several star formation and evolution processes, we also teach high energy and gravitational waves astrophysics, two relatively new fields. Finally, we dedicate a section to the description and use of simulations in astrophysics, a topic not well known to the general public and which has great importance and applications in current research.
- **Second part:** In this second part we give the details on the hands-on experiments and practices. This part includes all the activities we designed to settle the theory knowledge we give in the first part of the book. We include the following practices: (1) measurement of the Earth radius using the method use by Eratosthenes, (2) experimentation with distance scales, (3) validation of Titius-Bode's empirical law, (4) photometry of an open cluster, (5) stellar spectroscopy, (6) observation star forming regions, (7) construction of a cloud chamber to detect muons, (8) generation and analysis of an N-body simulation. These are eight hands-on exercises that are related to most of the topics described in the theoretical part, and which can be mostly undertook using accessible materials by high-schools and amateur astronomy associations. Some of them only need rudimentary materials (level, protractor) (1, 2 and 7). Others need a computer and access to public databases (3) or codes that we have designed ourselves and are available on public repositories (3 and 8). And others involve the use of more sophisticated instruments, such as telescopes, specialized cameras and spectrographs (4, 5 and 6). In this book we will also sort and group the practical sessions according to the necessary material and/or its increasing difficulty.

5. Conclusions

Our work within the Youth and Science program has been, on one hand, a constant source of motivation towards education of science; and on the other hand, a playground to test different ideas and proofs of concept. We have discovered which educational experiences work, which doesn't, and how to best present the different concepts of astronomy of our interest and knowledge. This has been done by intensively revising and evaluating the results of our educational activity. The current FCel project and its structure, captured in the outreach book, is the result of years of experience and iteration between four passionate astronomy teachers, 60 students and a supportive group of professionals from La Pedrera foundation.

Every year the stay in the MónNatura educational center surprises us with new challenges. Each generation of students strikes our methods and test our ideas in ways we have not foreseen. This interaction between trainers and trainees and the constant evaluation of the results and impact of our activity is what keeps the project up-to-date and in constant evolution. Therefore, it is easy to foresee that in the future this project will require of new changes on its methodology, and will incorporate new practical sessions and probably new fields in astronomy yet to be discovered.

Acknowledgements
The authors of this paper want to acknowledge the support of the Fundació Catalunya-la Pedrera, without which this project would not exist.
I.P.R. acknowledges support from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 754510.
S.R.F. acknowledges support from a Spanish postdoctoral fellowship, under grant No. 2017-T2/TIC-5592. His work has been supported by the Madrid Government (Comunidad de Madrid–Spain) under the Multiannual Agreement with Complutense University in the line Program to Stimulate Research for Young Doctors in the context of V PRICIT (Regional Programme of Research and Technological Innovation). He also acknowledges financial support from the Spanish Ministry of Economy and Competitiveness under grant Nos. AYA2016-75808-R, AYA2017-90589-REDT, and S2018/NMT-429, and from CAM-UCM under grant No. PR65/19-22462.

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Experiment collaboration program during a Martian analogue mission to introduce young students to human space exploration

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Abstract

The last decade has demonstrated an increased public and private interest towards crewed missions through the emergence of New Space and the Artemis program. There is therefore a need to form the next generation of scientists to prepare future crewed space exploration missions. In this context, it is important to familiarize teenagers with the scientific issues of today's world and to inspire them to engage in the space sector. Crew 263 is a group of seven students preparing a Martian analogue mission at the Mars Desert Research Station (MDRS) in the desert of Utah (United States). A Martian analogue mission at the MDRS, because is the perfect set-up to introduce young students to human space exploration. In the context of their mission, Crew 263 has organized a program of space educational activities for middle and high school students surrounding the topics of altered gravity, astronomy, health and safety procedures and robotic systems. Precisely, a set of four experiments that will be performed by the students was conceived to bring into light the various scientific topics surrounding space exploration missions.

The experiment "Plants in Microgravity" aims to illustrate the influence of gravity on plant growth by planting seeds in pots mounted on a rotating platform in a vertical plane, which will disturb their gravitational cues. "Beginner Astronomer" aims to introduce students to astronomy and astrophotography by establishing with the students a list of galaxies/nebulas to be observed during the Mission. Then, for "Emergency situation at the MDRS" students will put into practice the scientific approach by creating protocols to mitigate risk situations during space exploration missions. Finally, for the "Perseverance's little brother" experiment, students will develop a small rover to analyze the atmosphere condition around the MDRS station.

To maximize their involvement, prior to the mission at the MDRS, the middle and high school students prepare the experiments with the support of the crew. Then, the prepared experiment will be performed in parallel with the crew while they are simulating Martian life. To allow students to be immersed in the mission when the crew will be at the MDRS, short podcasts will be recorded describing the crew's daily life and the evolution of the different experiments. This podcast will be sent to the classes during the simulation, thus allowing the students to have an insight on the daily life of the analogue astronauts at the station.

Keywords

Analog, Education, Human, Outreach, Spaceflight

[1] ISAE-Supaero, France

Nomenclature

r	*Radius*
V	*Volt*

Acronyms/Abbreviations

EVA	*Extra-vehicular activity*
HAB	*Habitation Module*
ISAE	*Institut Supérieur de l'Aeronautique et de l'Espace*
ISS	*International Space Station*
MDRS	*Mars Desert Research Station*

1. Introduction

Inspiring the next generation of scientists in the space field and especially extra-terrestrial exploration is one of the goals of Club M.A.R.S, an association of the French Higher-Education Institute ISAE-Supaero specialised in educational outreach and martian analogue missions.

In the past 8 years, a crew from Club M.A.R.S performs a simulation mission at the Mars Desert Research Station (MDRS). In 2022, Crew 263 performed a 3-week isolation mission from February 20th to the 12th of March.

Figure 1. Aerial shot of the MDRS by Crew 263

During a simulation mission at the MDRS, on top of performing an isolation mission with the linked constraints, in communication, energy and water resource, scientific experiments are performed to study the human factors surrounding such missions as well as technological testing to prepare future crewed missions to the moon and mars.

Parallelly, Club M.A.R.S performs outreach activities at local middle schools and high schools about Martian robotic missions and human spaceflight.

Crew 263 wished to include this outreach activity in their mission. Indeed, a Martian analogue mission at the MDRS, because of its completeness in terms of accurate simulation and experiments performed, is the perfect set-up to introduce young students to human space exploration.

The developed educational activity consisted of a thorough program with a pre-mission preparation, experiments during the mission and post-mission de-brief sessions. Precisely, 9 classes in France chose an activity from a set of 4 space-related experiments. Preparing the experiment set-up and protocols was performed with the support of Crew 263 between September 2021 and January 2022. During the mission, the experiments set-up by the various classes were operated either by Crew 263 or jointly by Crew 263 and the classes. After the mission, a de-brief session on the analogue mission and on the experiments is planned.

To allow an immersive experience to the mission, a series of podcast was made by the Crew Journalist Nicolas Wattelle to give an update on the mission and on the various experiments.

The planned space educational activity experiment ranged from biology, astronomy, robotics to risk and safety topics surrounding crewed missions. Namely, the experiments “Plants in Microgravity”, “Beginner Astronomer”, “Emergency situation at the MDRS” and “Perseverance's little brother” experiments are detailed in Section 2 of this paper.

2. Activity Content

Crewed space missions represent a multidisciplinary domain with many areas of expertise involved. To allow a full scope vision to the young students regarding the future of crewed space exploration, it is important to allow an introduction to various topics.

Hence, 4 different experiments were produced leaving the choice of the activity to perform to the concerned classes. This allows a maximization of the student interest towards the activity. The 4 experiments are detailed in this section.

2.1. Plants in Microgravity

DOI: 10.5821/conference-9788419184405.090

Analysing the effect of gravity to understand the effects of long-term spaceflights is of importance.

During the first preparation sessions the various plant growth experiments performed on-board the ISS were presented as well as basics of mechanics to familiarize the students to the topic.

Then, during later sessions, the experimental set-up to alter the gravity experienced by the plants were identified with the students. Two rotational platforms were selected to alter the plant gravity reference frame, a horizontal one, like Knight's experiment, and a vertical one to further understand the physical relationships between the forces acting upon a plant.

The platforms were a 30 cm radius wooden made apparatus powered by a 12V motor connected to a power generator.

Figure 2. Horizontal Rotation Platform

Figure 3. Vertical Rotation Platform

Rotational platforms were made by the students with the support of Crew 263. This manufacturing process were adapted to each class level with an easier assembly process for lower grade classes and/or adapted to the time allocation for the Space Educational Activity in each school. An assembly process booklet was made for each class.

The same rotational platforms were made for use at the MDRS, these are illustrated in Figures 2 and 3.

During the mission period (20th of February – 12th of March), the rotational platforms were turned on to put the plants in constant acceleration for 3 weeks. At the same timeframe the school platforms were also turned on to allow observation by the school students.

The growth parameters such as length and direction of growth were then to be recorded for the school plants and the mission plants. This observation grid is as presented in Figure 4.

DATE	NOMBRE DE JOURS	HORIZONTAL TOURNANT			TEMOIN VERTICAL			TEMOIN HORIZONTAL		
		PLUS LONG GERME (en mm)	ANGLE A L'HORIZONTALE	DIRECTION	PLUS LONG GERME (en mm)	ANGLE A L'HORIZONTALE	DIRECTION	PLUS LONG GERME (en mm)	ANGLE A L'HORIZONTALE	DIRECTION

Figure 4. Gravitropism observation grid

2.2. *Beginner Astronomer*

Introducing students to Astronomy not only introduces them to scientific topics but also leads to broadening the students' perspectives on our planet, the Earth, in its global scale.

During the first sessions of this Activity, the students were familiarized with the comparisons between Earth and Mars. A topic of interest was also Astronomy in the context of crewed missions. Indeed, during a crewed mission, an understanding of the deep space and Martian environment is of importance to ensure the Astronaut safety. An example is monitoring the Sun's activity during crewed missions to prevent Solar storms which could lead to radiation poisoning. The MDRS is equipped with the Musk Observatory designed to observe the sun and allows the Crew Astronomer to monitor the analog Astronauts safeties during their mission.

To introduce students to this astronomical observation process, the *"Beginner Astronomer"* consists of introducing students to the observation of nebulae and galaxies.

To do so, a simplified Messier Catalog was presented to the students to aid them in the selection of nebulae to observe from the MDRS.

An introduction to other astronomical bodies using Stellarium was also performed during these pre-mission sessions.

The selected Nebulae were then observed during the mission by the Crew Astronomer.

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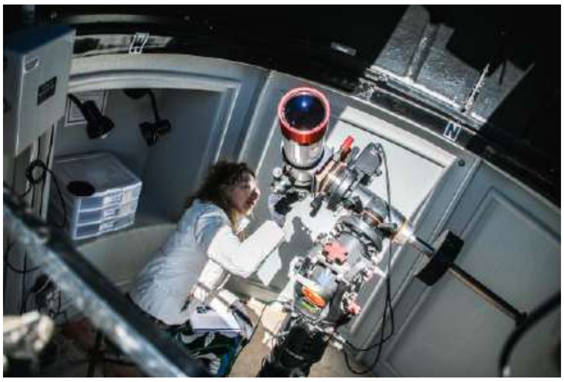


Figure 5. Crew 263's Astronomer in the Musk Observatory

2.3. Emergency situation at the MDRS

In any scientific experiment, the operator's risk and safety must be carefully considered. An understanding of the experimental set-up is of importance when preparing and establishing experiment protocols. This activity aims to cover such topics in the context of crewed space exploration missions.

During the pre-mission sessions, the topics of crewed space missions and existing safety protocols such as fire evacuation procedures are presented. Then, through a presentation of the facilities and tools present in the MDRS, safety protocols are established by students. Namely two scenarios of interest are studied:

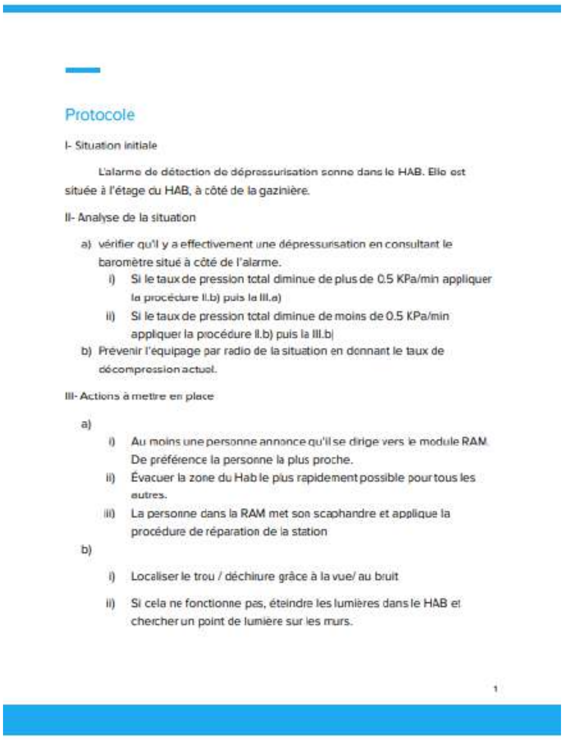
- HAB module depressurization
- Injured Astronaut during an EVA.

The first scenario corresponds to a depressurization of the Astronaut's habitation module (HAB). The Astronauts must identify the issue and act according to the depressurization level to place them in a safe situation by following the developed protocol.

The second scenario covers an injured astronaut during an EVA. The protocol shall indicate the course of action to be followed by the other (non-injured) EVA members to place the injured member in a safe place, evaluate the environment they are in, seek for external support and support the injured astronaut.

The ISS safety protocols are recalled for a comparison to the established protocols.

The two upper mentioned scenarios are simulated during Crew 263's mission and the student protocols are followed. The emergency situation timeline is recorded to provide feedback on the student protocols.



Protocole

I- Situation initiale

L'alarme de détection de dépressurisation sonne dans le HAB. Elle est située à l'étage du HAB, à côté de la gazinière.

II- Analyse de la situation

a) vérifier qu'il y a effectivement une dépressurisation en consultant le baromètre situé à côté de l'alarme.
   i) Si le taux de pression total diminue de plus de 0.5 KPa/min appliquer la procédure II.b) puis la III.a)
   ii) Si le taux de pression total diminue de moins de 0.5 KPa/min appliquer la procédure II.b) puis la III.b|
b) Prévenir l'équipage par radio de la situation en donnant le taux de décompression actuel.

III- Actions à mettre en place

a)
   i) Au moins une personne annonce qu'il se dirige vers le module RAM. De préférence la personne la plus proche.
   ii) Évacuer la zone du Hab le plus rapidement possible pour tous les autres.
   iii) La personne dans la RAM met son scaphandre et applique la procédure de réparation de la station
b)
   i) Localiser le trou / déchirure grâce à la vue/ au bruit
   ii) Si cela ne fonctionne pas, éteindre les lumières dans le HAB et chercher un point de lumière sur les murs.

1

Figure 6. Part of HAB depressurization protocol established by students with the support of Crew 263

2.4. Perseverance's little brother

2021 marked a successful year in Martian exploration missions with the Perseverance rover accomplishing new milestones and successful lights of the Ingenuity Helicopter.

To generate student enthusiasm about space exploration missions and more generally, scientific projects, space robotic systems are introduced through the "Perseverance little brother" activity.

Students are firstly introduced to Martian robotic missions and subsystems involved in space systems are presented.

With the support of Crew 263, the students then decided on a Mission Objective, manufactured a rover to be operated at the MDRS.

The selected mission objective by students is an atmospheric mapping experiment which ais to map atmospheric conditions surrounding the MDRS such as temperature and pressure as well as the rover health parameters (battery level, acceleration, and GPS location).

3. Activity Timeline

As mentioned in the introduction section, the MDRS Space Educational Activity counted 3 main parts. A pre-mission preparation, a during-

DOI: 10.5821/conference-9788419184405.090

mission operation and a post-mission analysis part.

The pre-mission part corresponds to slide supported presentation with interactive discussion parts including quizzes. Then, manufacturing of the experiment for the gravitropism and rover activities with the support of the Crew.

During the Mission, the students followed Crew 263's mission and the updates of the Educational Activities through podcast updated on a dedicated Youtube Channel: https://www.youtube.com/channel/UCeiAeMiOo-RhkQF9UoW_74g

Each podcast episode covered a different aspect of crewed missions from EVAs to the daily routine of Astronauts in the Habitation Module. The podcast format is in accordance with the data limitation at the MDRS to simulate the isolated environment.

Finally, a post-mission debrief is planned for the April to July 2022 period to share the obtained results by the students and Crew 263.

Figure 7. Steps of the Space Educational Activity by Crew 263

4. Results and Discussions

During their mission at the MDRS, Crew 263 and students obtained the results summarized in this section for the developed Space Educational Activity.

4.1. Plants in Microgravity

The rotational platforms were initially installed in the GreenHab, the MDRS greenhouse. However, due to a whitefly infection, the greenhouse had to be shutdown. The experiment apparatus thus had to be moved to the MDRS ScienceDome. The environment changes and low temperature in the ScienceDome led to a perturbation in the growth of the plants. The growth rate was not enough to observe gravitropism.

However, in the respective schools, no environment change was necessary for the rotational platform. A plant growth aligned to the centrifugal force was observed demonstrating gravitropism.

4.2. Beginner Astronomer

Introduction sessions to Astronomy were completed. However, for the Nebulae selection session, COVID-19 translated to rescheduling of the sessions. Hence, the selection by students were not performed before the mission by the students.

However, Nebulae and Galaxy observations were made by the Crew Astronomer, Marine Prunier. Thus, their observations will be presented to the students during interactive sessions in April-July 2022.

Figure 7. Galaxy M81, captured by Marine, Crew 263's astronomer

4.3. Emergency situation at the MDRS

The student developed protocols were tested out on 3 different situations.

The injured astronaut protocol was tested twice and the HAB depressurization once.

To test out the ability of Astronaut to follow the protocol and assess the effectiveness of the developed protocol while being in a simulation, an external stress factor could be included. Indeed, for the injured astronaut protocol, the analog astronaut who was supposed to simulate the injury switched to account for this additional stress factor. The stress response of the Analog Astronauts were recorded for this study and showcased a handled response as illustrated in Figure which shows normal heartrate responses.

DOI: 10.5821/conference-9788419184405.090

Figure 7. Heartrate response of the Analog Astronauts

While staying in simulation, the protocols allowed the injured astronauts to be recovered by the rescue crew and the astronauts in the breached HAB to move safely in a pressurized module.

Ways to improve the protocols were identified such as required additional information on first aid steps, additional ways to inform the rescue drone, additional ways to identify the breached area in the HAB .

4.4. Perseverance's little brother

Students at the Lycée International de Saint-Germain-en-Laye developed the *Kepler* rover (Figure 7) designed to take atmospheric measurements.

The rover mechanical part design, manufacture and assembly was successfully completed by the students. However, the students faced difficulties in the navigation code scripting related to operational constraints in the area surrounding the MDRS.

The rover will be tested out by the ISAE-Supaero 2023 Crew during their mission at the MDRS.

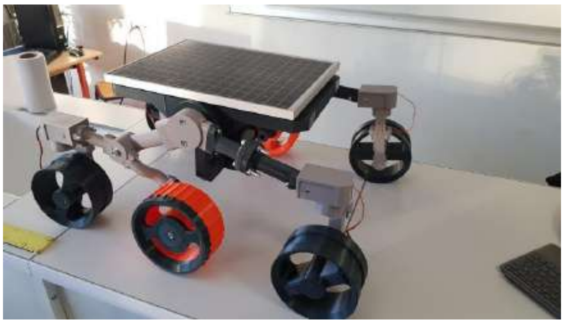


Figure 7. Kepler Rover

4.5. Mission Operation

All these experiments were part of an analog mission and hence, illustration of the full scope of crewed missions was of importance to give a global view to the students. Indeed, it helped understanding the environment present to operate the experiments. Podcast episodes dedicated to different aspects of a crewed missions were created.

The first episode covered SOL 0 to SOL 2, the first EVA and the explanation of atmospheric experiments: https://youtu.be/gJ3SfJVWgik

The second episode about SOL 3 to SOL 5 focused on human factor experiments, the gravitropism experiment, and the role of the Crew Astronomer: https://youtu.be/lC8IfZt5WGE

The third episode's focus (SOL 6 to SOL 8) were spirulina growth experiments through the GreenHab Officer's role and geology field studies presented by the Crew geologist : https://youtu.be/utLbL10MqUw

The fourth episode's covered SOL 9 to SOL 11, the emergency protocol experiments and radio communication experiments: https://youtu.be/33oURy4jzv4

The fifth episode (SOL 12 to SOL 14) detailed the EVAs in more detail and the role of the Crew Commander: https://youtu.be/qjua9auxdpE

The final episode (SOL 15 to SOL 17) presented the Crew Engineer's role, ultrasound medical surveillance surveys as well as the Space Educational Activities: https://youtu.be/j88USgAho1Y

5. Conclusions

Although some in-mission results could not be obtained due to environmental constraints or schedule issues related to the COVID-19 pandemic, an interactive and multi-disciplinary outreach to students was possible through Crew 263's mission at the MDRS.

The studied activities were all related to the national middle school and highschool study programs; this allowed both to generate enthusiasm

Acknowledgements

We would like to thank all the schools who participated to our Space Educational Activity. Namely, Collège Claude Nougaro (31, France), Lycée Toulouse Lautrec (31, France), Lycée Henry Matisse (31, France), Lycée International de Saint-Germain-en-Laye (78, France).

This experience was also made possible thanks to the help of Ose, the social outreach association of ISAE Supaero, which put us in contact with the secondary schools of Occitania.

Student perspective and lessons learned from participating in the European Rover Challenge 2021

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Abstract

The European Rover Challenge (ERC) is a competition where multiple teams from all around the world must face the technical, logistical, scientific and managerial difficulties of designing, building and operating a rover capable of performing a myriad of different tasks in a Mars analogue terrain (also known as Mars Yard). The competition, held in Kielce, Poland and organized by the Kielce University of Technology in collaboration with the European Space Foundation, regional governments, the European Space Agency, the Mars Society and other honorary patrons showcases each team's creativity, innovation, drive and passion to an expecting audience, serves as an entry point to complex large-scale engineering projects for students from all backgrounds, supplying them with essential soft skills often overlooked during regular university education and connects like-minded individuals from different countries, encouraging international communication and collaboration in the aerospace industry. The authors of this paper participated in last year's competition, ERC2021, and achieved 10th position. In this paper the insider perspective from first-time ERC participants will be discussed, including all the steps made to apply and qualify, the issues faced along the way, the lessons learned and the final experience of the on-site trials.

Keywords

Rover; European Rover Challenge; Robotics; Planetary Science; Planetary Exploration; Mars Analogue

Acronyms/Abbreviations

SSEA	*Symposium on Space Educational Activities*
UPC	*Universitat Politècnica de Catalunya*
ESEIAAT	*Escola Superior d'Enginyeries Industrial, Audiovisual i Aeroespacial de Terrassa*
UPCSP	*UPC Space Program*
ERC	*European Rover Challenge*
MY	*Mars Yard*
PDR	*Preliminary Design Report*

1. Introduction

As of the date of writing this paper, the only hope for humanity's exploration beyond the confines of our own planet lies in using remote exploration robots that, either from orbit or on another planet's surface, serve as our eyes, ears and other senses. Currently there are a total of 4 rovers exploring foreign cosmic objects [1], [2], [3]. Studies and investigations carried out by these rovers provide better insight into the mysteries of planetary geology than satellites thanks to their mobility and close proximity to points of interest. The technical complexity they entail, however, is a challenge on a global scale and problems faced in day-to-day rover operations are tackled by the international community. With this in mind plenty of competitions worldwide task up and coming engineering students with facing similar problems and coming up with creative and feasible solutions which might be applicable to martian or lunar rovers. One of these competitions is the European Rover Challenge.

2. The European Rover Challenge

The European Rover Challenge (ERC) [4] is an educational robotics and space event where teams from across the world design, build and operate a rover to perform a number of tasks in Mars analogue terrain, the Mars Yard (MY), built specifically for each year's edition in Kielce, Poland. The tasks that each rover needs to accomplish covers a broad range of technical challenges which are present in nowadays space exploration, and to qualify the teams are tasked with documenting their work to prove their capacity to face the following tasks:

- **Science task:** Before the competition begins the teams have delivered a science planning which is then executed in the MY. After exploring a science report must be delivered shortly after.
- **Maintenance task:** The rover must activate switches, measure voltage and connect jumpers and an ethernet cable on a maintenance panel.
- **Probing task:** The rover must place a total of 3 probes in the MY in previously selected locations and after performing other tasks collecting the probes back.
- **Navigation task:** The team is given a total of 4 waypoints which must be reached. During operation, however, the rover's operator must not be able to see from any cameras, and the rover must internally calculate its position and communicate it to the operator.
- **Presentation task:** The teams must present the project, the team and the rover in an oral presentation in front of the jury.

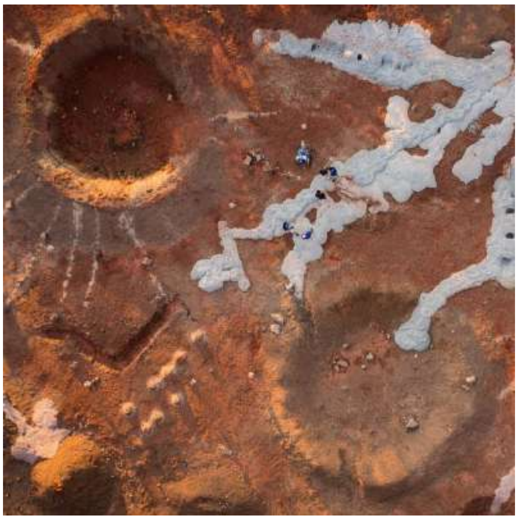

Figure 1. Mars Yard from above. [4]

3. The team

The team is part of the UPC Space Program [6] student association, which has the aim of acquiring knowledge and experience and transmitting it to the newer generations of engineering students. The UPC Space Program is currently separated in 5 missions: Ares, which designs and builds solid fuel rockets; Aldora, which develops and builds drones; Zephyros, which develops and builds high altitude balloons; Horus, which designs subsystems for CubeSats; and GRASS, which develops exploration rovers. The robotics branch of the UPC Space Program has a main objective of getting students acquainted with robotic exploration through the design and

DOI: 10.5821/conference-9788419184405.091

development of a rover for international competitions. The student association is predominantly multidisciplinary, with members ranging from aerospace engineering to industrial, mechanical and electrical engineering. The mission started in 2017 with the construction of mechanical parts and a first iteration of the electronics, but due to the members finishing their studies the mission was stopped. However, it was recovered in 2019 using the leftover materials of the 2017 rover to start testing new technologies such as terrain mapping, experimenting with new 3D printing techniques in order to build a new electronics box and a robotic arm to attach to the new base. The next year, however, the team focused on participating in international competitions, mainly the UAV Challenge Medical Rescue 2020. It was unfortunately postponed due to the COVID-19 pandemic, so an alternative was found in the European Rover Challenge.

Figure 2. Team members with the rover in the background. [5]

4. First phases: Documentation

The first step to apply is to produce a very brief document which includes the team's interpretation of the rulebook, the approach to solving each task and a preliminary risk assessment [6]. The format and the specific points included are a great guide on how to define the technical requirements for a project. With this proposal produced and delivered, the team is now in the competition and must start working on both the rover and the next keystone, the Preliminary Design Report.

Two months after, in May, comes the deadline for the most important document of the process: the Preliminary Design Report (PDR) [6]. In this PDR the process mentioned before in the proposal is repeated in more depth. The architectures, components, the budget, the safety systems and in general a Work Breakdown Structures (WBS) must be defined, even if it's not the final iteration. This serves as a follow-up guide on the more complicated aspects of managing such a project: thinking about inter-dependencies of the different subsystems, budget monitorization and constraints, and a deeper risk matrix with mitigation and contingency procedures. An initial science planning must also be delivered. After the delivery of the PDR all the documents delivered up to that point are evaluated, and the 15 teams with the most points qualify for the On-Site trials in Kielce, Poland. In this year's ERC there was a 3-way tie for 15th place, so a total of 17 teams qualified for the event. By mid-summer the final report with the final version of all previous sections with all the definitive components, schematics, and most importantly the reflection upon previous risk assessments, identifying strengths and weaknesses and the lessons learned along the project. A report on the radio communication systems of the rover and a science plan where the selected points of interest and what can be learned from them is explained.

The science report produced after the competition is delivered the same day as the science exploration. This year, in our case, due to technical issues that will be mentioned in sections 6 & 7, we didn't reach our selected point of interest and we had a very small amount of visual information to use for science purposes.

5. Qualification: Construction

After the design phase was completed in May with the delivery of the preliminary design report, the construction phase of the rover began. In this phase, 3d printed elements were produced and assembled and final code, electronics and wiring were planned to be implemented. Nonetheless, due to pandemics restrictions and mobility problems, all the construction phase was finally delayed causing a lack of validation and verification processes.

The difficulty of having face-to-face meetings generated misunderstandings that led to incompatibilities in the assembly. As a result, the final structure had several tolerance problems and many different kinds of unions that impeded making quick changes. For these reasons, a design review had to be executed in order to accomplish the assembly between the different interfaces.

The delays in the final assembly and the last time modifications forced the electronics department to manage against the clock in the wiring interface, since the planned design, which incorporated elaborated connections and a complex wiring system, was substituted by welded cables and protoboard connectors.

As regards to the software implementation, the final structure for testing was not available until a few weeks before the competition and many of the tests that were successful months before failed in the assembly general test. As an example, PID controllers were not able to ensure a soft motion of the assembled robotic arm or compensate for the imbalance between the wheels. Moreover, due to the inexperience of the software team, some advanced requirements such as location algorithms were in an embrionary phase in the last few days. Nevertheless, the communications between the rover and ground station were tested successfully and the rover was able to do some basic tasks before departing to Poland.

6. Journey to Kielce & trials in the MY

In order to manage the logistics of the transport, the rover was disarmed and transported in protected baggages. For this reason, at the arrival in Poland, some of the pieces suffered damages, which afterwards were repaired with in-situ materials, affecting the expected performance. Aside from this, due to a problem related to the power supply, the Raspberry pi, which was the master communicator between the ground station and the rover, was damaged and a reprogramming of the Jetson was required to accomplish this task. Hence, this implied the loss of the stereo vision, since the deteriorated device was also in charge of it. Moreover, since the power supply of the robotic arm was not able to fulfill its task also, a trip to Warsaw was needed to achieve some new operational electronic components.

Figure 3. The GRASS rover in the MY [5].

During the probing and maintenance tasks, due to the aforementioned complications, some issues related to the robotic arm were encountered. Even trying to solve these problems by changing some pieces and postponing the tasks, some of them were not able to be accomplished. In the navigation task, the rover was supposed to drive blindly, nevertheless, due to a malfunction and the lack of time to verify and validate the associated performances, as stated in the construction stage, the position of the robot could not be adequately found, therefore, the task was invalid. After switching on the cameras, the rover could move through the Mars Yard, however, it got blocked and, consequently, only one picture was taken.

Figure 4. Team members during the probing & science task. [5]

7. Results

In summary, a relevant number of components failed in their performance, for instance the stereo vision did not work, the robotic arm resulted uncontrollable and the navigation algorithm was not satisfactory.

Despite all these encountered issues and thanks to the produced documentation, including the preliminary science planning, and the small amount of points obtained from each task, the team was placed in 10th position.

8. Discussion

The results achieved this year were due to a clear lack of focus from early on in the project, apart from the lack of time and resources. Work started on the rover fairly late, and a lot of work was obsolete and incohesive. The lack of knowledge led to preventable errors, like the lack of care for the logistic aspects which led to the technical problems mentioned before. No members of the university were asked to provide support in the form of technical advice. From the point of view of the team, it was also a

DOI: 10.5821/conference-9788419184405.091

not ideal way of tackling such a challenge, since it entailed periods of crunch.

In essence, the participation in ERC2021 has been a nourishing experience for all the team members, which resulted in important lessons for the future of the mission. Since the structure of ERC2022 remains more or less similar to the previous year, thanks to the acquired background in the contest, the team is more capable of paying attention to the aforementioned errors and trying not to repeat them. Moreover, the most part of the elaborated documentation is available for this next edition, given its high rating in the previous one. Regarding the overall difficulties, they were mainly based in planning miscalculations and, for this reason, an early solid management process is currently being implemented for the participation of ERC2022.In reference to the technical part, the lack of specific knowledge is being overcome by the support of docents specialized in different areas, such as navigation and control systems. As future goals, the team aims to achieve a competitive baseline, become a habitual ERC participant and expand onto other international competitions across the globe.

9. Conclusions

This paper revolves around the experience of the UPC Space Program GRASS team in the European Rover Challenge 2021. The competition is explained, the team is introduced, and then the process through which the challenge was tackled is described. The results yielded by this process, which were not the best, are analysed and the reasons for the issues faced along the competition are explored. The nonoptimal results stem from improper management structures and a lack of clear focus, knowledge and resources. From this analysis, the lessons learned are disclosed and the steps to improve as a team that either are already in place or will be implemented in the future are enumerated.

Acknowledgements

We thank the Universitat Politècnica de Catalunya for funding the student association and providing it with space for its workshops, and we thank the European Rover Challenge organization [7], the other participants, and the voluntaries for the support and assistance. Last but not least, the team thanks the 4th SSEA22 [8] Scientific Board for giving young students the opportunity to present their projects and get in touch with the scientific community.

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Montsec Ground Station

M. Badia[12], A. Perez-Portero[12], Aina Garcia[3]

Abstract
In every space mission, the ability to contact the satellite to transmit or receive telecommands and data is one of the critical parts, so having a good ground segment is fundamental.

In support to [3]Cat-2 operations a ground station was first developed by the UPC NanoSat Lab at UPC Campus Nord premises. However, due to increasing radio frequency interference it was moved to the Institute Space Studies of Catalonia (IEEC) - Observatori del Montsec (OdM), located in Sant Esteve de la Sarga, Lleida. This location has outstanding reception conditions in terms of very weak interference levels, and excellent elevation mask (i.e. satellites can be tracked even below the horizon).

The ground station is equipped with a TX/RX Yagi antenna for amateur bands VHF (144-146 MHz) and UHF (435-438 MHz), and it also includes an S-band 3-meter dish in the commercial band (2025-2110 MHz, 2200-2290 MHz) for reception that will be upgraded for transmission in 2022. The antenna rotors, receivers etc. are remotely controlled to the operation-center in Barcelona and operations can be automated.

Nowadays, the ground station is jointly operated by the UPC NanoSat Lab and the IEEC in support to the Catalan New Space strategy, in addition to the upcoming UPC missions.

Keywords
CubeSat, Ground Segment, S-Band, UHF, VHF

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[2] Institude of Space Studies of Catalonia (IEEC) – CTE-UPC
[3] UPC, Universitat Politècnica de Catalunya – Barcelona Tech

Acronyms/Abbreviations

BDA	*Bi-Direccional Amplifier*
IEEC	*Institut d'Estudis Espacials de Catalunya*
LEO	*Low Earth Orbit*
LNA	*Low Noise Amplifier*
OdM	*Observatori del Montsec (Montsec Observatory)*
PA	*Power Amplifier*
UPC	*Universitat Politécnica de Catalunya*
SDR	*Software Defined Radio*
SSO	*Sun Synchronous Orbit*
TT&C	*Telemetry, Tracking and Control*

1. Introduction

As cubesats are in expansion due to affordable launch and procurement components.

The UPC Nano-Satellite and Payload Laboratory, NanoSat Lab, an initiative of the Dept of Signal Theory and Communications with the support of the School of Telecommunications Engineering of Barcelona to design and develop nano-satellite missions focused on the exploration of innovative small spacecrafts, subsystems and payloads for earth observation. In order to control, tracking and receive the data generated by satellites. It develops its ground station system. A VHF/UHF [1] and S-Band ground stations [2] were placed in Montsec mountain range with collaboration with IEEC.

And in addition, to control and operate the ground segment an operation center [2] was designed and implemented.

2. Barcelona station and issues

With the mission of ^{3}Cat-2, NanoSat Lab needs a ground station to perform the operations.

Its first option was place an UHF/VHF ground station in the top roof of UPC Campus Nord building in Barcelona.

The station was capable of VHF RX and UHF RX & TX (half duplex).

But due to the noise floor of this location is high and also tall buildings and mountains block part of the field of view. The station is not suitable to becomes the main operation VHF/UHF ground station of NanoSat Lab missions.

3. Montsec Observatory

The OdM is a scientific infrastructure manage by IEEC. It is located at altitude of 1570 meters in the Montsec montain range (Catalan Pre-Pyrenees), in Sant Esteve de la Sarga.

The area is recognized as one of the most suitable in Europe for conditions and low effect of light pollution.

As there are good conditions of signal reception due to very low noise floor and has good elevation masks. OdM was choose to place the UPC NanoSat Lab ground stations.

3.1. Satellite pass characteristics

In Montsec location the passes of SSO LEO satellites have an average time pass of 7.5 minutes and each day a satellite can view our ground stations an average of 3 or 4 times per day.

As Montsec location has very good elevation masks in some occasions the satellite signals can be receive below the horizon.

Figure 1. Montsec UHF/VHF antennas

4. Montsec VHF/UHF TT&C station

The VHF/UHF TT&C station, **Figure 1** is designed to have VHF RX and UHF TX and RX same as Barcelona ones and it is developed with full SDR capabilities.

DOI: 10.5821/conference-9788419184405.092

The VHF Yagi antenna has vertical and horizontal polarization components. And the antenna has a gain of 10.5 dBi. On the other hand, UHF antenna also has vertical and horizontal polarization components and its gain is 12.8 dBi.

The Rotor is an azimuth/elevation Yeaesu rotor controlled by an own design controller based and commanded via Ethernet by ground station computer.

This station was used in ^{3}Cat-1 missions and it will be used in ^{3}Cat-4 missions that will be launched soon.

5. Montsec S-Band TT&C Station

With FSSCat mission, the winner of the 2017 Copernicus Master ESA Small Satellite Challenge S^3 and Overall Winner. That it consists in an innovative concept of two federated 6-unit Cubesats, called ^{3}Cat-5/A and ^{3}Cat-5/B.

To download the scientific data an S-band downlink was required.

Therefore, the UPC NanoSat Lab designed and implemented a S-band ground station located in Montsec Observatory.

So far the station has only downlink capabilities but to achieve the full operations for NewSpace strategy satellite missions of government of Catalonia and also future ^{3}Cat missions as ^{3}Cat-6/RITA payload. The S-band ground station also needs to have the uplink.

As the implementation and installation of upgrades is performing now. The uplink upgrade will be ready soon.

Figure 2. Montsec S-Band Antenna

5.1. Main characteristics

The ground station is composed mainly by RF chain, antenna, rotor and controllers. With an antenna of 3-meter diameter dish, **Figure 2**, it can achieve 35 dBi as antenna gain.

Using a Bidirectional amplifier (LNA+ PA) near the feeder makes that ground station has maintained a low noise level on downlink channel. The other RF chain parts are located in rack cabinet inside the building with the Azimuth/Elevation controller, SDR, ground computer, and other related parts.

5.2. Downlink capabilities

With the described characteristics the S-band downlink can achieve better and bigger capabilities than VHF/UHF ground station, **Table 1**

Table 1. S-band Downlink Capabilities

Parameter	Value	Unit
Pass Duration	7.5	Min
Passes each day	3	-
Velocity	2	Mbps
Download data per day	337.5	MBytes
Download data per month	10.125	GBytes

6. Operation Center

To control VHF/UHF and S-band Montsec ground stations all its elements are managed by operation center and it can control remotely.

The operator can debug all the elements remotely if it is necessary. And also can manage and introduce new passes for each satellite.

To track a satellite, the ground station uses the TLE, orbital parameters, that each satellite has, propagating its orbit, its orbital position is obtained at any point of time and the antenna can track and move it to follow it.

In addition to visualize the satellite passes the operation center has a live viewer to control the movement of antenna, the orbital location of the satellite and the received signal, **Figure 3**.

DOI: 10.5821/conference-9788419184405.092

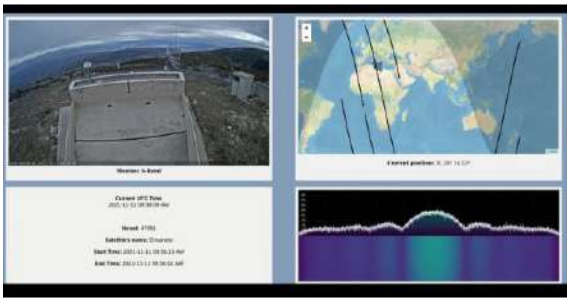

Figure 32. Montsec S-band viewer during 3B5GSAT (Enxaneta) pass

7. Conclusions

The ground stations located in Montsec, Observatory in special the S-band ground station has become an indispensable piece of excellent results of missions as FSSCat mission.

The ground stations will continue use for next launches of ^{3}Cat missions as ^{3}cat-4 and ^{3}Cat-6/RITA Payload and also for the NewSpace strategy satellites missions.

To increase the capabilities to download more data in Montsec. The X-band downlink capability also will be acquiring.

Acknowledgements

I would like to thank the professor Adriano Camps for the great experience that I have acquired by to involve in the projects performed in the UPC NanoSat Lab.

Also the UPC NanoSat Lab team for the help to develop the ground station upgrades. And finally to IEEC to give me the opportunity to work with S-band and future upgrade capabilities of TT&C stations in OdM.

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Adaptation of the AcubeSAT nanosatellite project into remote working during the COVID-19 era

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Abstract

The global COVID-19 pandemic has undoubtedly forced the global community to embrace the transition to a world where remote and hybrid work models are becoming the new standard. But for the space engineering community, this change is more impactful than other engineering fields. Switching the entire workload from in-person concurrent design and verification activities to a hybrid or an online model has dominated the discussions in relevant symposia since the start of the pandemic. This switch is also more challenging when you must accommodate more than 50 developers who are volunteer students.

The AcubeSAT team underwent this transition during 2020-2021, where all design and prototyping activities for the team's nanosatellite were moved to a remote work scheme. After several adaptations, this scheme has been fine-tuned and experimented upon to ensure that development activities could continue at a normal pace, and that the physical and mental health of the entire team was guaranteed. These adaptations include changes in infrastructure, team structure and meetings, but most notably they attempt to answer the question of how the concurrent design technique and the review processes can be implemented in an online world.

More specifically, a number of ready-made and in-house platforms and utilities, mostly based on the open-source philosophy, were used to bridge the gap between in-person and online workloads. In an attempt to combine the advantages of online conferencing with the casualness, directness and availability of in-person meetings, we analysed and experimented with various online platforms and project management tools to foster organic collaboration. Furthermore, the use of version control systems as a main tool for internal and external reviews and the documentation produced by the team allowed for a more transparent, reliable and streamlined review process.

All of these changes enabled the conclusion of AcubeSAT's Critical Design Review remotely in summer 2021. The project is now in the manufacturing and verification phase, with the hybrid work model still in place. With this contribution, lessons learned from the project's transition to an online and subsequently to a hybrid work scheme will be shared, showing how a large-scale educational project can be implemented under these conditions. The changes performed to accommodate this scheme, along with the rationale behind them and the subsequent challenges posed by them, will also be discussed. Finally, the benefits of such a transition will also be presented, which include more efficient use of time, superior project documentation and the enlargement of the project to students from international universities.

Keywords

concurrent engineering, COVID-19, CubeSat, project management, remote work

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Acronyms/Abbreviations

CDF	*Concurrent Design Facility*
CDR	*Critical Design Review*
ESA	*European Space Agency*
FYS	*“Fly Your Satellite!”*
HIL	*Hardware-in-the-loop*

1. Introduction

1.1. SpaceDot and AcubeSAT

It is evident that the COVID-19 pandemic has imposed a fundamental transition to hybrid or totally remote working schemes on a global scale [1]. This evolution has hugely affected the Space Engineering Sector [2], introducing challenges especially in university teams which employ a major number of developers, volunteer students. The SpaceDot team in Aristotle University of Thessaloniki currently consists of 79 members from 16 university departments from Greece and abroad, all of which are part of the AcubeSAT nanosatellite project, one of the 3 selected projects in the “Fly Your Satellite!” (FYS) 3 programme of the European Space Agency (ESA) Education Office [3], [4]. AcubeSAT is a 3U nanosatellite with a biological payload, designed to explore the effects of space conditions on eukaryotic cells, aiming at a 2024 launch [5]. During the last 2 years, much debate has been stirred regarding the positive and negative impact of the remote working model [6]–[8]. Of course, the characterization of the impact can only be subjective and heavily depends on the philosophy and the objective of the members. However, the lessons learned from the adaptation of the team in the new scheme and the use of specific tools for concurrent engineering, indicate that some key aspects of remote working are affected in a quite similar way among most members of AcubeSAT.

1.2. Concurrent Engineering

For the design of AcubeSAT, SpaceDot uses the concurrent engineering technique. In contrast to “traditional” engineering approaches, such as the over-the-fence approach, concurrent engineering enables the parallelization of tasks in the development of a product [9]. This approach can lead to faster development times, but does also require the combination of technical and human factors to be realised, which usually happens at a dedicated facility, such as the Concurrent Design Facility (CDF) [9]. The impact of COVID-19 to concurrent engineering and ways to mitigate it have been a matter of debate in recent conferences [9], [10] and will also be briefly discussed in this paper.

1.3. Internal AcubeSAT study

An internal AcubeSAT study was performed in early March 2022, with the goal of evaluating the team’s remote and hybrid work scheme from the perspective of the members. 58 AcubeSAT members (participation rate: 73.4%) took part in this study by answering a short questionnaire. Key findings from this study will be provided throughout this paper.

2. Background

To provide a better understanding of the problem being faced, some background information on the organisation of the AcubeSAT project is required. The team is composed of university students who work on a volunteer basis, with a mean tenure of 1.14 years. The number of actual members fluctuates throughout an academic year from around 60 to 80 students, currently the project has 79 active members.

In 2019, around the time of the FYS 3 selection workshop, AcubeSAT was at Phase B or the preliminary design phase. Up until that point, design efforts consisted of two main activities: a) concurrent design sessions being performed during the weekend to catch up on interdependencies, subsystem updates, system level budgets and issues, which provided input for b) subsystem level work and analysis being performed throughout the week. It is also important to note that the majority of these activities took place at the team’s facilities within the university, ensuring a high level of interactions between members from different domains of expertise, which aids the concurrent design effort. The team followed a horizontal organisational structure and actively encouraged communication, transparency and rapid feedback. This process was followed for most of 2019, with breaks occurring mostly for holidays and exam periods.

After the submission of the AcubeSAT proposal, the team confirmed its participation in the programme in February 2020, 1 month before the suspension of all educational institutions operation in Greece as part of the announced measures to prevent the spread of the COVID-19 pandemic [11]. The date of our acceptance at the program coincided with the beginning of the Phase C or the detailed design phase, during which the Critical Design Review (CDR) had to be prepared. The impact of the abrupt change into remote working in March 2020 had to be absorbed as quickly as possible, in order to preserve the workflow of the members and to keep the project on track. While the work ethic in AcubeSAT was maintained, the number of concurrent design sessions between subsystems was significantly increased to address issues that occurred due to interdependencies.

The main goal of the team for the remote switch was to simulate the real life work environment which the team had created as much as possible, ensuring that the productivity remains high and the experience is rewarding and fun for all members, despite the presence of the COVID-19 restrictions. Communication (through text and speech) was the primary concern during the switch. At the same time, the team had to ensure the access of all members to its infrastructure and an effective process for documenting and reviewing.

3. Infrastructure & tools chosen for remote working

3.1. *Existing infrastructure*

Prior to the COVID-19 pandemic, the AcubeSAT team had already invested in a supporting infrastructure to enable text based communications, information and document sharing and access to planning and organisational tools. Upon entering the team, AcubeSAT members are logged in a Lightweight Directory Access Protocol (LDAP) authentication database, which provides them access to all self-hosted platforms.

Those platforms include mainly the internal chat server of the team, *Mattermost* and one of the two main file storage places, *Nextcloud*, which also stores all the confidential files. Besides them, SpaceDot servers also host the *LimeSurvey* tool for all surveys conducted in the team, the *4minitz* platform where all meeting minutes are saved as well as the *Postfix* / *Dovecot* / *Roundcube* combination to handle sending and receiving e-mails.

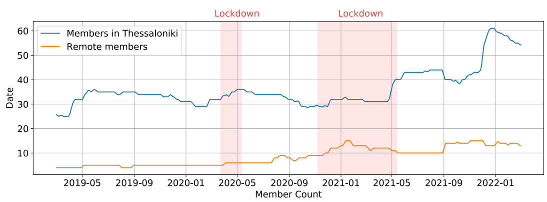

Figure 1. Number of remote and on-site members vs time (7 day rolling average)

3.2. *Meeting solutions*

In order to keep all the work on track and cover all interdependencies between subsystems, organic interactions between students were replaced by multiple meetings during the week. Selecting a suitable meeting platform was the first step towards a smooth transition. For internal meetings, SpaceDot opted for a Discord server which is free of charge, while combining usability, availability for various rooms, easy access and the option to retain messages [12]. However, Discord has a limitation on the number of video participants, which is why the team prefers to hold any session with more than 25 participants on other platforms, specifically Google Meet or BigBlueButton, which offer reliable, free of charge and online access to our larger meetings [13], [14]. The Microsoft Teams, Cisco Webex and Zoom platforms are also used when required by an external participant.

One of the most significant points for our team involved the ability to quickly switch between different "rooms", emulating member interactions in a physical location. We found that the ability to observe and quickly join workgroups in other rooms not only made access to information easier, but increased member engagement and encouraged participation. The ease-of-use of the software plays a major role in providing the feel of an actual work environment, instead of a routine meeting (Table 1).

Table 1. Clicks needed for a user to choose and join a breakout room, for different platforms

Platform	"Clicks-to-breakout"
Discord	1
Webex	2
Zoom	3
BigBlueButton	3
Microsoft Teams	*Participant cannot choose arbitrary room*
Google Meet	*Participant cannot choose arbitrary room*

3.3. *Remote development (HIL)*

The development work of upstream aerospace projects often requires collaborative access to physical hardware. While remote desktop connections already are a universal solution to work at a distance [15], it is still a challenge to find low-cost solutions for low-level hardware that is based on traditional wired protocols, such as microcontrollers or FPGAs. To allow remote access to the team's microcontrollers, AcubeSAT is developing a Hardware-in-the-loop (HIL) framework [16], using SEGGER J-Link [17] or the combination of OpenOCD [18] and gdb [19]. Both solutions expose a microcontroller's programming interface to the network.

Apart from execution of software, the framework allows debugging, profiling and tracing, also emulating functions of physical measurement instruments. Especially using J-Link, connecting to a microcontroller requires only 4 clicks, ensuring that ease-of-access is not hindered by the lack of physical presence. While the HIL platform inevitably requires occasional maintenance, its ease of access has made it the main firmware execution target of AcubeSAT. It has also been combined with Continuous Integration, allowing our software to be executed and verified after every commit, without developer intervention.

We also note that several similar implementations already exist that enable remotely executed activities [20]. However, the necessity of on-site personnel for maintenance purposes and activities which require physical access to equipment, renders the applications of the HIL platform limited to software development and reduced functional testing.

4. Survey Results & Discussion

We noticed a significant increase in productivity during the remote/hybrid work scheme. This opinion is also shared by a majority of AcubeSAT members, with over 50% answering that productivity has improved during the remote/hybrid work scheme, as seen in Figure 2.

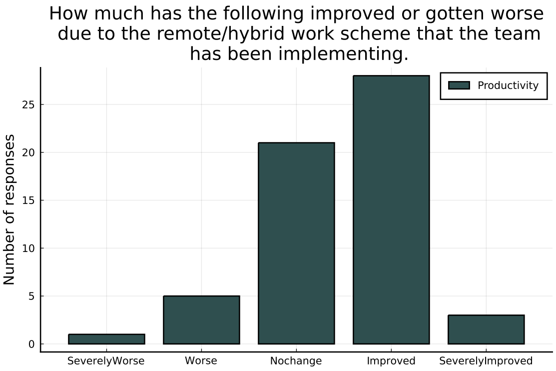

Figure 2. How has productivity changed due to remote/hybrid work

This can be explained by the high availability of most members during remote work, leading to immediate responses to questions and meetings being booked earlier, compared to similar real-life situations. This phenomenon is further amplified during lockdown periods, where members are forced to stay at home leading to even greater availability. This can be observed using raw data by tracking the number of messages sent by team members in Figure 3, which is noticeably increased during lockdown periods.

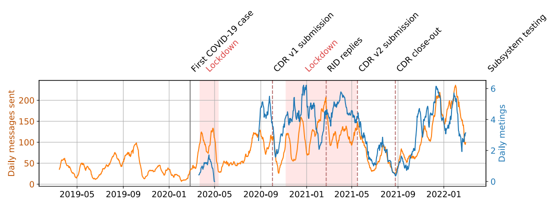

Figure 3. Number of messages and online meetings vs time (14 day rolling average)

As far as practical benefits are concerned, the reduction of time spent by team members commuting towards the team's facilities and back is important. Figure 4 shows that about one third of the team can save more than 1 hour of commuting whenever they have to visit the university exclusively for team related activities.

Another important benefit of the remote/hybrid work scheme is that it enables the team to recruit student members with no geographical limitation.

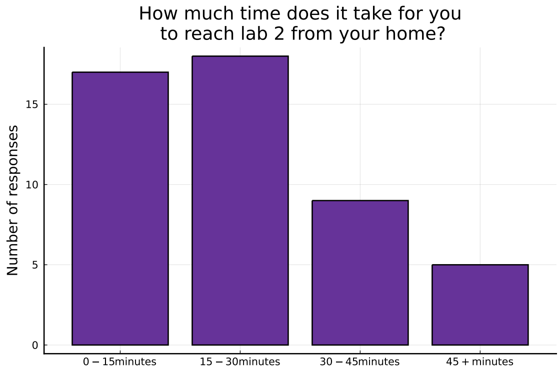

Figure 4. Time spent commuting by AcubeSAT members (one-way)

While living in Thessaloniki, Greece was a requirement before COVID-19, the new work conditions allowed students from universities in Greece or abroad to join without any limitations. Approximately 13% of team members are not based in Thessaloniki (Figure 3) and 12% haven't had any affiliation with the Aristotle University of Thessaloniki, providing opportunities to students who would normally not have the chance to work on a nanosatellite project.

The remote/hybrid work scheme is claimed to not have affected the correctness of the work being performed, with AcubeSAT members almost unanimously agreeing there was no change in the amount of errors or mistakes (Figure 5).

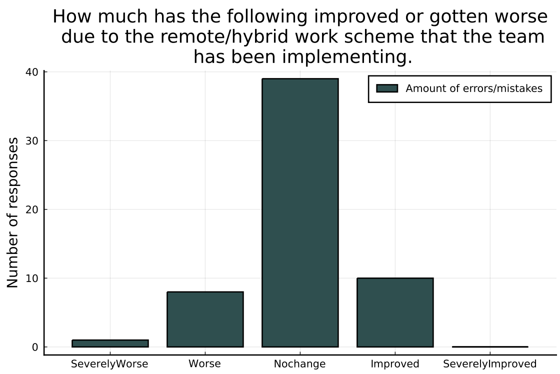

Figure 5. How has the amount of errors/ mistakes changed due to remote/hybrid work

DOI: 10.5821/conference-9788419184405.093

However, there are also clear limitations to this remote/hybrid work scheme. The majority of the survey participants stated that their psychological well-being has worsened due to the remote environment (Figure 6) and that the working experience is overall less fun and rewarding. This finding is consistent with the described phenomenon of "Zoom fatigue", which is caused by a number of physical, psychological and contextual reasons and leads to negative emotional consequences for team members [21]. In an attempt to mitigate these effects, the team planned several team bonding activities online, such as gaming nights and open discussions, but based on the survey responses these activities only made little improvements to the psychological well-being of members.

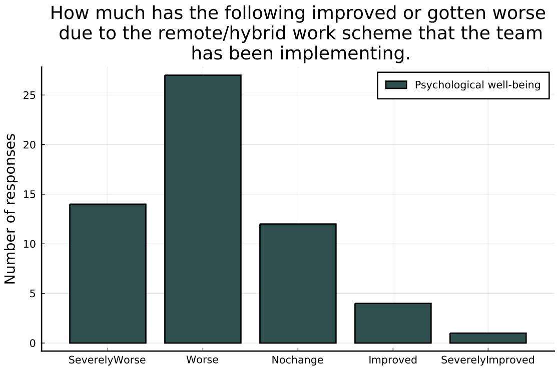

Figure 6. How has the psychological well-being of members changed due to remote/hybrid work

With respect to the concurrent design methodology, we identified an important drawback to our team's approach. As discussed in [22], concurrent design embodies team values of cooperation, trust and sharing which enables decision making by consensus. To realise this definition, it is important that team members conducting these activities get to know each other and most importantly get familiar with each other, to enable trust. To find out whether this holds true for the remote/hybrid work scheme, members who joined during the COVID-19 pandemic were asked if the on-boarding experience enabled them to get to know their colleagues from their own subsystem and different subsystems.

Based on Figure 7, it is apparent that while the on-boarding process allows a new member to be integrated within their own subsystem fairly well, it falls short of introducing a new member to their colleagues from different subsystems. This will in turn cause problems to the concurrent design process, since the current on-boarding process may not fully instil the values required to enable decision making by consensus to new members. We believe that AcubeSAT's on-boarding process can therefore be improved, to match the interactivity required during the normal technical work.

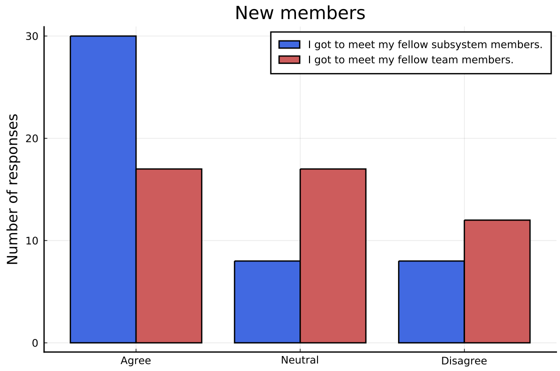

Figure 7. Integration feeling of new members in their subsystem and the team in general

Finally, AcubeSAT members were asked how they would prefer specific team activities to be performed from now on. From Table 2, it is evident that the team prefers a hybrid work scheme for subsystem work and most types of meetings, while there is also a strong preference for technical sessions to be performed on-site.

Table 2. Percentage of responses for "How should the following team activities be performed"

	Subsystem work	Subsystem meetings	AcubeSAT meetings	Technical sessions	1-on-1 meetings
Totally Remote	1.7	19	43.1	1.7	13.8
Hybrid & Mostly Remote	39.7	53.5	31	1.7	36.2
Hybrid & Mostly On-site	56.9	25.9	22.4	44.8	39.7
Totally On-site	1.7	1.7	3.5	51.7	10.3

5. Conclusions

It is evident that there are both benefits and limitations to the implementation of a remote/hybrid work scheme in a space educational project. Teams implementing such a scheme will experience increased efficiency, benefits in productivity, less time commuting and can also recruit members for their projects with no geographical limitations. However, they will also have to deal with the negative effects of this model, such as the apparent decline in psychological well-being of the members and lack of motivation. Remote teams which also opt for the concurrent engineering approach for the design should pay extra care to the integration of new members at a team level in addition to the subteam level, in order to enable trust and cooperation between members. Finally, it should be noted that even during the design process of a space educational project, a number of on-site personnel will be required for prototyping and maintenance activities at a minimum. For AcubeSAT, the benefits of a hybrid work scheme outweigh the limitations, and thus the team will continue working in a hybrid work environment.

Acknowledgements

We would like to thank AcubeSAT's financial sponsors and the Aristotle University of Thessaloniki for enabling the realisation of the AcubeSAT project. Special thanks to all AcubeSAT members who participated in the study which was used for this paper. Finally, we want to thank ESA's Education Office for the continuous support on all levels towards our team and our team members over the past 4 years.

The source code used for the generation of the presented data can be found at: https://gitlab.com/acubesat/education/ssea/.

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A multi-perspective comparison of ESA Academy's Training and Learning Programme experiences before and throughout COVID-19 pandemic through the eyes of 6 students

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Abstract

The forced transition from fully in-person learning to online methodologies incurred by the proliferation of the COVID-19 pandemic has been a major blow to most organisations worldwide. The aim of the present paper is to analyse the impact of the COVID-19 in ESA educational activities from students' perspective, in order to stimulate the future creation of both online and on-site courses.

The participation of the authors in the ESA Academy training sessions covers the period from February 2019 to September 2021, thus experiencing not only both on-site and online courses, but also pre- and mid-pandemic learning experiences and course adaptations due to the impact of COVID-19.

The wide range of space education experiences gathered by the authors enables a multi-perspective comparison of a variety of topics involving the ESA Academy training sessions such as networking possibilities, course dynamics and content, motivation induced by the course environment, impact on the future career and professional development of the participants, as well as compared to the academic experience of the students at their home universities.

The analysis and comparison of the authors' experiences allow to establish correlations between the learning method (in-person or online) and the specific experience outcomes of attending an ESA Academy training session. Finally, some recommendations are provided to further mitigate the COVID-19 impact on space educational activities.

Keywords

COVID-19, ESA Academy, Experience comparison, Multi-perspective, University students

Acronyms/Abbreviations

ESA *European Space Agency*

ESEC *European Space Security and Education Centre*

ESEIAAT *Escola Superior d'Enginyeria Industrial Aeroespacial i Audiovisual de Terrassa*

TLP *Training and Learning Programme*

UPC *Universitat Politècnica de Catalunya*

1. Introduction

Authors are 6 students of aerospace engineering from Escola Superior d'Enginyeria Industrial Aeroespacial i Audiovisual de Terrassa (ESEIAAT) of Universitat Politècnica

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DOI: 10.5821/conference-9788419184405.094

de Catalunya (UPC), even though now just two of them remain at the school – at masters level –, while the rest are pursuing their masters at other top European universities.

All of them had the opportunity to be selected to participate at one of the Training and Learning Programme (TLP) [1] training sessions offered by the European Space Agency (ESA) Academy. However, some of them undertook the course in a livestream (of an in-person course) or online format, because of the willingness of ESA Academy to allow more students to take a determined course or due to the COVID-19 pandemic.

That is why, the authors wondered how time and the pandemic had influenced the student experience at the ESA Academy training sessions, whether if in-person is better than online, and if so, what could be improved to the online format, as in the end it also has its advantages (e.g.: allow more students)

2. ESA Academy background of the students

To give the reader a vision of who did what (and when), as to associate student codification in results (S"X") with the qualitative extracts cited in the article, a brief relation is presented next:

In-person (at the European Space Security and Education Centre (ESEC) facilities in Transinne, Belgium):

Student 1 (S1): Oscar – Ladybird Guide to Spacecraft Communications Training Course – February 2019

Student 2 (S2): Fernando – Introduction to Space Law Training Course – June 2019

Student 3 (S3): Elena – Ladybird Guide to Spacecraft Operations Training Course – September 2019

Online:

Student 4 (S4): Andrea – Ladybird Guide to Spacecraft Operations Training Course – September 2019* (Livestream format)

Student 5 (S5): Magda – Ladybird Guide to Spacecraft Operations Training Course – September 2020

Student 6 (S6): Iván - CubeSat Design Training Week – September 2021

3. Methodology

To perform a solid multi-variable comparison with such a reduced group of people, it is necessary to stablish a framework that sets the basis to obtain valuable and relevant results.

A combination of a quantitative and qualitative assessments has been decided to obtain the results. In this type of experiences, there are factors of which the evaluation can be standardized setting a punctuation scale and a definition for the factor. However, to grasp highlights and remarkable evidence of each experience and provide better understanding to how the factors have been marked by each student, a qualitative description of the experience is also done.

On a second term, all 6 authors have studied in the same period the same degree (Bachelor's Degree in Aerospace Technology Engineering) in the same University and school (UPC-ESEIAAT). This fact provides further foundations to a common background for comparing the overall experience at ESA Academy with the experience at the home University.

3.1. Quantitative evaluation

For this part of the evaluation, the 6 students decided on thinking about factors based on two criteria:

1) Factors that allow to get an overall impression of the course experience regardless of its specific topic, so they can be compared throughout time (before and during the COVID-19 pandemic).
2) Factors that are not usually contemplated on the feedback surveys that participants have to fill after the ESA Academy course, but that can be relevant regarding the impact the course has on them, to see how COVID-19 impacted on them.

Each of the factors was given a mark between 1 and 5 (being the 1 lowest, 5 the highest).

The following 7 factors are defined:

Networking: ability of the course to provide networking opportunities both among the students and with the lecturers.

Induced motivation: the motivation that generates the course content and dynamics to the participating students.

Impact on career/studies path: the impact that the course (being it its content, lectures, further opportunities one may hear of thanks to the course, etc) has on the students' future career path, studies, etc.

DOI: 10.5821/conference-9788419184405.094

Experience vs home university: how the overall experience of an ESA Academy course differs from the one the student has at university and how best or worse it is.

Student interaction: how fluid is the interaction among the ESA Academy course participants.

Infrastructure: it involves the physical facilities - ESA Education Training Centre of ESA's ESEC-Galaxia in Transinne, Belgium - online platforms -livestream or videoconference-, etc used to host and perform the course.

Complimentary activities: those activities besides the course lectures but that are planned as part of the schedule (i.e.: visit to Redu, visit to the CubeSat Support Facility and the rest of ESEC, online events, etc).

Out of these factors, the ones of networking, induced motivation and student interaction are used to make a comparison of those factors between the ESA Academy experience and the one at home university, UPC. Two more factors are added to this later comparison:

Course dynamics: whether the course is more theory-based (1) or project-based (5)

Course content suitability: how well the different modules contribute to the overall knowledge about the training and how adequate they are to provide an overall learning experience.

3.2. Qualitative evaluation

To perform the qualitative part, based on autoethnography [2], each student had to do a short description of his/her experience around two axes: academic and non-academic. The academic part must describe the experience on 1) course content, 2) course lecturers, 3) methodology, 4) course support material and infrastructure. The non-academic part must include the experience on 1) organisation and coordination of the course, 2) contact with the rest of participants. Each contributor should also include any remarkable information or facts that stood out from their experience in one of the ESA Academy training sessions.

On another side, the quantitative results are supported by a colour and descriptive scale linked to the mark to add another dimension in the figures or tables.

4. Results and Discussion

4.1. ESA Academy experience

The overall results for the in-person students, Table 1, and the online students, Table 2, are presented, followed by a discussion on a factor-by-factor basis. The colour code is stated in Table 3, while Table 4 shows overall results comparison between in-person and online.

Table 1. Overall results for in-person students

	S1	S2	S3	mean
Networking	3	5	3	3,7
Induced motivation	4	5	3	4,0
Impact on future path	2	3	2	2,3
Experience vs home university	5	5	4	4,7
Student interaction	5	5	2	4,0
Infrastructure	4	5	3	4,0
Complimentary activities	4	3	4	3,7

Table 2. Overall results for online students

	S4	S5	S6	mean
Networking	2	3	3	2,7
Induced motivation	3	5	5	4,3
Impact on future path	3	4	5	4,0
Experience vs home university	2	4	4	3,3
Student interaction	2	2	2	2,0
Infrastructure	3	3	3	3,0
Complimentary activities	1	1	4	2,0

Table 3. Color code

mark	colour
(4,5]	(excellent)
(3,4]	(very good)
(2,3]	(good)
(1,2]	(mediocre)
1	(poor)

Table 4. Overall results comparison for ESA Academy experiences (factors in the same order of previous tables)

in-person (mean)	online (mean)	difference
3,7	2,7	1,0
4,0	4,3	- 0,3
2,3	4,0	- 1,7
4,7	3,3	1,3
4,0	2,0	2,0
4,0	3,0	1,0
3,7	2,0	1,7

Networking

Mark for in-person students is one full grade better than for online, for which the level of satisfaction is just good. This might be an obvious statement and therefore, one of the main impacted factors by COVID-19.

Prior to COVID-19, in the livestream version of the Ladybird's course "...while the on-site attendees had visits into the facilities or had networking activities, the online students were offered the opportunity to network and get to know each other in a Slack workspace.", says Andrea. From that, one can see that ESA Academy had put some efforts on mitigating one of the negative sides of the online format, although even through COVID-19, this remains a drawback for the student experience, as seen in the results.

Induced motivation

An excellent mark is obtained to the eyes of both in-person and online students. Thus, it seems the potential of ESA Academy TLP courses to motivate students has not been affected by COVID-19.

The courses are intense and concentrated in few days, with timetables spanning for 5-8 hours per day, so even if it is obvious that attending students have great interest on the topic of the course, it is not always easy to always keep motivation for it. Fernando states on this matter that "some sessions were done via videoconference, a format which at that time the participants were not used to. Still, the combination of trainer on-site and trainer online (videoconference) gave the course a more dynamic pace.

Impact on career/studies path

For this factor, online students' future career/studies path seems to be much more impacted by the course than in-person students.

Thinking about it, in-person students took their course earlier than online students, which means that they had more time to explore (through other activities) what they want on their future studies/career and that the impact of the course may have diluted over time. Anyhow, given the results, this might be a very personal factor, for which a sample of 6 students is just not adequate.

Experience vs home University

In this case, the in-person result is excellent while the online student experience is just good. This could be directly related to the online format, which highlights the added value of doing the in-person format of the courses. In this aspect, COVID-19 has severely impacted the student experience.

Anyhow, it seems the learning experience at an ESA Academy course is better than the one at a regular subject at university. Why? Magda states that "The course was very challenging in terms of critical thinking, spacecraft operations which requires considerable thinking-outside-the-box abilities outside academia.", while Fernando comments that "A practical exercise was planned at the last part of the course. There, not only the participants could experience the implications of the concepts learned, but also, they manifested a vibrant passion for a quite unknown topic they only have been familiar with for some days. A passion clearly spread by the main instructor of the training course.".

Student interaction

This is yet another factor in which the online results are mediocre compared to an excellent mark of the in-person case. This is a general problem of online platforms, which still is to be mitigated by organizations across the globe.

Through the qualitative descriptions, some interesting information can be extracted. Prior to COVID-19, Andrea states that "Maybe due the fact that was one of the first times they were trying the livestream format, or just due the fact of being offered hybrid with only an assistant in charge of online students, the feeling was generally of abandonment. You did not feel much included in the group and in everything that was happening in the room. … On the other hand, you had to spend a lot of hours every day behind your screen attending to extremely theoretical lectures and the interactions they expect from you simply involved chatting in a collaborative tool channel and then trying to communicate with people you have never seen through Discord, a platform where you only hear voices that by not knowing people become more difficult to associate with someone."

Meanwhile, nowadays "The training session combined a website where all the files could be found with a videoconference channel to simulate the physical infrastructure, where classes were given, and everyone could chat with the whole class, their reduced groups or directly with the experts." and "The Ice Breaker Quiz, based on space knowledge, strengthened the group's initial interactions and encouraged healthy competition between groups." states Iván, meaning that at ESA Academy there has been an on-going effort to improve this aspect even though it seems that the problem doesn't improve to the eyes of the students.

On another side, the in-person students state that "Being able to share the spare time, not only during the coffee breaks or lunch time, but also after a long day at ESEC, getting to know each other - lecturers included -, sharing backgrounds, stories, and projects together in a terrace or in the hotel longue really built an ideal atmosphere to make class and project interactions much more likely and fruitful." (Fernando). "Late dinner, everyone was tired yet eager to meet each other. Coffee and lunch breaks helped a lot to interact with other students from different backgrounds, nationalities, and cultures but also staff supporting ESA Academy." (Oscar).

From this reflection, one can also link that a better mark in the networking factor would be related to a better mark in the student interaction factor.

<u>Infrastructure</u>

The evaluation of this factor is better for in-person students than for the online ones, which falls one full grade – from very good to good –. Some of the comments from the in-person students are "The seating was placed in such a way that allowed for efficient communication across the teams." (Elena) and "The teaching room was perfectly suitable to accommodate the training course and offer an enhanced experience." (Oscar). This is difficult to translate in an online format, as Andrea states: "they tried to show the whole aula, but that does not make you feel part of the class anyways"

<u>Complimentary activities</u>

While for in-person students there is an overall satisfaction regarding this factor, the result is mediocre for online students, which is natural given the nature of these activities. Among online students that a "very good" mark counterbalances two "poor" marks. Being the first one given by student 6, the last of the students that has attended an ESA Academy course, it can be observed that there have been efforts to mitigate the impact of the pandemic in this aspect as, as Iván states: "The physical infrastructure was recorded and shown live while one university group was testing their satellite. As a result, it was possible to feel the experience of visiting a state-of-the-art laboratory without leaving your home.".

4.2. ESA Academy vs UPC learning experiences

It has been seen that the learning experience at an ESA Academy course is considered better than the one experienced at the home university of the students, UPC. The aim of this subsection is to compare the learning experiences of an ESA Academy training session with the one of a class at university, namely UPC, to identify what could be some of the factors that make the first one stand out from the latter. Thus, to identify their stronger points. In Table 5, the mean marks the selection of factors named in section 3.1 both for ESA Academy and for the home university are show, as well as the difference between them.

Table 5. Overall results comparison between ESA Academy and home university experience

	ESA Academy (mean)	UPC (mean)	difference
Course dynamics	2,5	1,8	0,7
Networking	3,2	1,0	2,2
Induced motivation	4,2	1,8	2,3
Student interaction	3,0	3,2	-0,2
Course content suitability	4,3	3,0	1,3

From the results of Table 5, the induced motivation and the course content suitability are the ones the 6 students value the most from the ESA Academy experience in comparison to UPC, with excellent results. Networking can also be highlighted, as while it is good at ESA Academy, it is considered poor for the home university.

The two newly added factors are discussed next.

DOI: 10.5821/conference-9788419184405.094

Course dynamics

Regarding the course dynamics, the ESA Academy training sessions, while are mostly theory-based, do have a project/activity to complement the learning experience, which provides a better impression compared to the UPC regular course experience, that most times lacks to propose to the students adequate projects or activities in their highly theoretical courses.

Course content suitability

Of course, the ESA Academy training sessions are highly specialized and tailored to give the most complete knowledge on the topic to the participants, which somehow plays in its favour. However, each individual university course should have had these same purposes in mind when designed, so it is important to bring the attention to the margin of improvement that quite a bunch of the UPC-ESEIAAT aerospace engineering courses have in terms of content, whether it is because it is excessive, it has no direct link to aerospace studies as they are shared with other degrees, or do not have the adequate activities to create an overall learning experience out of its content for the students to find them useful.

Conclusions

First, authors would like to state that this article has been an exploratory exercise to try to build up a methodology to analyze the experience of ESA Academy through their eyes and through factors that are of importance to the students, and see at the same time if it changed from on-site and livestream experience to online experience due to the COVID-19 pandemic. Of course, some failures have been found (e.g.: impact on current career/study plan may not be appropriate to evaluate for such a small sample) and what can be extracted may not be as valid as large sample feedback questionnaires, but some relevant conclusions are worth to mention.

The strong points of the ESA Academy experience, regardless of its format – in-person or online –, compared to the one at the home university of the authors, are the induced motivation that the courses give to the students and its content suitability. These two factors may be correlated, as well-built up courses could better motivate students (or keep their motivation, which is just as important) to make the experience a valuable one.

Then, it has been found/confirmed, that the in-person ESA Academy TLP course experience is better/more beneficial for the author students, across most factors. In turn, the online experience has its weaknesses in their inability to provide a fruitful student interaction, which also influences the limited effective networking possibilities that the online format has.

This aspect could be improved by ESA Academy staff, on one side by continuing the efforts seen through the assessed time, towards building a dedicated and cohesive online learning platform to cover the lack of a physical infrastructure like the one at ESEC prepared to these type of trainings as well as to think about which trainings of the TLP catalogue could be delivered online and which ones should be limited to on-site due to its nature and, on the other side, to propose and allocate social time slots where to perform a range of activities that allow participants – including lecturers too – to generate interaction momentum and that facilitate effective networking. As the TLP online courses are usually more extended over time (e.g.: duration of two weeks in half-days instead of one in full-days), this can be a good opportunity to include these “social modules” without having to compromise the rest of the schedule.

Acknowledgements

Thank you to ESA Academy and its staff for the opportunities that have provided us by following one of their TLP training courses and for the work they do on space education.

The participation of the speaker, Fernando, at the 4th SSEA is sponsored by the DISCOVERER project. This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 737183. This publication reflects only the view of the authors. The European Commission is not responsible for any use that may be made of the information it contains.

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FlatSat Workshops Teaching Fundamental Electronics Skills for CubeSat Building

Luis Cormier[1], *Daniel Robson*[2], *Henry Cope*[1]

Abstract

The University of Nottingham (UoN) recently established its own CubeSat programme, with the team commencing design, construction and testing of the first CubeSats in late 2020. However, one major challenge encountered was a common lack of practical applied electronics skills amongst students. This was repeatedly noted by students as a major obstacle to project success in progress reviews for WormSail, our first CubeSat project. Notably, these sorts of skills are also an area of common concern for young workers and employers in the UK Space Sector. This skill gap existed despite the student team coming from a variety of STEM (Science, Technology, Engineering and Math) undergraduate backgrounds, including physics, computer science, and aerospace and mechanical engineering. With insufficient time to recruit students with electronic engineering backgrounds, it proved difficult to find "all-rounders" to join the team with the broad range of skills required for the project.

One advantage that several students had however was their experience from informal hobbies involving Arduino and Raspberry Pi (RPi) based microcontroller electronics. These were found to endow highly transferrable skills, with these members providing significant contributions to the team through their skills and teaching. Team members found these so useful, that the "FlatSat" programme was set up to provide electronics teaching resources for new members of the CubeSat team. Sessions within the programme could be planned and delivered by the experienced team members, and hence be targeted to include applicable, referrable, and important skills and knowledge for building CubeSats.

Through developing these resources, the team realised it may be beneficial to include this programme in taught modules offered in the Faculty of Engineering, to enhance practical skills for all students enrolled in these modules.

This paper is intended to overview the work carried out in developing the FlatSat teaching workshop, and highlight the resources and their benefits to groups including other higher education space module conveners, developing CubeSat teams, School and further education teachers, STEM Outreach Coordinators, and general hobbyists. It is hoped that boosting confidence with such in-demand skills will be of great benefit to learners. We will also review case studies of the first large-scale workshop sessions and outline plans for future developments, particularly taking into consideration the feedback of demonstrators, students, and observers to the workshop.

Keywords

FlatSat, CubeSat, Electronics, Education, Outreach

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Introduction

In the Autumn-Winter of 2020, the University of Nottingham (UoN) commenced work on its first student CubeSat project, eventually named "WormSail" [1]. WormSail had a challenging delivery schedule of approximately 4 months, owing to a discounted short notice launch slot. This necessitated an accelerated and flexible approach to CubeSat development and in particular assembly, integration, testing and validation (AITV) activities. Consequently, the project was approached using the LeanSat design philosophy to varying degrees of success as discussed elsewhere [1].

One result of this was that the inexperienced student team had to rapidly acquire a variety of practical electronics skills for successfully integrating the commercial off-the-shelf (COTS) components of the CubeSat, along with developing custom student payloads from different components and circuits. Despite members of the team having had several years of university education in engineering, physics, or computer science (all regarded as heavily technical degrees which did include some electronics modules and labs), very few were confident enough to develop, test, and verify many electronics setups. As this initial project was ran mainly through Aerospace Engineering, it was difficult to involve students from Electronics Engineering at such short notice.

Self-admittedly, even simple methods and skills for laboratory electronics were either missing, half-remembered or based solely on theory; progress was further hindered by the high price tag of the components being worked on, which reduced the confidence of students to work with the electronics lest they be damaged. Some of the skills discussed as important but missing include:

- Use of benchtop power supplies to safely provide the correct voltage to components, without under- or over-limiting the current to them, such as re-charging Electrical Power System (EPS) batteries or deployment thermal cutters
- Understanding how to read pinouts and how they showed power and data connections over jumper pins and PC104 stacks
- The different common data transfer protocols in microelectronics (UART, I2C, SPI) and how these functioned with their pins and software. If something wasn't a USB or phone cable – we were lost!
- How common grounds would function for power and data transfer applications, and that sometimes loads are required for proper and stable power circuits
- The differences in other pins on microelectronics including GPIO, digital and analogue – and how these relate to input and output logic voltage levels and power transfer
- How breadboards, jumpers, multimeters, and oscilloscopes could be used to fault-find in circuits.

As can be seen, even these relatively basic electronics skills have direct and beneficial applications to the building of real, flight-capable CubeSats. Notably, a lack of "Practical, hands-on electronics" training amongst job candidates is a key area of concern for young workers and employers the UK Space Sector, as highlighted by recent a survey commissioned by the UK Space Agency [2] and elsewhere [3].

A few of the team members, however, had limited experience working on extra-curricular projects and hobbies using microcontrollers such as Raspberry Pi's (RPi's) and Arduinos. Skills they had acquired from these hobby electronics were immensely transferable to CubeSat development and were quickly communicated and disseminated throughout the team. Following postponement of the launch date for WormSail, the team decided to utilise these experiences to develop a solution to the "skills shortage" within the CubeSat team. These would teach students many of the simple electronics skills listed above that were found to be lacking, in a way that would bridge the gap between electronics and IT theory they were familiar with and what is required for CubeSat development. Thus, the idea for developing our "FlatSat training kit" was born. Alongside inspiration from hobby electronics, the idea of the training kit was inspired by the use of so called 'FlatSats' which are used as high-fidelity engineering models for testing during actual CubeSat missions [4]. Ultimately, while the involvement of students with backgrounds in electronic engineering is desirable for university CubeSat development, we believe that the FlatSat training kit is also a valuable tool for education and outreach.

1. The General FlatSat Kit & Design

1.1. FlatSat Kit Overview

The general aims of what we wanted our kit to look like included:

- Fit within a small breadboard: ~ PocketQube or CubeSat sized
- Be buildable (and dis-assembled) without requiring any additional soldering by students. Using jumper wires would be ideal due to their ease of use and reusability
- At least show primary satellite functions: on-board computer (OBC) coding, battery power, sensors for science payloads, radio transceivers with data messages
- Programming through COTS micro-controllers (RPi, Arduino, Micro:bit, etc)
- Programmable/controllable from student laptops, with minimum installation required
- Be very expandable/modular - easy to add/remove new components or activities as required
- All components easily (and cheaply) available, can be “bulk” ordered
- Budget of ~£100 per kit, and need to make at least 8 kits
- Be capable of running an activity workshop with school/university students within 2 hours
- Would be centered around 4 main “teaching objectives” - electronics, coding, team working, and spacecraft systems engineering

These initial requirements drove the team to plan the kit around a miniature setup of breadboards COTS microcontroller boards, jumper cables and the other components.

Many of the commercially available CubeSat training or teaching products are of reduced benefit in situations such as these. Some are prohibitively expensive (of the order of several hundred or thousand dollars each) and/or are aimed at teaching such specific skillsets (Attitude Determination and Control System (ADCS), Telemetry, Tracking and Command (TT&C), etc.) that they “skip” steps in teaching basic electronics (understandably they assume some previous experience). Expensive kits, while able to offer excellent learning tools and experience with space technology, means limited numbers can be bought or used at once, physically limiting student opportunities for hands-on work (which students clearly value greatly as a rare opportunity with space technology) [2,3]. Others can be simplified and are more accessible, but also typically come with printed circuit boards (PCBs) fully assembled, and thus removing key opportunities for students to develop their electronics understanding such as wiring or data interface methods. These more accessible approaches are very useful for training students familiar with the systems (but for mostly testing software rather than building skills) but are either too simple to assemble or too complex to rapidly understand the precise processes occurring through the circuitry for shorter learning sessions. Even the scratch-built, open-source projects available online typically assume a competency with skills such as electronics and coding that is not particularly new-user-friendly, and has limited scope for advice given the designs’ often unique characteristics. Furthermore, “real” CubeSat hardware (with flight potential) is very rarely as “plug and play” as advertised, and (paradoxically) usually requires some experience to setup, integrate, configure and test for the first-time use (even with instructions).The team envisioned FlatSat kits to be a simpler, more affordable, more “ground-up” solution to these products, and to ensure it was obvious to students that the pieces they were handling weren’t specialty components that need an expert to select and integrate, but could be done easily by anyone once certain core principles are learned.

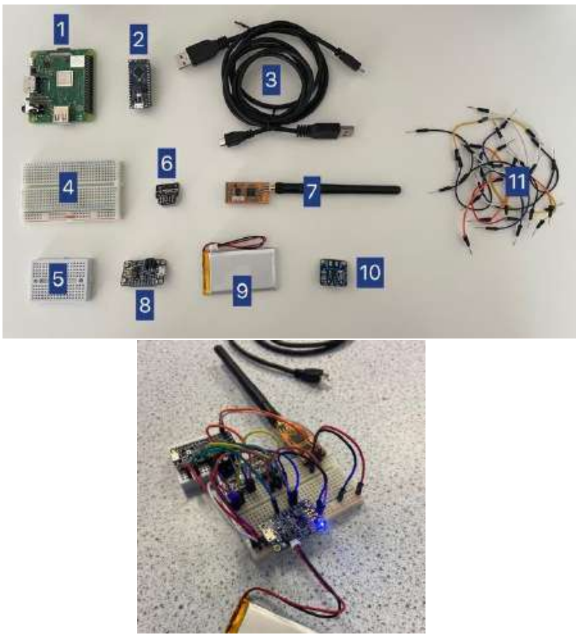

Figure 1: Top, all the components required for the basic kit, as provided to the students. Bottom, the fully assembled basic kit (~£100)

As seen in Figure 1, the basic initial kit would function using:

- An Arduino Nano Every microcontroller as the OBC controlling the individual subsystems.
- A radio transceiver using an APC220 – selected for its simple interface using UART pins; a “wireless serial port” as someone quipped.
- A power regulator board would enable flexible input options from Lithium-ion cells, solar panels or power banks; while also providing jumper outputs to match the rest of the kit (teaching power doesn’t always need to come through a USB cable with a connector).
- Sensors including an INA260 power meter that could be used to monitor current consumption by the kit (showing what needs 3V3 vs 5V too), or input from mini solar panels (providing EPS-functionality).
- Additionally mini “payload” sensors were used such as an inertial measurement unit (IMU) or environmental sensor for proof of the kit's utility and flexibility. Software for all these components was formed by modifying pre-existing open-source libraries online.

1.2. FlatSat Implementation in Workshops

After discussions with teaching staff at the University, we outlined some initial lesson plans to involve teaching small teams of 2-4 students per kit, how to assemble and test their kits while following written instructions in 1–2-hour sessions. These would initially be aimed at third- and fourth-year engineering undergraduates undertaking space modules, as well as training sessions for our extra-curricular CubeSat team, or fun outreach sessions such as enrichment activities at the university.

When developing the FlatSat kit, the team intended to bridge the skillsets from common sense computing and microelectronics, to CubeSat AITV, as closely as possible. This meant that a system such as Arduino microcontrollers was superbly suitable. Their one-program-at-a-time method of coding, compared to a system such as a RPi that has a full user-interfaced operating system (OS), provided an additional analogue to CubeSat OBCs. It is however advisable to carefully introduce this method of programming to students, as full graphical user interface (GUI)-based OSs (e.g. laptops, phones, etc.) will be more familiar to them.

However, requiring students to pre-install and understand a selection of software and Arduino libraries before the workshop was deemed too complex for an introductory session. Instead, all the required software was bundled onto RPi 3A+ “programming stations” that were distributed alongside each kit. These were accessed in the sessions over a dedicated LAN website by selecting the appropriate MAC address of a team’s programming station from a list (we simplified this by having the RPis appear as pre-determined team colours on the list). Hence students would select the code they wanted to be uploaded to the Arduino from the list on the website (e.g. the beacon code to test the APC220 radio was wired correctly), and were able to flash this to the Arduino via the programming station, without requiring any additional software on their own device.

Students would come to the workshops with only their laptops, assemble the kits in teams and then plug them (via a RPi-based programming station) into their laptops and upload pre-written codes to them from our “homemade” LAN website, complete with accessible GUI (see Figure 2). Once complete, students could send radio messages from their kits (including text they wrote and data from the sensors) to a lab “ground station” (a RPi 4, with a APC220 receiver), which would print their messages (in their team colours!) to a projector screen at the front of the class (see Figure 3). The LAN website for code uploading was also hosted on this RPi 4, which enabled a centralised method for checking if any teams’ laptops or RPis were failing to connect to the LAN properly.

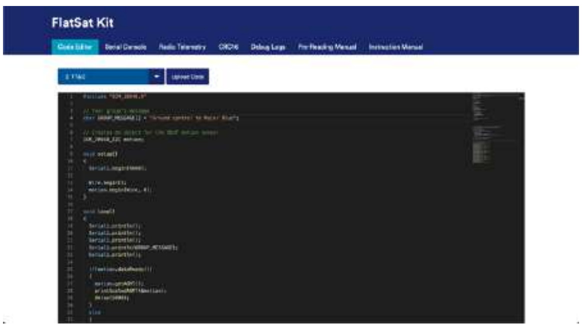

Figure 2: The front-facing LAN website, for editing and uploading code to Arduinos

DOI: 10.5821/conference-9788419184405.095

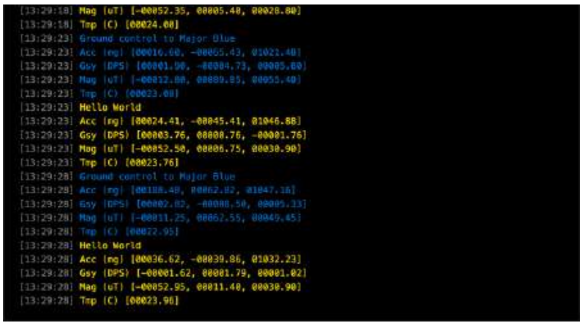

Figure 3: A screenshot from the ground station interface, showing two teams' data

2. FlatSat Workshop Activities

2.1. MMME3079 Test Workshops

Following test sessions with trusted members of the CubeSat team and staff, the first FlatSat workshops were first run as an optional workshop session available to third year engineering students taking the "Introduction to Space" (MMME3079) module. In these workshops, students received a short pre-reading manual explaining various useful terminology and principles (e.g. how breadboards function) to read before the workshop. They would then assemble the kits piece by piece (testing at various steps through uploading different pre-made codes) until it was the complete setup shown in Figure 1 above. Invitation to sign up for these workshops were also sent to members of the student Space Society, with some attendance. The total of estimated participants was 20-25 students.

Figure 4: Students working in small groups during the first workshop session in Nov 2021

2.2. Enrichment Week Workshops

As part of extra-curricular "enrichment week" activities ran by the Faculty of Engineering, students from any Department and year were encouraged to come along. Within the sign-up sheet going online, all 30 slots were filled within 3 days. These teams performed the same workshop activities as described in 3.1, although with revised instructions based on feedback from the first session.

2.3. MMME4038 Workshops & Lab Report

25% of the credits available for the "Spacecraft System and Design" (MMME4038) fourth-year module came from students' grades in a laboratory report, to be filled with data acquired during in-person lab sessions. These sessions included three 1-hour FlatSat workshop sessions and two 1-hour sessions with the Theia Space ESAT simulator. As a masters-level module, the depth of learning required for these sessions would be greater than before, hence the team split each 1-hour session into subsystem dedicated subjects – EPS, TT&C, and Payloads.

1. The EPS session involved building the base kit (without the radio) but using solar panels as a power source. Students recorded power input/output values using the INA260 sensor by changing jumper positions in the circuit. They also tested solar panel performance at different inclinations and distances from light sources, using an angle-labelled turntable and mobile phone torches respectively.
2. The TT&C session added the APC220 radios to the setup, and required students to analyse a simple pre-coded beacon message using 16-bit cyclic redundancy checks (CRC16) to identify errors artificially introduced to the message using a random character replacement function. They also experimented with sending and receiving data commands to control an RGB programmable LED, and fix a purposefully hidden coding error using a method analogous to bus-injection.
3. The Payloads session used a combination of the previous environmental sensors to teach differences between UART, SPI, and I2C data lines. Students also got to examine samples in a "mystery box" using miniature cameras and spectrometers. They would then be asked to identify them based on data sent back – e.g. "what colour is the sample?", "what part of Earth have you just imaged?"

The data students acquired in these workshops would be used to write up a module "lab report", to review what they had learned from using the kits, and prove they could interpret their results and its relevance to real space missions.

Figure 5: Groups of students assembling their kits during the EPS session

3. Student Feedback

Informal feedback from students who have participated in these workshops highlighted how these sessions were able to offer a range of benefits, from helping with individual project theses, to solidifying the content taught in lectures via practical activities. One student mentioned how the skills learned through these workshops helped them during job applications, as they were able to show key skills which other applicants lacked. Several people also encouraged the team to adjusting the workshops to be more suitable for outreach and then utilise them for events in high schools, university open days or welcome week activities.

4. Conclusions

We present an open-source, affordable, and most importantly, accessible kit design for educational organisations to use and adapt for teaching students about technology. This includes electronics, coding, radio, and power systems; the fact we based ours around a CubeSat setup is just one vehicle for delivering these skills and learning outcomes. Similar setups with a few additional components could be used to teach about automobiles, drones, mobile phones or remote-controlled robots.

A further take-home message to aspiring CubeSat, or other space project, development teams is not to underestimate the number of blind spots and skill gaps you and your team will have. Any and all large-scale systems engineering projects require dedicated cooperation between disciplines and specialties, and so does the space sector. Assumptions that one's large theoretical knowledge of space systems and a capacity for learning new skills in world-record time is enough to carry your team through, is likely to lead to blockages, delays, and undue stress.

Future plans include simplifying the kit and its messages for use in school-level outreach; "de-mystifying" what is commonly thought of as technology levels beyond the understanding of most students in a class. Additionally, there are plans to enhance the fidelity of FlatSats towards a CubeSat or PocketQube sized system, including stackable subsystem boards with purpose made PCBs and headers. These extended activities should maintain good accessibility, but would enable differentiation to prioritise software or hardware focussed lessons. Following student feedback, the team will also include greater emphasis on interactive coding and increased emphasis on providing pinouts. Additionally, the team plans to incorporate LEDs into the design to help with easy fault finding, and the use of alternative programmers (such as Python-based RPi Picos) to reduce issues with software.

Acknowledgements

The authors wish to express their gratitude to Mark Jabbal and Chantal Cappelletti of the Department of Mechanical, Materials, and Manufacturing Engineering, University of Nottingham, who allocated funds to support the development of the FlatSat as a teaching tool at UoN. The authors also want to thank their colleagues, namely Angel Arcia Gil and Samuel Thompson, for their support and testing of workshops, as well as the students who took part and provided feedback.

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Lotus: Testing Origami-Inspired Structures in Microgravity

Augustin Gallois[1], Karthik Mallabadi[2], Clément Lopez[2], Eliott Marceau[2], Sérgio Silva[3], Stéphanie Lizy-Destrez[2]

Abstract

Many space technologies are enabled by deployable mechanisms or structures to function: solar panels, radiators, and even crewed stations and rovers subsystems need to be stowed and deployed to fit in a launcher fairing and avoid unwanted vibrations during launch. Among those structures, the deployment of large membranes and panels can be designed with the help of an unexpected technique: origami folding. The idea has been spreading in every field of engineering in the past few years; compact, rigid-folded structures that can change shape in one simple motion fascinate micro-robotics as well as aerospace engineers.

Origami-inspired structures can be engineered to answer many needs. The available launch volume can be optimized, creases can improve the rigidity of a structure while keeping it lightweight, thickness can be accounted for, and complex surfaces can be approximated by flat-foldable mechanisms. Several major space actors, such as the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA), have already implemented such techniques successfully or plan to do so in the near future.

Following these breakthroughs, student project “Lotus” was submitted to the Parabole 2022 contest, an opportunity to test student projects in microgravity during a parabolic flight campaign organized by the French Space Agency and its subsidiary Novespace. The 5-members international student team will characterize and analyse the deployment and folding of innovative origami structure models for current and future space applications, especially volumes for deployable habitats, fuel tanks, or other resource containers such as asteroids and regolith; three stereo cameras will capture the geometry at different set speeds. To maximize the scientific return, several shapes and geometric parameters will be tested: three distinct structures are proposed to be tested, mostly limited by the volume available for the experiment. The models tested will be as similar as possible to their full-size counterparts, being made of space-grade polyimide, and their dynamics will be assessed in near-0g conditions to have a deployment environment that is as accurate as possible. These results will be compared with on-ground experiments with a similar experimental setup.

Keywords

deployable structures, origami, parabolic flight, student project

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Acronyms/Abbreviations

CNES	*Centre National d'Études Spatiales (French Space Agency)*
DART	*Double Asteroid Redirection Test*
DOF	*Degree of Freedom*
ISAE	*Institut Supérieur de l'Aéronautique et de l'Espace*
ISRU	*In-Situ Resource Utilization*
ISS	*International Space Station*
IST	*Instituto Superior Técnico*
JAXA	*Japan Aerospace Exploration Agency*
MLI	*Multi-Layer Insulation*
NASA	*National Aeronautics and Space Administration*
ROSA	*Roll-Out Solar Array*
SSEA	*Symposium on Space Educational Activities*

1. Introduction

1.1. Parabole 2022

Each year, the French Space Agency (in French: *Centre National d'Études Spatiales*, CNES) issues a call for student projects to study, design and perform experiments to be carried out in near-weightlessness, aboard its subsidiary Novespace's Airbus A310-0G: the Parabole project [1]. This bid allows to select three student projects, among which the one presented in this paper, "Lotus". The Parabole 2022 edition puts an emphasis on French-Portuguese cooperation and encourages the inclusion of international teams.

Figure 1. Novespace's Airbus A310-0G.

1.2. Context and scope

JAXA was the first aerospace actor to test origami-inspired solar panels in space in 1995 aboard the Space Flyer Unit [2]; NASA is currently considering a similar approach for a future telescope mission, by deploying a compactly folded Starshade demonstrator, deploying as a large membrane to allow for exoplanets to be observed by occulting their star [3]. This design philosophy impacts other large flexible and rigid-deployable systems with high compression ratios, such as ultra-light solar array blankets ; prime examples include the Roll-Out Solar Array (ROSA) [4], currently under implementation on the International Space Station (ISS) and on the recently launched Double Asteroid Redirection Test (DART) [5] spacecraft, or the UltraFlex fanfold flexible-blanket solar array [6], or solar sails (such as IKAROS [7], the first ever solar sail, deployed by JAXA in 2010).

Inspired by these breakthroughs, the objective of the Lotus project is to test, characterize and analyze the deployment and folding of innovative origami structure models for current and future space applications. The working hypothesis is that origami-inspired space structures can be reliably deployed and folded back in the absence of significant gravity disturbances. The structures to be tested are limited to models that will approximate complex, enclosed volumes such as half-spheres, domes or cylinders with collapsible origami patterns, simulating future space structures:

- Space station or crewed spaceship modules: with the recent announcement of the Axiom, Orbital Reef and Starlab commercial space stations, deployable habitats will only find more relevance.
- Habitats or enclosed structures on the surface of low-gravity bodies (asteroids, Moon, Mars, gas giants' moons).
- Deployable, tight tanks to be refilled within an In-Situ Resource Utilization (ISRU) economy: water, oxygen, hydrogen, regolith, etc.
- Shells embracing asteroids or parts of minor bodies for volatile resource extraction, such as water, methane…

DOI: 10.5821/conference-9788419184405.096

Therefore, excluding large flat-deploying structures, such as high-span solar panels or radiators, starshades or solar sails from the study. This will allow to maximize the useful volume allocated for the experiment in the plane, while having centimeter-scale models that best approximate real-scale structures and avoid singularities at the millimeter-scale that would not appear at the meter scale.

Through this experiment, such structures need to be practically designed, then deployed and folded back. Flexible mechanisms designed with repeating origami patterns have been theorized in depth but lack actual practical implementation and applications despite their huge potential. The designs will be based on the Miura-Ori pattern [8], a type of base origami cell that can be used to approximate the surfaces discussed in this study. The details for the design method for these structures are described in the following section.

Design issues directly linked to manufacturing are also accounted for. Several mathematical parameters need to be constrained and respected to enable both the flat-folding and rigid deployment of the origami structure according to L. Dudte et al. (2016) [8]. Panel thickness can be accommodated by applying an adaptation method developed by T. Tachi (2010) [9]. The deployment and folding motions will be captured with a set of three stereo infrared depth cameras to cross-refine the measurements and triangulate the position of the structures' vertices with accuracy. These results will be compared with on-ground experiments at 1G with a similar experimental setup; however, the 1G experiment can only be relevant as a comparison with more faithful 0G tests. Despite their lightweightness, these rigid-foldable structures are still weighty and can invalidate results at 1G, especially for models supposed to depict structures for space applications. This issue increases the relevance of a parabolic flight for this kind of experiment, even though it is impossible to practically remove other disturbances such as airflow and flight vibrations.

To conclude, this microgravity experiment has several scientific returns:

- Validate or invalidate the possibility of deploying and folding back enclosed origami-based structure models for future space applications (success criterion of the whole experiment).
- Provide solutions to design and manufacturing issues: panel thickness, flexible behaviours, single sheet folding and more.
- Characterize their deployment in an environment that is closer to outer space (weightlessness) than on-ground experiments.
- Compare 1G deployments to 0G deployments and their relevance.
- Compare geometric variations on the origami pattern within a similar base shape.

2. Method

2.1. Technical description

A total of three structure models are implemented within an open experiment mechanical frame provided by Novespace. This number depends on several factors to balance:

- Comply with the volume available within the experiment mechanical frame.
- Maximize the size of the models to have accurate scale deployment.
- Maximize the number and nature of structures to be tested to maximize scientific returns and parameters comparisons.
- Comply with the field of view of the stereo cameras, which limits the total volume within the available experimental frame.
- Balance the available parabola test windows with the number of tests on a single origami structure, while keeping some margins for quality tests.

These structures will be manufactured from Kapton, a high-performance polyimide plastic used in aerospace engineering for its chemical, thermal and mechanical properties to isolate systems from the thermal environment (Multi-Layer Insulation, or MLI) or make thin membranes and blankets. This material is already used for solar sails demonstrators and deployable sunshields (such as on the James Webb Space Telescope [10]): it will provide an accurate simulant of what an actual deployable space structure might be made of; it can be laser or mechanically cut with the tooling at disposal and is perfect to manufacture bendable rigid panels such as the ones envisioned for the project.

The key method to design such structures comes from L. Dudte et al. (2016) [8], which details the steps of approximating almost any discretized surface with completely flat-foldable Miura-ori patterns as shown in Figure 2. The initial Miura-ori pattern has four important geometric properties that directly interest us for a fully foldable envelope:

- "It can be rigidly folded (that is, it can be continuously and isometrically deformed from its flat, planar state to a folded state).
- It has only one isometric degree of freedom (DOF), with the shape of the entire structure determined by the folding angle of any single crease.
- It exhibits negative Poisson's ratio (folding the Miura-ori decreases its projected extent in both planar directions).
- It is flat-foldable (that is, when the Miura-ori has been maximally folded along its one degree of freedom, all faces of the pattern are coplanar)."

To retain these properties, the paper proposes two major steps:

- Discretize a target surface and extrude an initial guess for the origami pattern.
- Ensure the previously mentioned geometric properties for each face and vertex by performing a complex non-linear optimization, while keeping the optimized geometry as close to the initial surface as possible.

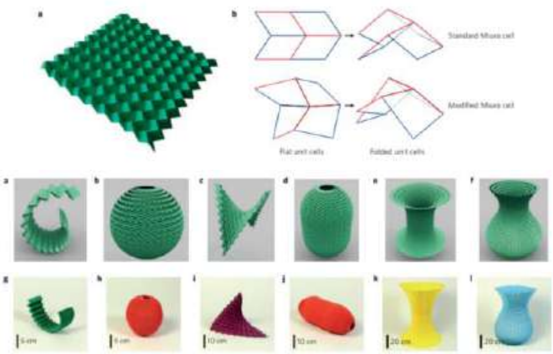

Figure 2. Geometry of a base Miura-ori cell and examples of optimal calculated origami tessellations (L. Dudte et al., 2016 [8])

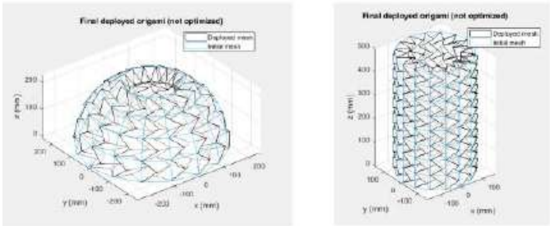

Figure 3. Current unoptimized origami models of the structures proposed, approximating a dome and a cylinder.

A major benefit of this pattern is that the entire structure can be deployed and flat-folded with only one DOF, displaying an impressive potential for simple and reliable actuation. For this specific experiment, each origami structure will be provided with a motorized linear actuator and an interface deployment mechanism to ensure a consistent deployment at the base of the structure. Additionally, three stereo depth cameras will triangulate the position of each visible vertex on the deploying structure.

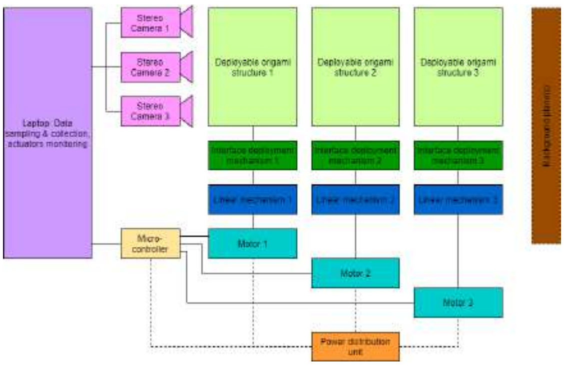

Figure 4. Conceptual diagram of the experimental setup with three structures.

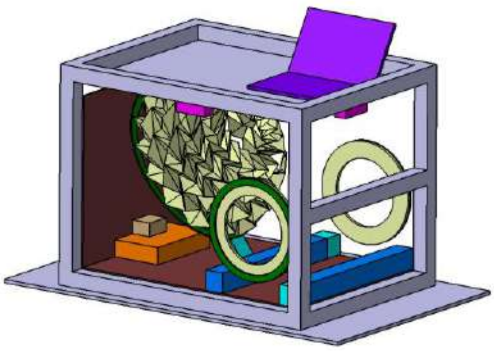

Figure 5. Preliminary computer-aided design of the experimental setup with the dome-shaped structure deployed. The color code is the same as in Figure 4.

2.2. *Experimental protocol*

According to CNES and Novespace, the plane will perform six series of five useful parabolas, with each microgravity phase lasting approximately 22 seconds [11].

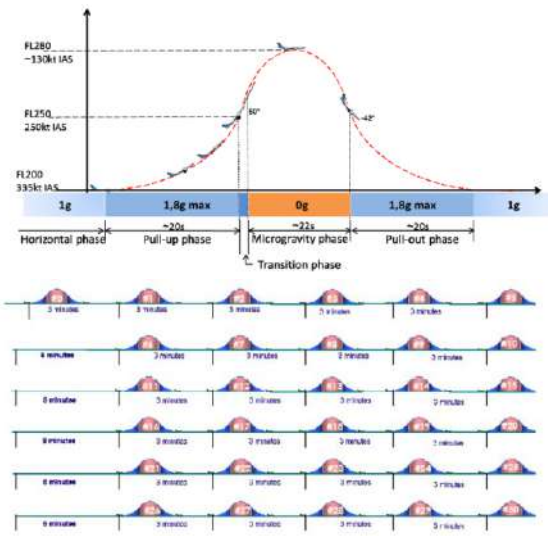

Figure 6. Parabola profile and series.

The current protocol proposes, for each structure, to test the deployment and folding twice: and once at a low speed, that would be practical during a single parabola, and once at a "high" (still undefined) speed, to assess dynamical behaviours. Between each deployment and folding, the structure will be observed in microgravity. A reserve of margin parabolas is kept as an extra measure to carry failed deployments or repeat the experiments if possible.

Initial parabola	Stowed flat observation	Slow deployment	Deployed observation	Slow flattening	Fast deployment	Parabola series 1	Structure 1 test
	Deployed observation	Slow flattening	Margin	Margin	Margin	Parabola series 2	
(Structure 1 stowed back)	Stowed flat observation	Slow deployment	Deployed observation	Slow flattening	Fast deployment	Parabola series 3	Structure 2 test
	Deployed observation	Slow flattening	Margin	Margin	Margin	Parabola series 4	
(Structure 2 stowed back)	Stowed flat observation	Slow deployment	Deployed observation	Slow flattening	Fast deployment	Parabola series 5	Structure 3 test
	Deployed observation	Slow flattening	Margin	Margin	Margin	Parabola series 6	
(Structure 3 stowed back)							

Figure 7. Current protocol proposal (following the profile shown in Figure 6)

3. Current progress and results

At the time of the submission of this paper, several paper prototypes have been produced and the stereo camera measurement method has been approved.

It is already confirmed with empirical evidence that a dome-like or cylindrical structure as desired for the experiment can fold flat, and that its deployment can be ensured by an interface mechanism allowing a homogeneous 1 DOF expansion. Such an interface mechanism has been identified as a Hoberman mechanism and is undergoing a detailed analysis and design phase as this paper is submitted. The suitable dimensions and final optimized geometries should be finalized five months before the flight.

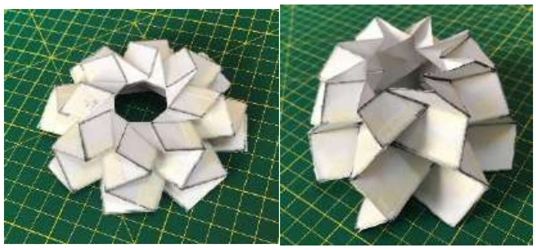

Figure 8. Dome-shaped origami paper prototype stowed (left) and deployed (right).

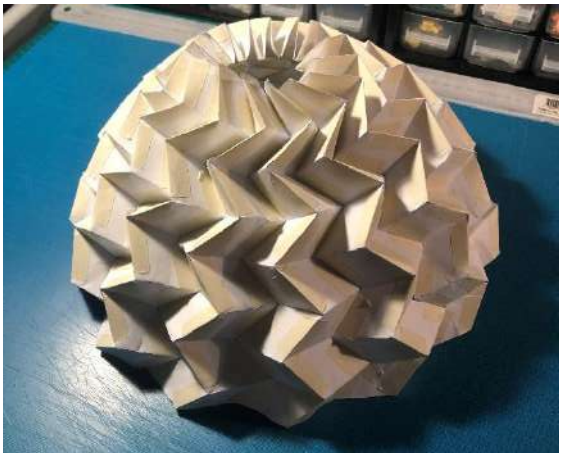

Figure 9. Latest dome-shaped origami paper prototype, directly output from the algorithm developed for the project. The geometry is not yet optimized for flat foldability.

4. Conclusions and further progress

The Lotus student project is on good track to test, characterize and analyse the deployment and folding of origami-inspired structures for current and future space applications in October 2022 aboard a parabolic flight. Currently, the theoretical concept of using thin Kapton panels in a Miura-ori pattern has been validated and is undergoing the design phase with paper prototypes. The following steps will include manufacturing four months before the experiment, leading to a functional concept on ground. During the summer, the algorithm for stereo measurements and monitoring will be extensively developed and tested.

Acknowledgements

We would like to thank ISAE-SUPAERO, the Fondation ISAE-SUPAERO and PT Space for supporting our project and enabling our participation at the SSEA. Thank you very much to Novespace and CNES for the selection of our project and this one-of-a-kind research opportunity.

Appendix

The progress of the Lotus project will be available online through the social media pages:

- Instagram (https://www.instagram.com/lotus_0g/)
- Linkedin (https://www.linkedin.com/company/lotus-project-0g/)
- Facebook (https://www.facebook.com/lotusproject2022)

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Artery in Microgravity (AIM): Assembly, Integration, and Testing for a Student Payload for the ISS

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Abstract

The Artery in Microgravity (AIM) project was the first experiment to be selected for the "Orbit Your Thesis!" programme of the European Space Agency Academy. It is a 2U cube experiment that will be operated in the International Commercial Experiment (ICE) Cubes facility onboard the International Space Station. The experiment is expected to be launched on SpaceX-25 in mid-2022. The project is being developed by an international group of students from ISAE-SUPAERO and Politecnico di Torino.

The objective of the experiment is to study haemodynamics in the space environment applied to coronary heart disease. The outcomes of this testbench will contribute to understanding the effects of radiation and microgravity on the circulatory system of an astronaut, specifically the behaviour in long-term human spaceflight. It will also help to ascertain the feasibility of individuals suffering from this kind of disease going to space someday. The cornerstones of the experiment are two models of 3D-printed artificial arteries, in stenotic and stented conditions respectively. Blood-mimicking fluid composed of water and glycerol is circulated through the arteries in a closed hydraulic loop, and a red dye is injected for flow visualisation. Drops of pressure and image analysis of the flow will be studied with the corresponding sensors and camera. The pH of the fluid will also be monitored to assess the effect of augmented radiation levels on the release of particles from the metallic stent.

Some delays were experienced in the project due to the COVID-19 pandemic and to implement design improvements. Improvements were made to several aspects of the design including mechanics (e.g. remanufacturing the reservoir with surface treatment against corrosion, leak prevention measures), software (e.g. upgrading to Odroid-C4 and migrating the code to Python), and electronics (e.g. several iterations of the interface PCB design). This iterative process of identifying areas of concern and designing and implementing solutions has resulted in many lessons learned.

The paper will outline in detail Phase D – Qualification and Production of the AIM experiment cube, with special insight on the implementation of the improvements. Previously, at the Symposium on Space Educational Activities in 2019 in Leicester, the initial phases of the design and development of the cube were presented. This year, the final flight model and the results of validation testing before launching on SpaceX-25 are presented. Lessons learned throughout the course of the project are also highlighted for students embarking on their own space-related educational activities.

Keywords

AIT, haemodynamics, leak prevention, microgravity, Orbit Your Thesis!

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Acronyms/Abbreviations

AIM	*Artery in Microgravity*
AIT	*Assembly, Integration, and Testing*
BMF	*Blood Mimicking Fluid*
COTS	*Commercial Off-the-Shelf*
ESA	*European Space Agency*
I2C	*Inter-Integrated Circuit*
ICE	*International Commercial Experiment*
ICMCC	*ICE Cubes Mission Control Centre*
ISS	*International Space Station*
LED	*Light Emitting Diode*
NASA	*National Aeronautics and Space Administration*
OBC	*On-Board Computer*
PCB	*Printed Circuit Board*
PWM	*Pulse-Width Modulation*
REST API	*Representational State Transfer Application Programming Interface*
VPN	*Virtual Private Network*

1. Introduction

The Artery in Microgravity (AIM) project is a 2U cube experiment that will be housed within the International Commercial Experiment (ICE) Cubes facility by Space Applications Services in the Columbus module of the International Space Station (ISS). The cube has been developed by an international and interdisciplinary group of students from ISAE-SUPAERO in Toulouse, France and Politecnico di Torino in Italy. The project was selected for the 'Orbit Your Thesis!' Programme of the European Space Agency (ESA) Academy.

Space Applications Services' ICE Cubes Service provides access to the ISS for scientific research, technological demonstrators and for educational purposes that require microgravity conditions and radiation exposure in a pressurised volume. The ICE Cubes Facility is a sliding platform permanently installed on-board the ISS that accommodates "plug-and-play" experiment cubes, hosting the functional interfaces to the ISS infrastructure [1].

An experiment that investigates haemodynamics in coronary arteries was thus developed to investigate how the altered vascular flow in microgravity may exacerbate or diminish atherosclerotic lesions in coronary arteries and thereby determine how the risk to astronauts of myocardial infarction is affected by space travel. In addition, the experiment makes use of the radiation environment on-board the ISS to investigate if implantable devices, such as coronary stents, are at risk of re-stenosis due to the release of metallic ions stimulated by radiation exposure [1].

2. Summary of Project Timeline

The AIM project was selected by ESA Academy for the "Orbit Your Thesis!" programme in October 2018. Since then, almost 40 students have collaborated on the project over the different generations of teams. The experiment was expected to launch on the SpaceX-20 mission in March 2020; however, due to delays because of the COVID-19 pandemic and time taken to implement design changes, the expected launch has been pushed back to the SpaceX-25 mission in mid-2022.

Phase D (Qualification and Production) [2], which this paper describes in detail, started in mid-2021 and will conclude with the launch of the AIM cube experiment to the ISS in mid-2022. The phase includes assembly, integration, and testing (AIT) of the cube, as well as launching to the ISS. In March 2022, the Flight Acceptance Review was passed, receiving permission to launch at the next opportunity. Phase E (Operations) is expected to last between one and four months in orbit [2].

2.1. Testing campaign overview

The main goal of Phase D was to conduct a series of tests to ensure the compliance of the experiment cube with all the applicable requirements in terms of safety and functionality. This section depicts the different tests that were carried out to this end.

2.1.1. Electromagnetic Compatibility Test

Objectives: To verify that the cube hardware complies with the ICE Cubes Facility's electromagnetic interference requirements.

Facilities: INSA's Laboratoire d'Analyse et d'Architecture des Systèmes IT and Electronics Department from 20/07/2021 to 22/07/2021.

Approach: Measuring the electrical field emissions, magnetic field emissions, and conducted emissions and verifying their conformance with the applicable requirements.

2.1.2. Vacuum Test

Objectives: To guarantee the structural integrity of the cube and the absence of leaks in case of an unforeseen depressurization during launch or once installed on-board the ISS.

Facilities: ISAE-SUPAERO Space Vacuum Chamber (Building 38) on 24/11/2021.

Approach: Place the unpowered cube in the vacuum chamber and de-pressurize to below 1 mbar for 5 minutes. Re-pressurize and carry out a full visual inspection and a functional check.

2.1.3. Full Functional Test

Objectives: To check the integral functionality and operability of the cube to accomplish the mission requirements on-board the ISS.

Facilities: ESEC-GALAXIA's CubeSat Support Facility on 19/01/2022.

Approach: General check of all functional features of the cube in-flight experiment conditions: power-up and connection, pressure and pH sensors operability, pumps functioning with video recording of dye injection.

2.1.4. Audible Noise Test

Objectives: To verify that the total unweighted Sound Pressure Level generated by the cube in the noisiest functioning conditions does not exceed the Columbus module's limits.

Facilities: ISAE-SUPAERO's DCAS Electronics Lab on 11/01/2022.

Approach: Setting the cube in its noisiest operating scenario (pump running at 100%) and measuring the noise levels at a distance of 16 centimetres from the six sides of the cube.

2.1.5. Vibration Test

Objectives: To guarantee that the structural and functional integrity of the cube will withstand the random vibration loads expected during launch.

Facilities: ESEC-GALAXIA's CubeSat Support Facility from 17/01/2022 to 19/01/2022.

Approach: Perform an initial visual inspection and functional test. Then, carry out a resonance search shaking along one principal axis of the cube. Next, apply a random vibration load of 2.09 g_{rms} for 1 minute, and then repeat the resonance search. Repeat for the three principal axes. Finally, perform a second full functional test and full visual inspection.

2.1.6. Interface Test

Objectives: Space Applications Services to verify the compliance of the AIM cube with all the applicable hardware and software requirements for its safe installation on the ICE Cubes Facility on-board the ISS.

Facilities: Space Applications Services clean room and ICE Cubes Mission Control Centre (ICMCC) on 24/01/2022 and 25/01/2022.

Approach: Conducted by Space Applications Services to sequentially verify physical and electrical features, mechanical and electrical interface with ICE Cubes Facility, and software communication interface with the ICMCC.

3. AIM Experiment Cube Overview

The design of the cube can be divided into three main areas of work: mechanics (including the fluidics loop), electronics, and software. This section will provide a broad overview of the design solutions applied for each of these areas.

3.1. Mechanics and fluidics sub-system

The mechanical design of the AIM cube is roughly based on a 2U form factor. The only interface with the exterior is a DB13W3P connector used to receive power and data communication from the ICE Cubes Facility on-board the ISS. Figure 1 presents an overview of the fluidics sub-system and its associated instrumentation, and Figure 2 is a picture of the AIM experiment cube.

An internal frame is used to support all internal components including sensors, pumps, and the two models of artificial arteries that constitute the core of the science experiment. These arteries were manufactured by Elastrat, a company specialised in making silicone phantoms that mimic the mechanical properties of real arteries. The internal frame is attached to the external structure and to the aluminium reservoir. The reservoir contains a large fraction of the Blood Mimicking Fluid (BMF) that circulates through the fluidics loop. The reservoir is closed by a movable piston that allows the fluidics loop to be filled correctly. It is also effective for removal of trapped air, which is critical for the functioning of the system.

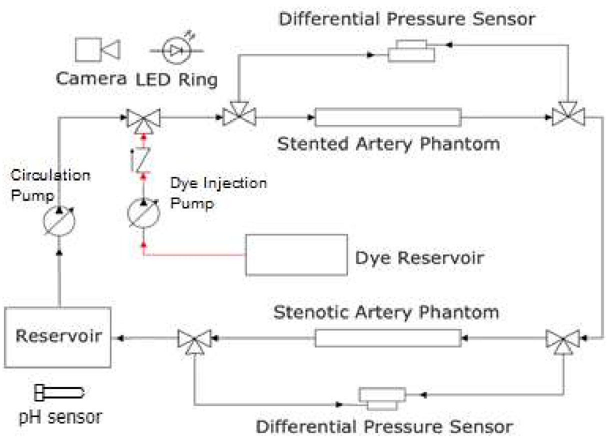

Figure 1. Fluidics system and instrumentation

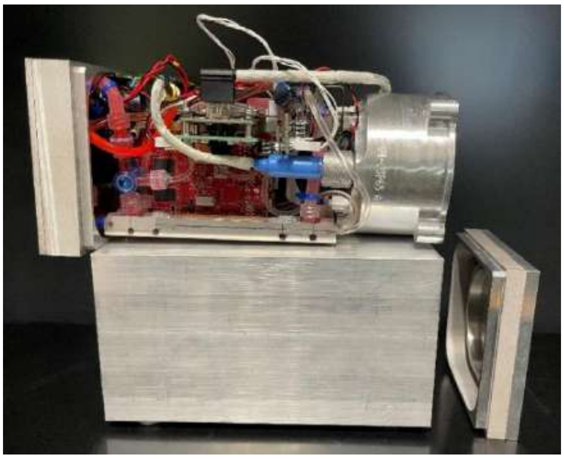

Figure 2. AIM experiment cube hardware

This BMF is made of a mixture of glycerol and distilled water to reach a similar viscosity and density to that of real blood. BMF is extracted from the reservoir thanks to a micropump and circulated through the two arteries, the first having a stent and the second one being in stenotic condition. Fluid then returns to the reservoir to continue circulating in closed loop. pH is also monitored in the reservoir to observe possible fluctuations due to the release of ions from the metallic stent in microgravity.

In addition, four smaller tubes feed the differential pressure sensors that measure, respectively, the pressure drops along the stented artery and along the stenotic artery. Finally, an isolated branch of the fluidics system consists of a pouch of red dye diluted in glycerol and water that gets injected into the main loop right before the artery models. The injection is done drop by drop thanks to a second micropump. This allows the streamlines of the dye drops flowing through the arteries to be observed thanks to a camera located above them.

3.2. *Electronics sub-system*

To accomplish the scientific purpose, the assembly of the instruments is achieved with three different interface printed circuit boards (PCB): main, LEDs, and pressure sensors. These are used to operate the sensors, pumps, and camera from the on-board computer (OBC) of the AIM cube. Figure 3 shows the final electrical implementation link diagram. The boards were subject to several iterations during the project, optimized in consecutive phases:

1. Basic electrical conception: a first diagram was drawn in cooperation with the scientific and mechanical teams.
2. Components' selection: Commercial off-the-shelf (COTS) components were selected to comply with the requirements of the experiment and standards from ESA and partners.
3. Proof-of-concept: A basic proof-of-concept was manufactured to validate the functionalities of the electronics.
4. Validation: Extensive validation was performed, considering functionality, power consumption, and electromagnetic interferences. Once success was achieved, the layout of the boards was fixed.
5. Flight model: This model was developed with the final layout of the board and mounted onto the AIM cube for flight.

3.3. *Software sub-system*

In order to run the experiments required for the scientific purpose of the experiment cube, the Odroid-C4 OBC had to be configured and operated accordingly. This was achieved by implementing software applications on-board and on-ground.

3.3.1. *On-board software application*

The on-board module operates several subsystems within the Ubuntu 20.04 Minimal Operating System that is running on the on-board computer. These are:

- Command handling using a REST API service, which receives telecommands sent from the on-ground station and forwards the command to the corresponding on-board subsystems.
- Data acquisition modules, which use hardware-based Inter-Integrated Circuit (I2C) communication to fetch data from the pressure and pH sensors.

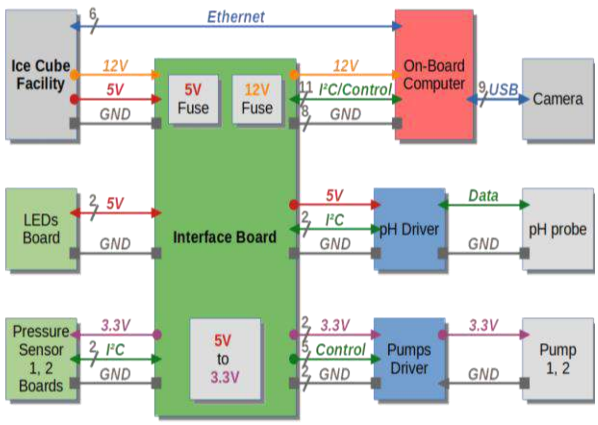

Figure 3. Electrical implementation link diagram

DOI: 10.5821/conference-9788419184405.097

- On-board database using Docker PostgreSQL container, which is used to store sensor data and operational logs.
- Visual data (images and videos) retrieval via a custom-made camera module. The images are saved on the SD card of the Odroid OBC and synchronized to an on-ground storage location.
- Hardware-based Pulse-Width Modulation (PWM) modules, which control the actuators (LEDs and pumps) used to run the experiments

All the modules, with the exception of the database, are coded using Python 3.

3.3.2. On-ground software application
Meanwhile, the on-ground module monitors and sends operational commands from a Grafana dashboard. In addition, it runs an on-ground database, which automatically collects data from and synchronizes with the on-board database. The camera data is automatically synchronized with the ground using a separate synchronization module.

3.3.3. Communication architecture
The machine hosting the on-ground application is connected to the on-board application using a Virtual Private Network (VPN), hosted on a local server. The VPN then connects to the ICMCC, which forwards the connection to the cube on-board the ISS.

4. Main Challenges and Lessons Learned

Throughout the final development of the cube, several issues were tackled by the team, introducing substantial design improvements that resulted in valuable lessons learned.

4.1. Mechanics and fluidics sub-system
Qualifying an experiment full of liquids to comply with all the safety requirements needed for its launch and operation on-board the ISS has turned out to be an enormous challenge for this student project.

The first problem addressed was the appearance of corrosion in the reservoir. After more than one year of the system being closed, and not correctly cleaned from fluids during the stop of the project for COVID-19 lockdowns, the piston was found stuck in the reservoir due to corrosion. The whole reservoir and piston, specifically built for this project, had to be re-manufactured in June 2021. To avoid the problem from reoccurring, it was then manufactured in Aluminium EN-AW 6061 surface treated with Surtec 650 [3]. Strict cleaning procedures after every re-filling were also introduced.

Afterwards, the main challenge faced was the spontaneous formation of bubbles inside the fluidics loop, that appeared after some days of the fluids sitting inside the closed loop. After deep investigations and with the input of experts from ESA, the following actions were carried out to minimise the formation of bubbles:

- Degassing of the BMF and dye in vacuum, at about 11 mbar, to get rid of dissolved gasses in the fluids.
- Replacement of part of the tubing materials from silicone to Tygon S3 E-3603 [4], to reduce the gas permeability across the walls of the tubes.
- Granting of a late cargo delivery opportunity by ESA's Payload Integration Management, allowing the shipment of the cube to the Launch Base two weeks before launch. This allows for the last refilling to be done as late as possible prior to launch.

In addition, a major point of concern was improving the sealing of the fluidics system in all interfaces. This was also motivated by leakage issues encountered during the vacuum test. The following enhancements were introduced to this end:

- Reinforcement of the sealing of the dye bag, after a failure during the first vacuum test due to fatigue cycling.
- Gluing of the pressure sensor tubes to the sensors with Epoxy glue.
- Reinforcement of all joints between tubes and fluidics components with o-rings for threaded joints and with silicone sealant.
- Application of high vacuum grease on the reservoir piston o-ring.

4.2. Electronics sub-system
Given that the development, integration, and validation of the different models of PCBs were done in a very short time, several issues were encountered, and solutions proposed.

To this end, the iteration on PCBs shall be minimized to reduce costs and waiting time. In addition, it is essential to keep good communication between sub-teams to ensure the coordination with mechanical and software interfaces to avoid delays and cost overruns.

In any case, the development of electronics for scientific payloads is getting easier and more accessible also for students in recent years, with an increasingly broader panel of COTS components offered at an affordable price.

4.3. Software sub-system

Throughout the software development process, there were several issues that needed to be corrected, with the most important ones listed.

Firstly, due to compatibility issues between an open-source library used within the software and the hardware, the PWM and I2C peripherals could not be controlled from the software itself but had to be controlled from the Operating System directly.

Also, in the original versions of the software implementation, the on-board software was developed using the C programming language. However, due to compatibility and accessibility issues, combined with the sheer operational difficulty of the C language for team members that were less familiar with programming, it was decided to migrate the software to Python.

4.4. Documentation and knowledge transfer

In this project that involved several generations of students taking over the work from the previous teams, avoidable delays and misunderstandings happened due to a lack of communication and formation of the new students that joined the project when the previous team left. To prevent this from happening again a good strategy for knowledge transfer is important. New students were recruited early in September 2021, giving ample time for them to understand the project and be integrated into the team before senior members departed in April 2022.

It is also essential to make a good effort to document all manipulations of the hardware, with detailed reports including photos. For the most critical operations and tests, composing step-by-step procedures and following them carefully has been found to be the best practice to have a proper record of these actions, and also to prove that all of them were executed correctly for the validation phase.

5. Conclusion

Phase D – Qualification and Production consisted of completing the manufacturing, assembly, integration, and environmental testing of the Artery in Microgravity experiment cube. Many lessons were learned in this phase of the project which could provide valuable knowledge for students embarking on their own space-related educational activities. Special insight was provided on the implementation of design improvements to the AIM experiment cube, and the respective lessons that were learned throughout the design and AIT process.

Many of the challenges faced were related to qualifying a fluid-based experiment for a space mission. Careful selection of impermeable materials and sealing solutions for all interfaces has proven essential.

A good strategy of knowledge transfer between students' generations and across sub-teams is also key to avoiding unnecessary design iterations, for instance with electronics PCBs, saving precious time and cost.

In conclusion, the Artery in Microgravity project has been a unique and invaluable experience for all team members, with being involved in the dynamics of a real space project and having to meet all the typical requirements and reviews. All the students are eager to continue learning throughout the operations phase that will commence in mid-2022.

Acknowledgements

We would like to thank the sponsors of this project for their support: ESA Academy, Fondation ISAE-SUPAERO, Elastrat, Alvimedica and AIRBUS. Special thanks to Space Application Services, ISAE-SUPAERO and Politecnico di Torino.

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Demonstrating Cosmological and Doppler Redshift in the Classroom

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Abstract

Cosmology is often a difficult subject to teach as it can involve many confusing and sometimes abstract concepts. One particular topic with many existing misconceptions and difficulties surrounding it is redshift, specifically the difference between Doppler shift (due to the peculiar velocities of galaxies) and cosmological redshift (due to the expansion of the side). Redshift of galaxies, despite being an extremely useful and interesting scientific tool, can often become a tedious subject to teach as it is largely theoretical and usually does not include demonstrations or interaction in the classroom. It can be challenging to understand, and therefore also challenging to explain, the differences between Doppler and cosmological redshift, often leading to this distinction being overlooked entirely. The set of demonstrations developed during this astrophysics masters project, along with the accompanying presentation, worksheet, and teacher notes, aim to explain both Doppler and cosmological redshift clearly and in an engaging and memorable way. The demonstrations use remote control vehicles to represent peaks of a travelling wave of light. When demonstrating Doppler shift, the vehicles are released from a plastic board that is being pulled away, representing a receding source of light. When demonstrating cosmological redshift, the vehicles are driven along a wide stretchy exercise band, representing a section of the expanding Universe through which this wave of light is travelling. This teaching resource will introduce interactive learning, proven to be very effective when teaching astronomy, and provides a useful and fun physical analogy to demonstrate an often-misunderstood subject.

Keywords
Cosmology, classroom, demonstrations, interactive, redshift

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1. Introduction

1.1. Pedagogical motivations

Cosmology can be a daunting subject [1] with many existing misconceptions [2]. The topic is often taught using purely theoretical and numerical methods, making it difficult for teachers and students alike to stay focused and interested. It has been shown that interactive learning is very effective in teaching astronomy [3]–[5] therefore the teaching materials described in this paper are focused around interactive demonstrations.

1.2. Scientific motivation

Redshift is an important tool for research in Astrophysics [6],[7], and when being taught in schools it should be done correctly. Doppler shift is covered in most school physics curricula, so students will likely be comfortable with the idea of Doppler redshift of galaxies (due to the peculiar velocities of the galaxies) however, cosmological redshift (due to the expansion of the Universe) is often either not explained in schools, or is taught inaccurately, resulting in misunderstandings. For example, if the redshift used in Hubble's law is explained as being a Doppler shift this leads to students and teachers confounding the concepts of cosmological redshift and Doppler shift. This paper describes a set of teaching resources that will explain both of these effects behind redshift.

2. Redshift

When observing galaxies, astronomers often split up the light to display its constituent wavelengths, creating a spectrum. The amount of light emitted and absorbed by a galaxy at each wavelength is determined by the galaxy's chemical composition. Astronomers know which spectral line positions and spacings are expected when looking at a galaxy because they know what the chemical composition is likely to be. However, when galaxies are observed, almost all of them have spectral lines at a longer (redder) wavelength than expected, a visual example of this effect can be seen in Figure 1. This effect is called redshift.

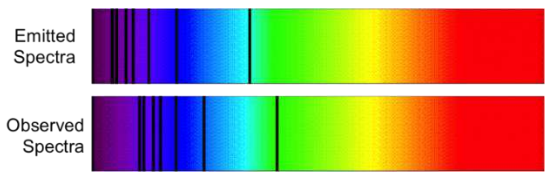

Figure 1. A representation of spectral lines on both an emitted spectra and a redshifted observed spectrum

The redshifting of light from galaxies is due to a combination of both Doppler shift and cosmological redshift.

2.1. Doppler Shift

Classical Doppler shift is the effect that causes the variation in pitch you hear when a fast car is passing you. The sound waves are compressed in front of the car (making the wavelength shorter), and stretched out behind the car (making the wavelengths longer), this is shown in Figure 2.

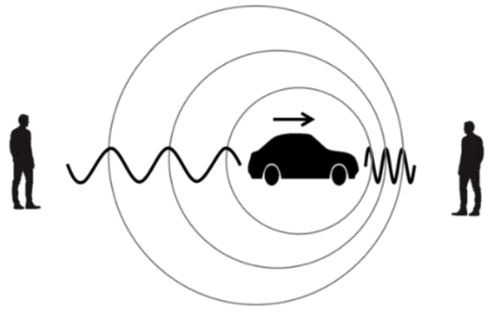

Figure 2. Doppler shift changing the pitch of the sound of a fast car

Figure 2 shows that when the car is moving away from the observer the wavelength is longer, so the pitch will be lower. When the car is moving towards the observer, the wavelength is compressed so the pitch will be higher.

This same effect can be seen with the light from galaxies, as shown in Figure 3. When galaxies are moving away from us the light observed from them will shift towards longer (redder) wavelengths, and when galaxies are moving towards us the light observed will shift towards shorter (bluer) wavelengths.

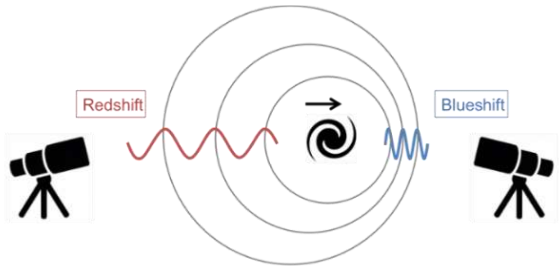

Figure 3. Doppler shift changing the colour of the light being observed from a moving galaxy

The motions that cause Doppler shift of galaxies are called peculiar velocities; for example, motion due to gravitational attraction between galaxies. Note that this is an effect that is not

DOI: 10.5821/conference-9788419184405.098

seen in day-to-day life on earth due to the large velocities required.

2.2. Cosmological Redshift

Cosmological redshift is another method by which the wavelength of light travelling from a galaxy may be lengthened. This lengthening of wavelength is due to the expansion of the Universe. The basic idea behind why the expansion of the Universe shifts light to a longer wavelength can be explained as follows: Imagine two galaxies; galaxy A and galaxy B, as represented by the black galaxies in Figure 4. There is a large enough distance between the galaxies that the gravitational attraction between them is not significant. Some pulse of light travels from galaxy A to galaxy B. If the distance between A and B is constant with time then the light will arrive at B with the same wavelength that was emitted from A. However, if the distance between A and B is increasing, as in Figure 4, the wavelength of light must also increase. The space through which the light is travelling is expanding, and therefore the wavelength also expands. The light will reach galaxy B with a longer wavelength than when it was emitted from galaxy A.

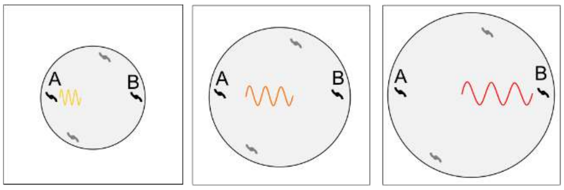

Figure 4. A 2 dimensional diagram showing cosmological redshift.

The grey circle in Figure 4 represents a random section of the expanding Universe and each image in the figure represents a `snapshot' in time.

3. Demonstrations

In order to demonstrate redshift, a physical analogy was created. In this analogy, three remote control vehicles are used to represent the peaks of a wave of light, as seen in Figure 5.

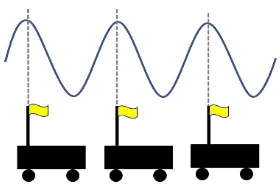

Figure 5. remote control vehicles representing the peaks of a wave of light

A photo of one of the vehicles, along with the controller, can be seen in Figure 6.

Figure 6. One LEGO vehicle and the controller

Instructions for assembling the vehicles along with a kit list detailing the equipment needed and approximate cost can be found at the following website:

www.orielmarshall.com/redshift

Once the vehicles are assembled it is important to ensure you can control them reliably and effectively. All three vehicles will be controlled with the same controller, and must move at the same time. It is recommended you practice using the vehicles before the lesson. At the website linked above, there is also a trouble shooting document that may help to address any practical issues you have with assembling or operating the vehicles.

3.1. Demonstrating Doppler Shift

For Doppler redshift, there must be a wave of light moving towards an observer, and the source of the light must be moving away from the observer. For this demonstration, the vehicles represent the wave of light, and a plastic board represents the galaxy. The vehicles all begin on the board, spaced evenly and relatively close together. The board is pulled slowly at a constant speed away from the observer, while the vehicles are all driven at the same speed off the board towards the observer. This process is shown in Figure 7.

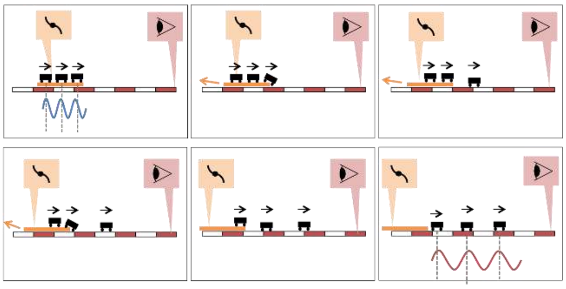

Figure 7. Step by step diagrams showing the doppler shift demonstration.

The orange board represents the galaxy emitting light, the observer in this analogy would be stationary at the right end of the table.

As seen in Figures 7 the spacing at the beginning of the demonstration is relatively small. Once all of the vehicles have travelled off the board, the spacing between them is larger and will remain at this larger spacing regardless of the distance they travel. Before and after photos of the demonstration can be seen in Figure 8, with the positions of the vehicles being measured against the measuring tape on the table. The increase in spacing of the vehicles is analogous to the wavelength of light from a galaxy increasing as it leaves a galaxy that is receding from the observer.

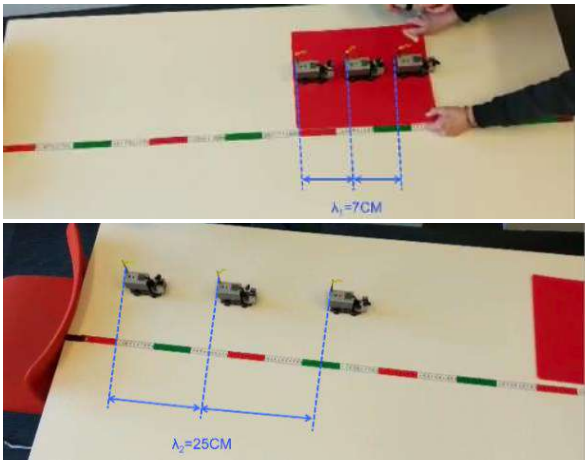

Figure 8. Video stills from the beginning (top) and the end (top) of the doppler shift demonstration

A video of the demonstration for Doppler redshift can be found at:

https://vimeo.com/702909321

3.2. *Demonstrating Cosmological Redshift*

In order to demonstrate cosmological redshift, we must show a wave of light travelling through an expanding Universe. This is done by placing the three vehicles, representing the peaks of a wave of light, onto a wide exercise band, representing a one-dimensional section of the expanding Universe. The band is continuously stretched while the vehicles travel along it, thus resulting in the spacing between the vehicles increasing. The set up and equipment for this can be seen in Figure 9.

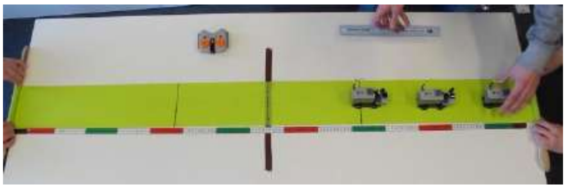

Figure 9. Photo of the setup and equipment for demonstrating cosmological redshift

The setup is operated by three people, one person to control the vehicles, and two to hold the handles at each end of the band. The band must be and stretched consistently and evenly as the vehicles travel across it, this can take a little practice. Figure 10 shows a diagram of the demonstration in action.

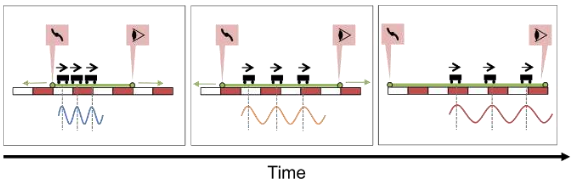

Figure 10. A step-by-step diagram showing the cosmological redshift demonstration

It can be seen in Figure 10 that the constant stretching of the band as the vehicles travel along it results in the distance between the vehicles increasing. The left end of the band that the vehicles are travelling away from represents the source of the light (e.g. the galaxy). The right end of the band that the vehicles are travelling towards represents the observer.

Stills from a video of the cosmological redshift demonstration in action can be seen in Figure 11.

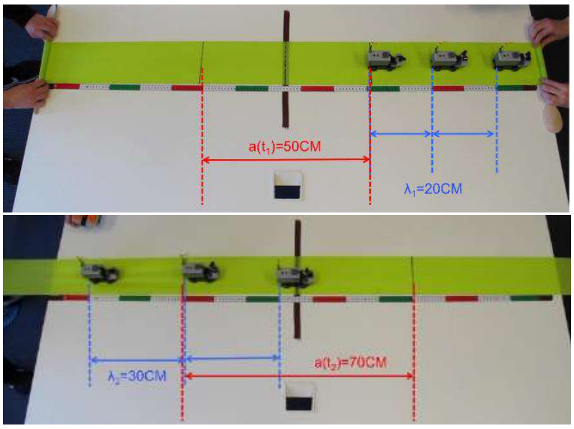

Figure 11. Video stills from the beginning (top) and the end (top) of the cosmological redshift demonstration

In Figure 11 the `light source' is on the right-hand side; the `observer' on the left. The green strip is the stretchy band representing a one-dimensional section of the Universe. The band is wrapped around wooden spoons at each end, these spoons act as handles. During the demonstration, the vehicles travel from right to left, and the volunteers holding the handles walk backwards to stretch the band. It can be seen in Figure 11 that by the time the vehicles have travelled across the stretching band, the spacing between them is larger, as expected. This is analogous to a wave of light travelling across a section of the Universe, and the light being redshifted as the Universe expands.

A video of the cosmological redshift demonstration can be found at:

https://vimeo.com/702909575

4. Discussion

4.1. Limitations of the analogies

The demonstrations explained in this paper act as physical analogies for redshift. As with all analogies it is important to be aware of their limitations in order to understand the extent of their pedagogical impact. Additionally, there are many existing misconceptions in cosmology [2], so it is important these are not perpetuated by these demonstrations.

4.1.1. There is no center of the Universe

As seen in Figure 9 there is a dotted like drawn along the middle of the band. The central line is used to ensure the band is being stretched evenly from both sides and is for practical purposes only. When this demonstration is being presented to the class, it should be made clear that there is no centre to of the Universe, and that the Universe does not expand from a central point, but expands everywhere all at once. It should be stated that this central line is drawn on due to the limitations of the analogy, and should not be applied to their understanding of the Universe.

4.1.2. One-dimensional demonstrations as analogies for three dimensional effects

Another limitation of these demonstrations is the dimensionality. Both of the demonstrations are using a one-demonstrational analogy to explain a three-dimensional effect. For the Doppler shift demonstration, it is not as difficult to translate to an analogy as the Doppler effect is only present along the same direction as the movement of the source of the wave of light. However, for cosmological redshift, the expansion of the Universe is occurring in all three dimensions, and the demonstration is only showing the effect in one dimension. Due to this, it is important to try to explain to the students that in this demonstration we are only mimicking the effect in one dimension. In reality cosmological redshift would be occurring in every direction at the same time, and would look the same regardless of what section of the Universe it was in.

4.2. Benefits of the analogies

As well as pointing out the limitations of the analogies, it is also important to be aware of the aspects in which the demonstrations act as effective analogies. In addition to the clear benefit that the analogies may help students to understand the effects that cause redshift, the demonstrations may also help students to better understand the scale factor of the Universe, and the difference between Doppler shift and cosmological redshift over long distances.

4.2.1. Scale factor of the Universe

In the cosmological redshift demonstration, there are two dashed lines on either side of the centre, seen in Figure 9. These are used to compare with the measuring tape on the table to keep track of how much the band has expanded over time, this is analogous with the scale factor of the Universe a(t). The scale factor of the Universe is a value used to track the relative size of the Universe over time, and is found by taking a ratio of the value a(t) at two different times. This value is used in the cosmological redshift equation, so by having a physical measurement that can be used to show the scale factor of the Universe this can help students understand the concept.

4.2.2. Differences over long distances

One of the key differences between Doppler shift and cosmological redshift are their limiting variables, and how they act over long distances. Doppler shift is calculated using only the speed of light and the speed that the light source is moving at. The speed of light is constant, and galaxies have a peculiar velocity of the order of $100 kms^{-1}$, so there is a limit on how large redshift due to the Doppler effect can be. Cosmological redshift is calculated using a ratio of the scale factor of the Universe at two different times, therefore the only limit on how

DOI: 10.5821/conference-9788419184405.098

large this can be is time between the light being emitted and observed. These differences can be understood further through a simple thought experiment based on the demonstrations.

Imagine that in each demonstration you have an infinitely long table. For the Doppler demonstration, once the vehicles have left the board, they will remain at that same spacing regardless of how long they travel for. Their spacing is determined by, and capped by, the speed of the board's movement, and is not changed once all the vehicles have left the board. For the cosmological redshift demonstration, as long as the band continues to stretch as the vehicles are travelling, the spacing between them will continue to grow indefinitely. There is no limiting factor on how much the spacing can increase by, just as there is no limit to how much light can be cosmologically redshifted by.

5. Conclusions

The results of this project consist of two hands-on interactive demonstrations explaining both cosmological redshift and Doppler redshift and the differences between them. These are accompanied by a lesson plan, a presentation, a student work sheet, and detailed instructions on how to assemble and use the demonstrations. These resources can all be found at:

www.orielmarshall.com/redshift

Although there are inherit limitations to the physical analogies used in the demonstrations, they clearly show how both effects can result in an observed wavelength from a galaxy that is longer (towards the red) than the emitted wavelength from the galaxy. This set of resources allows students to learn about the causes and limitations behind the important astronomical tool of redshift. The demonstrations show how the expansion of the Universe can increase the wavelength of light in cosmological expansion, and how the receding peculiar velocity of a galaxy can cause the wavelength of light from a galaxy to increase through Doppler shift.

Were there time available, the next steps in this project would be to validate the materials by testing them in schools and make adjustments and adaptations to the teaching resources and demonstrations based on feedback from both the students and teachers.

Acknowledgements

I would like to thank Fiona Lindsay and Harriet Gilzean for their feedback, and Aleksanteri Vattulainen, Yorick Enters and Michael Williams for their flawless performance in the instructional videos.

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Six-year evolution of a space-inspired collaborative problem-solving study program in Finland

Ana Gebejes[1], *Heikki Immonen*[2], *Charles J. Camarda*[3]

Abstract

This paper presents the results of the six-year qualitative longitudinal case-study of the Epic Challenge study program in Finland. Created in 2008 for NASA engineers, the Epic Challenge program has grown and evolved to teach collaborative problem solving that reaches across different disciplines and ages. The paper presents an overview and evolution of program features and teaching methodologies. In the program, students learn a challenge-based methodology called Innovative Conceptual Engineering Design (ICED) and use this methodology to develop innovative solutions connected to the overarching challenge of sustainable human habitation of Mars. The program is built around the assumption that space exploration as a complex, multidisciplinary challenge provides the inspiration, a driving force and integrated curriculum for teaching Science, Technology, Engineering and Math (STEM) concepts and problem-solving techniques in four key areas: teamworking, networking, systems thinking and innovation. In 2015 the program was adopted and fused with a phenomenon-based learning curriculum in Finland, and it grew to be taught to students of various backgrounds from high-school to doctoral level. The course delivery and content were modified annually based on lessons learned and more than 500 students have gone through the program in Finland. The paper presents the evolution of key program features and concludes by presenting the most robust features of the program implementations that could benefit space agencies, companies and faculty interested in promoting space and STEM related competences.

Keywords

challenge-based learning, collaborative problem solving, innovation education, STEM

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Acronyms/Abbreviations

ICED	*Innovative Conceptual Engineering Design*
STEM	*Science, Technology, Engineering and Math*
ECP	*Epic Challenge Program*

1. Introduction

Epic challenges are problems that are very complex by nature due to many interacting elements within and to be solved they require expertise from many fields. Due to their importance, urgency, and complexity they become a motivational force for large audiences. In this paper we present an educational program that shows success in passing skills and attitudes that are needed for solving such challenges. Moreover, it seems to encourage younger students to study STEM subjects and pursue careers in Science, Technology, Engineering and Math (STEM) [1] and entrepreneurship [2]. Space as an extreme and still to be discovered environment has been the driver of the program as a great source of highly complex, unsolved challenges.

Problem-based and collaborative learning have been shown to promote skills (negotiation, organization, leadership, teamwork, communication etc.) needed for twenty-first century workers in STEM areas [3]. As these teaching strategies are problem-oriented rather than subject oriented they encourage students to become active participants during the learning process as they are using knowledge rather than just recalling it [4,5]. It has also been defined that to manage change in the society and in the work life, new types of competencies, such as collaborative learning, self-leadership, and flexibility, are needed [6]. One example of a nationwide action to combine aspects of problem-based learning, explorative learning, and project-based learning can be seen in Finland where phenomenon-based learning has been introduced to the core national curriculum for basic education since 2016 [7].

The Epic Challenge Program (ECP) teaches team-based problem-solving skills in four key areas: teamworking, networking, systems thinking and innovation. In this paper we study the features of the program implementations in Finland and discuss the most robust features as the program expanded from being taught to NASA junior engineers to the general public. Section 2 introduces the origins of the ECP and its expansion in Finland. Section 3 introduces the methodology used in analysing the features of the program. Section 4 provides an overview of the program features. Section 5 offers explanation on why some features remained, evolved, or faded away. Section 6 concludes the paper with listing the most robust program features.

2. Epic Challenge Program

2.1. Origins of the program

The original idea for such a program occurred to astronaut Dr. Camarda in 2003 while training as a backup crewmember for an Expedition 8 mission to the International Space Station. During his training, the Space Shuttle Columbia and its crew were lost during entry from space. NASA struggled for the next 2.5 years trying to understand the “root” causes of the accident. During this time, it became apparent to Dr. Camarda that critical skills to develop innovative solutions to complex problems were sorely missing at the Johnson Space Center, where he was training as an Astronaut. He used his skills to help the center develop several teams to solve critical problems and to develop technologies needed prior to his launch on the return-to-flight mission, STS-114. He initiated and led a research team which verified the technical cause of the accident and accurately predicted impact damage to Orbiter vehicles and an R&D team which developed an on-orbit repair technique to fix a damaged wing leading edge in space. When returned from space he formalized his innovative engineering design strategy into a pedagogy called Innovative Conceptual Engineering Design (ICED) [8].

2.2. ICED Methodology

The ICED methodology is based on the creation of psychologically safe virtual and physical environments to solve real-world engineering problems. Throughout this process, students are encouraged to explore, experiment, fail, discover, and learn. The methodology draws upon the teaming of very diverse groups of students, engineers, scientists, designers, artists, etc. to explore an open-ended design space and exercise both hemispheres of their brain, the analytical left and creative right, to conceive and develop innovative solutions.

The ICED methodology was initially taught as a formal summer short course as part of the NASA Engineering and Safety Center Academy Program in July 2008 at Penn State University to instruct NASA engineers in the art and science of innovative engineering design [8]. A follow-on study, led by a small university student team, selected one of the concepts generated during the course and developed a solution to a problem NASA was struggling to solve for over 50-years, the safe land landing of a crewed space capsule [9]. This was proof that this challenge-based methodology would work both as a motivating force to attract and sustain student interest and as a mechanism to explore and rapidly mature innovative ideas.

The ECP was founded in 2010 and has attracted thousands of students in the United States to help solve challenges related to human spaceflight and the colonization of space. A 501(c)(3) educational nonprofit, the Epic Education Foundation [10], was formed to formalize the educational components and to run challenges for students around the world. Some of the results of early projects can be found in reference [1]. The program has grown to reach students in Finland and Australia and is planning to reach students in Mexico and Brazil this coming year.

2.3. Program expansion in Finland

EPC has been running in Finland since the 2015-16 school year [2,11]. Until now it has been implemented every school year and within each there were multiple iterations. Since the start the EPC has hosted over 500 participants from different study levels (doctoral, MSc, BSc, vocational college, and high school), from which over 35% identify as female. The participants represented over 15 different degree programs, from both natural and social sciences, and 17 different nationalities. Each program iteration allowed the local teachers to test and adjust different features of the program to suit these different backgrounds and levels of education. The participating teams, challenges they tackled and some of the solution they developed can be seen at the Finnish programs' website [11].

3. Research Methodology

Scientific knowledge evolves from early descriptive forms to practically useful prescriptive theories [12]. This current paper contributes to the field at the level of late-stage descriptive theory-building where relationships between different observable phenomena are defined. Specifically, different educational program features are rank-ordered based on their robustness. Here, robustness is defined in the most general way as the age of various program features still in use. Statistically, the expected lifetime of a non-perishable thing, such as a practice, is proportional to its age [13]. This principle is captured for example in the TRL classification, where highest readiness is assigned to technologies that have been used repeatedly in real missions [14]. In this paper, listed program features and their age are based on a past paper [2], existing documentation and the authors own personal memory of past implementations of the ECP.

4. Epic Challenge Program Features

The following section describes the key features of the program and how these features evolved over the six years. Figure 1 lists features in use by school year since 2015 until 2021.The blue line indicates when a feature was in use.

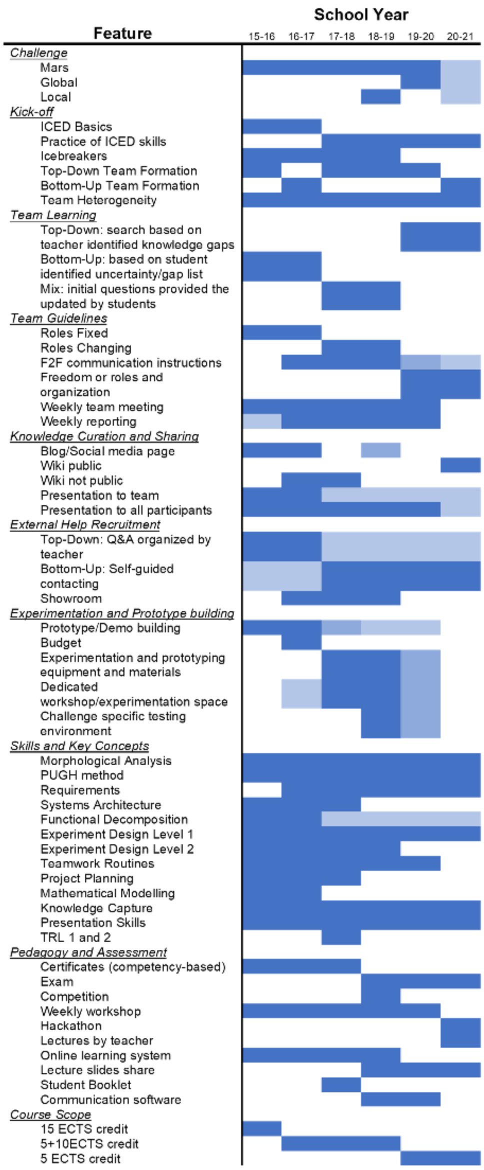

Figure 1. List of program features. The blue line indicates when a feature was used. The shading indicates degree of usage: dark blue = fully in use, medium blue = reduced usage, light blue = further reduced usage

Originally, ECP was a one-week intensive learning program [1]. In Finland it started as nine months long 15 ECTS credits course. Over the six years it evolved to fit the Finnish university course scope better. In the second year it was divided into a 5 ECTS introductory and 10 ECTS advanced course and in the third it was compressed so that the 5 ECTS course could be completed in one period (8 weeks) and the 10 ECTS course in two periods (16 weeks).

Every year a variety of ***challenges*** was offered for student teams to choose from. In addition to clarity and epicness, in the challenge definition, linkage to local R&D resources were considered. The methodology has been applied also to solving global challenges concerning Earth and local challenges relevant for the region. Some of these challenges had an analogous Mars-themed challenge.

The ***Kick-off Week*** is an introductory intensive week at the beginning of the program aiming at familiarization and team formation. The content of this week has evolved from introducing the methodology to practicing the skills and tools needed to implement the methodology to solve the challenge. ***Team Formation*** supporting activities such as icebreakers, introduction rounds, mingling exercises, mini-challenges were part of the kick-off. The forming of the teams was done either by teachers' decision based on team heterogeneity and challenge interest criteria obtained from participant survey (*Top-Down*) or by participants' decisions during activities (*Bottom-Up)*. ***Team Heterogeneity*** in terms of study field, age, gender, and skills was present during all the years.

Solving any epic challenge requires a lot of knowledge and information to be understood. As the challenge is epic, it is complex by nature and doesn't have a solution yet, one discipline cannot solve it and hence no one person, instructor nor participant will know everything that is needed to solve the problem. ***Team Learning*** draws on identifying team knowledge gaps and closing them. Early on freedom was given to teams to identify uncertainties and gaps in their cumulative knowledge (***Bottom-Up***). Then it evolved to a mixed approach where teachers provide initial questions as a starting point for teams to use, update and expand (***Mix***). Finally, teacher identified knowledge gaps (***Top-Down***) were given as a frame for teams to base their search and learning on.

Team Guidelines on roles, communication and teamwork management were provided. Initially teams were provided with defined ***roles*** (manager, recorder, communications manager) that needed to be assigned and fixed to each team member. In later years these roles were changeable and finally became free to use as needed. Instructions and dedicated activities for ***face-to-face (F2F) communication*** were implemented after the first year to stimulate distributed communication between team members early on. Teams were instructed to have at least one ***weekly team meeting*** and after the first year they adopted a ***weekly reporting*** routine.

Knowledge Curation and Sharing in practice means that the knowledge of an individual, pre-existing, or learned during the program, needs to become the knowledge of the whole team and the future generations. ***Presenting within the team*** was an early instructed practice that became a recommendation. ***Presenting to all participants*** was required at different stages of the program with the final presentation being mandatory. Other ways to share knowledge were public ***blogs and social media posts*** that transformed into a more organized ***private Wiki*** and finally evolved into a ***public Wiki***, i.e., a public document that many people can edit.

External Help Recruitment is encouraged as the teacher cannot be the sole source of all information that is needed to solve a challenge that is so complex in nature. Early on teachers were the main organizers of Q&A sessions with experts (***Top-Down***). Later on, this has evolved so that teams were instructed and encouraged to find relevant experts themselves, interview them and mobilize them as needed (***Bottom-Up***). ***Showrooms*** as a way for the students to present their progress and build their own networks were organized by teachers as well.

Early ***Experimentation and Prototype Building*** are the key aspects of the ICED methodology. Over the years the way it has been encouraged and implemented varied depending on availability of budget, materials, components, and experimentation facilities. Early on teams had to mobilize their own networks to acquire needed materials. As the program grew, a budget for experimentation was acquired and dedicated facilities, workshop areas and materials became available for teams to use. This culminated with a dedicated challenge-specific testing environment teams could use to test their final prototypes. During the pandemic quarantine experimentation had to move back to the level of simple experiments that can be done at home.

The ***Skills and Key Concepts*** participants need to learn and acquire to be able to successfully apply the ICED methodology has been evolving as the program was expanding from being taught to NASA engineers to everyone. Figure 1 lists 13 skills and key concepts that were adjusted and iterated over the years based on the participant response.

Pedagogy and Assessment. The teaching was organized so that the contact hours with the teachers are one day a week in the form of a four-hour evening ***workshop***. Portion of the workshop is dedicated for direct instruction when the instructor introduces new concepts, methods or tools and goes through a worked example. The remainder of the four hours is then used for the teams to apply the method to solve the challenge. The last year workshop has been swapped with a ***hackathon*** and ***lectures*** given prior to it. For three years the instruction and assessment were organized in a competency-based manner where each skill/concept was iterated and improved by each participant until 100% mastery. After the mastery was demonstrated, the participant achieved a ***certificate***. For the following three years the certificate assessment system was replaced by an ***exam*** assessment system. One year a ***competition*** was added where the relative performance of the prototypes the students designed and build defined part of the grade of each student. Besides the F2F interaction different ***online tools*** were used as well for sharing learning materials and supporting participant-participant and teacher-participant communication.

5. Discussion

In this section we offer explanations of why certain features remained to be in use for a long time and certain features didn't.

The ***Challenge*** is the key driving force of the program and as such it must be defined well. Firstly, the challenge must be defined to be epic enough and the epicness comes from stating the situation, the goal, and the requirements. Secondly, the challenge must be made such that it truly requires more than one discipline to solve it. Thirdly, the challenge definition should not include any suggestions of what the form of the solution should be. To achieve this, we must use language that focuses on stating the function that needs to be achieved rather than the form that accomplishes the function. Finally, we need to make sure that we are really describing the problem and not the solution. Following these key principles one can use the EC way of approaching problems in any field. Linkage to local R&D resources and availability of experts locally raises the popularity of the program and provides access to subject-matter-experts close by. ***Kick-off Week*** activities should also be designed to promote a psychologically safe environment for the participants to try things and fail, to share opinions and ask questions and to build connections. We observed that practicing ICED skills early-on sets participant expectations and makes the complex engineering tools and concepts more approachable. Hence, ***icebreaker*** activities morphed into early practice and implementation of ICED skills. This also allowed for delivering more course content in a shorter amount of time and compressed the introductory course to only 8 weeks. The kick-off week should end with the formed teams having the first team meeting where participants will make an inventory of their common skills, start finding their knowledge and skill gaps and make a weekly routine for the team. ***Team Heterogeneity*** has remained a key aspect as different people come with different social circles which allows them to share novel ideas which in turn leads to a much larger pool of ideas a team can pull from. With heterogeneity also come difficulties for teachers as their instruction needs to cover different skill levels and learning practices. These difficulties were driving the evolution of the pedagogical practices and the curriculum. Hence the ***skills and key concepts*** and the order in which they have been taught has been evolving as well. Participants learn about many systems engineering concepts and tools such as: systems architecture, functional decomposition, morphological analysis, and decision matrix method. ***System architecture*** and ***mathematical modelling*** have been challenging to instruct to such a wide audience. ***Functional decomposition*** on the other hand has remained an essential part of a clear problem definition. Designing and executing experiments has remained the key aspect of the program. Having a dedicated budget allowed for bringing experiments to a higher level, building prototypes, and testing them. Without budget and facilities, the experiments are forced to stay on a lower level. Also, the amount and level of experimentation depends on the duration of the course. Therefore, to keep the course at the most popular ***5ECTS scope*** the level of experimentation and the amount of content needs to be reduced. When working with diverse teams and with an epic topic no one team member is fully an expert in the topic. Therefore, making an inventory of cumulative team skills and identifying knowledge gaps is a key first step. Furthermore, teams need to create an environment that promotes learning from each other. ***Bottom-Up*** and ***Mixed team learning*** faded away as the course scope became shorter. Teacher identified knowledge gaps (***Top-Down***) has shown to provide a structure that participants can use to frame and expand their search. ***Presentations*** have remained the main way of sharing knowledge and public documentation of knowledge has been present in different forms as well. Certificates as pedagogy and assessment technique were a very successful model from skill mastery point of view. However, the model was not sustainable when the course became shorter to fit the usual university schedule. As the number of participants grew it was no longer possible for one instructor to maintain the number of iterations that was needed for mastery. For these reasons a shift towards the exam as an assessment method was made.

6. Conclusions

The paper presented an overview and evolution of the key features of the ECP in Finland. We have shared how these features have evolved to suit local teaching and a much wider audience. Based on the findings in this paper the most robust features were a Mars themed challenge, focus on Team Heterogeneity, intra- and inter-team knowledge sharing in a form of presentations, Q&A organized by teacher and self-guided expert contacting. Of the skills, Morphological Analysis, PUGH method, Functional Decomposition, simple Experimentation, Knowledge Capture and Presentation Skills were the most robust. It remains to be further explored how to make systems engineering concepts and tools even more appealing to all fields.

Acknowledgements

The authors would like to acknowledge School of Computing and Institute of Photonics at University of Eastern Finland, Karelia University of Applies Sciences, Valamis Group Ltd., and Epic Education Foundation.

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[3]Cat-4 Mission, 1-Unit CubeSat for Earth Observation: Evaluation on the qualification and production during Phase D

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Abstract

The [3]Cat-4 mission is a 1-unit CubeSat platform that serves as a technology demonstrator and educational platform for students at Universitat Politècnica de Catalunya (UPC). Promoted by the UPC Nanosatellite and Payload Laboratory (UPC NanoSatLab), the most notable subsystems that innovate in the nanosatellite scenario are (1) the Flexible Microwave Payload - 1 (FMPL-1) [1], a cost-effective payload to execute Global Navigation Satellite System Reflectometry (GNSS-R), and L-band microwave radiometry experiments using a commercial off-the-shelf (COTS) software-defined radio (SDR) and (2) the Nadir Antenna Deployment Subsystem (NADS) [2], an in-orbit deployable high-directivity antenna used by Earth Observation (EO) payloads. This paper presents the findings of the [3]Cat-4 mission during Phase D, the qualification and production phase of the project. Since the publication of the first introductory work for this mission in 2019[3], several sections of the subsystems have been redesigned and upgraded to correct previous design flaws or to meet new requirements. In addition, this paper addresses the educational perspective of this mission, analyzing its performance and usefulness in the aforementioned subject.

Keywords

CubeSat, Earth Observation, Phase D, COTS, SDR, Education

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Acronyms/Abbreviations

ADCS	*Attitude and Determination Control Subsystem*
AIS	*Automatic Identification System*
AIV	*Assembly, Integration and Verification*
ATC	*Ambient Test Campaign*
COMMS	*Communications Subsystem*
COTS	*Commercial Off the Shelf*
DITL	*Day In The Life*
EO	*Earth Observation*
EPS	*Electric and Power Subsystem*
ESA	*European Space Agency*
ETC	*Environmental Test Campaign*
FFT	*Full Functional Test*
FMPL-1	*Flexible Microwave Payload-1*
GNSS-R	*Global Navigation Satellite System-Reflectometer*
QM	*Qualification Model*
LOS	*Line Of Sight*
MT	*Mission Test*
NADS	*Nadir Antenna Deployment Subsystem*
OBC	*On-board Computer*
SDR	*Software Defined Radio*
TVAC	*Thermal and Vacuum Chamber*
UHF	*Ultra High Frequency*
UPC	*Universitat Politècnica de Catalunya*
ZADS	*Zenit Antenna Deployment Subsystem*

1. Introduction

In the frame of NewSpace, the research centre based in Universitat Politècnica de Catalunya (UPC), Nanosatellite and Payload Laboratory, known as NanoSat Lab, develops CubeSats missions specializing in Earth Observation (EO) payloads. One of these missions is ^{3}Cat-4, a nanosatellite that follows the standard of 1 Unit of envelope. ^{3}Cat-4 develops under the scope of the framework of the "Fly Your Satellite! II" program of the European Space Agency (ESA) Education Office – ESA Academy.

2. Mission and objectives

The ^{3}Cat-4 mission is a research and educational CubeSat mission based on a 1U standardized envelope. Its main objective is to demonstrate the capabilities of using nanosatellites for challenging Earth Observation (EO) applications.

The satellite is equipped with the in-house developed payload known as Flexible Microwave Payload 1 (FMPL-1). FMPL-1 combines three different instruments in a single board: An Automatic Identification System (AIS) receiver; a L-band radiometer; a Global Navigation System - Reflectometer (GNSS-R). All of them are executed in the same Software Defined Radio (SDR) commercial of the shelf (COTS) component, powered by a Linux operative system.

Regarding the scientific experiments: (1) the Automatic Identification System (AIS) operates in the maritime Very High Frequency (VHF) band (between 30-300 MHz) and enables the wireless exchange of navigation status between vessels. The broadcast messages include the vessel's name, course, speed and current navigation status. Having this receiver as a pay-load for the mission allows to receive AIS messages from vessels that are far from land, and cannot be collected from the fixed network of AIS receivers. (2) An L-band radiometer is an instrument that receives the radiation emitted by the Earth at L band [3] (1.5 - 2.7 GHz). These measurements can be processed to obtain several environmental parameters such as soil moisture, sea surface salinity, snow density and vegetation optical depth. (3) The GNSS-R technique consists of measuring the direct GNSS signals in their way to the Earth, and also their corresponding reflections on the Earth's surface [3]. Comparing the variations between both signals, which theoretically are the same, it is possible to infer properties of the reflection surface. Using this technique, it is possible to obtain environmental parameters relevant for research in altimetry, oceanographic wave height and wind speed, cryosphere monitoring and soil moisture.

In terms of educational objectives, the ^{3}Cat-4 mission is conducted entirely at the UPC-NanoSat Lab. The whole team is composed by students from different engineering backgrounds, such as telecommunications, electronics and aerospace engineers, ranging from different educational levels from undergraduates to doctoral students. The main educational objective is to provide a significant experience and knowledge to promote qualified future professionals in the related fields.

2.1. Phase D of the mission

The mission beginnings date back to 2017, when the definition of the proposal was presented and selected by ESA Academy "Fly your Satellite! II" program. Since 2019, the mission entered in the design and implementation of most of the in-house built subsystems. Finally, since early 2021, the mission entered the Phase D to qualify and test the designed subsystems, integrate them, and execute more qualification and testing at a system level.

3. Satellite architecture

The ^{3}Cat-4 satellite is formed by several subsystems that provide the required power, communications capability and processing capacity. These subsystems are the Electrical and Power Subsystem (EPS), the On-Board Computer (OBC), the Communications Subsystem (COMMS) and finally and linked to COMMS, the Zenith Antenna Deployment Subsystem (ZADS), which provides an Ultra-High Frequency (UHF) Antenna for communications. Then, the payload-oriented subsystems are the FMPL-1, which contains an independent computer, and SDR that executes the EO experiments, and the Nadir Antenna Deployment Subsystem (NADS), which is an in-house developed in-orbit deployment system formed by a 50 centimeters long helix antenna.

In the following figure, an exploited view of the stack is available:

Figure 1. ^{3}Cat-4 stack exploited view

Starting from the left, there is the top face. The components are stacked as seen in the 3D model, detailing hereunder each number to the component: (1) ZADS, (2) COMMS and ADCS, (3) EPS, (4) OBC, (5) FMPL-1, (6) 1U CubeSat Structure.

In the following figure, a render of the spacecraft with the deployed NADS configuration is available:

Figure 2. ^{3}Cat-4 configuration with NADS deployed

4. Subsystem level qualification

After the design and validation of the different subsystems that compose the spacecraft, the qualification phase starts. The different subsystems will be separated in two determinant groups: (1) first, the COTS group, meaning that all the components that are COTS are not needed to be tested at subsystem level as their manufacturers and flight heritage certify them. These are the EPS, OBC, ZADS and the mechanical structure; (2) second, the in-house designed and manufactured subsystems, which are needed to be tested to ensure its correct functioning under mission requirements. These are the COMMS, NADS, FMPL-1 and ADCS.

For this reason, the COTS components are not standalone tested or the executed tests are by far less restrictive than in the in-house group. In-house components shall pass a Thermal and Vacuum Chamber test, which tests its operative and non-operative temperature range and a Vibrations test, that ensures the integrity and function of the subsystem under launch conditions.

4.1. Electrical and power subsystem

As a COTS, the GomSpace EPS did not experience a standalone TVAC and Vibrations test. Nonetheless, a different TVAC test was scheduled in order to verify the proper functioning of the battery heaters. Its main intention was to ensure that it was possible to upload a configuration file from the ground segment to the EPS subsystem software, setting the hysteresis temperature that defines the heaters operation range.

DOI: 10.5821/conference-9788419184405.100

Figure 3. EPS subsystem preparation for TVAC testing

4.2. Communications subsystem
As an in-house component, the communications subsystem has undergone a TVAC test as well as a Vibrations test, successfully passing both of them.

4.3. Zenit Antenna Deployment Subsystem
As a COTS, the ZADS provided by ISISpace did not experience a standalone TVAC and Vibrations test. Nonetheless, strong testing regarding communications has been taken in place, as well as an ambient deployment test to ensure the correct functionality of the deployment subsystem and validate that there are no mechanical stresses when the COTS is mounted on the satellite that prevents it from deploying.

4.4. Nadir Antenna Deployment Subsystem
As an in-house component, the Nadir Antenna Deployment Subsystem has passed an extensive test campaign as a standalone subsystem due to its high complexity and several failure points.

The first test was the Vibrations test, applied to the NADS Qualification Model (QM). In the following figure, a picture of the test is available:

Figure 4. NADS subsystem vibrations test

Then, one of the most significant problems with the NADS deployment was the high current consumption used by the subsystem when burning the wires. For this reason, the system was tested several times in different configurations, being the most relevant critical parameter the cable length that connects the NADS to the rest of the satellite (mainly the stack EPS-OBC).

First, an ambient deployment was attempted, with a successful result, as it can be seen in the following figure:

Figure 5. NADS subsystem ambient deployment

Once the ambient deployment attempt was a success, a TVAC deployment was scheduled. In the following figure, a picture of the NADS deployment inside the TVAC can be observed.

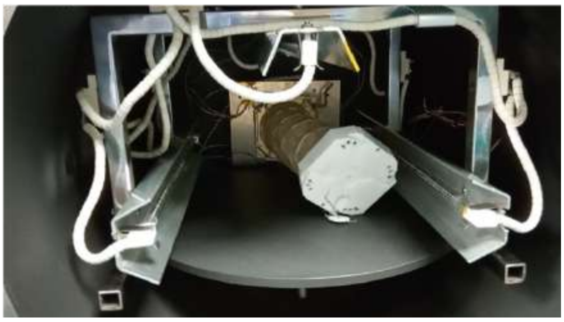

Figure 6. NADS subsystem TVAC deployment

The most relevant outcome of this test is the detection of untrustworthy behavior from deployment switches for temperatures below - 5ºC. This generates a condition for the operation of the mission to only deploy the NADS for temperatures higher than - 5 ºC.

4.5. Flexible Microwave Payload
As an in-house developed component, the communications subsystem has undergone a TVAC test as well as a Vibrations test, successfully passing both of them.

4.6. Attitude and Determination Control Subsystem

As the ADCS subsystem shares the same board with COMMS, the subsystem has undergone a TVAC test as well as a Vibrations test, successfully passing both of them.

Nonetheless, the last implementation of the ADCS subsystem was the creation of a specific mode that increases the sampling rate of sensor data so as to perform an in-orbit ellipsoid fitting and calibration of the magnetometers. This test mode has been tested in the FlatSat randomly moving the sensors to generate a demand for attitude control by the system.

5. System level qualification

Once the standalone subsystem verification has been executed, the integration must be completed before starting the system level qualification. Figure 7 shows a picture of the spacecraft fully integrated:

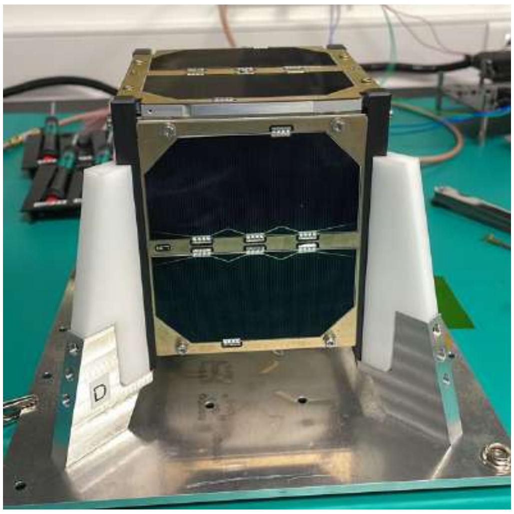

Figure 7. [3]Cat-4 completely integrated

Once the system is complete, the system level qualification must take place.

5.1. Ambient Test Campaign

The Ambient Test Campaign (ATC) is a test campaign focused on the validation of the overall spacecraft functionalities and capabilities. It is divided in two different tests:

5.1.1. Full Functional Test

The Full Functional Test (FFT) is a compilation of tests that aims to validate the overall functioning of the spacecraft. It is divided in the Basic Functional Tests, which consists in the simplest requirements needed to be performed by each subsystem as the sending of accurate telemetry and the Mission Oriented Tests, which are more complex functionalities required for the correct development of the mission. In the FFT all the tests are isolated from each other, meaning that the satellite can be powered off between them. No logical time sequence is required to follow, as well as no radio-frequency communications are needed as long as the umbilical cord ones are used through the serial port.

5.1.2. Mission Test

The Mission Test (MT) is the second test of the ATC. Also known as Day In the Life (DITL), this test comprises the same testing executed in FFT but in a scenario that mimics the conditions that the satellite will encounter in orbit. The main intention is to simulate the real operations of the satellite. One of the particularities of this test is that only radiofrequency communications are available as well as Line Of Sight (LOS) between the satellite and the operator are not allowed. Also, both the power and communications regime mimics the real one, with the possibility to only communicate with the satellite for 10 minutes (pass duration) every 90 minutes (orbit) and to apply a sequence of charge/discharge of the satellite's batteries to mimic the real conditions. In order to properly organize and execute this test, at least three roles are needed: Test Operator, who will be the one in charge of the ground segment to operate, the Test Support Operator, a position inside the cleanroom who is monitoring the umbilical debug of the satellite to spot malfunctions and finally the Test Responsible, who is the one in charge of ensuring that the stated constraints are respected and to communicate with both operators and to prevent communications between them.

5.2. Environmental Test Campaign

The Environmental Test Campaign (ETC) is a test campaign focused on the validation and qualification of the spacecraft while recreating real conditions suffered throughout the mission. The ETC is divided in two tests:

5.2.1. Vibrations Test

The vibrations test consists of exposing the spacecraft to different types of vibrations patterns (random, quasistatic and shock) in each of the three axes to validate the correct functioning of the system. The conceptual explanation of this test is that the vibrations used are the ones provided by the launch authority as a minimum profile required to pass

DOI: 10.5821/conference-9788419184405.100

in order to launch the satellite with them. A successful vibrations test ensures that the satellite will not suffer during the launch as well as it will not damage any other satellite in the deployer.

5.2.2. TVAC Test

The TVAC test consists of exposing the spacecraft to the ambient conditions that it will suffer while in orbit. Being in orbit affects two main parameters: temperature and pressure. First, temperature can range from – 20 to 60 ºC, depending on the launch orbit and, specifically, on its LTAN. The used values to test the spacecraft at a system level are the qualification values, which are -20 ºC as lower bound and 60 ºC as upper bound. Up to four thermal cycles, which mimic the behavior experienced in orbit, are scheduled and executed to characterize the system response to temperature variations. Nonetheless, these thermal cycles are executed while the ambient pressure is under 10^{-5} mbar, really close to the value experienced in-orbit.

6. Discussion

This work emphasizes the importance of testing, both at subsystem and system level, in order to increase the success rate of our mission. Nonetheless, the future is unpredictable and, although conceptually prediction of possible contingency cases, most of them cannot be tested (specifically at system level) as it is impossible to simulate almost every point of failure of the system, which has several layers of complexity.

7. Conclusions

The main conclusion of this work is that adequate and well-thought test campaigns must be organized at both subsystem and system level to validate the stated requirements. Although, it is important to consider the constraints of each scenario and that a simulation is only a modeling of the future, and modeling is not perfect. Thus, the system must be equipped with recovery procedures in order to cover the potential failures throughout the mission. It is also crucial to train the future satellite operators adequately as they will be the ones who would analyze the telemetry, spot malfunctions and launch recovery protocols.

Acknowledgements

This work has been sponsored by UPC internal funds. The authors are grateful to the ESA staff that created and executed the “ESA Fly your Satellite II”, for the wise advices and willingness to support us in every challenge we have faced.

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Development of a Proof-of-Concept Space Propulsion System for Nano-satellite applications using Additive Manufacturing

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Abstract

In this project, Additive Manufacturing techniques was used to develop a proof-of-concept space propulsion system for nanosatellite applications. The main propulsion unit is made up of a metallic structural housing that is additively manufactured using aluminium powder (AlSi10Mg) on the EOS M290 machine. This housing serves as the reservoir that stores nitrogen gas as the propellant, and other components of the propellant system are assembled into it. The novel feature of the housing is that the propellant feed lines are integrated into the structure. This eliminated welds and joints typically found in conventional propellant storage tank, thereby minimizing leakage whilst simplifying assembly and integration. At the same time, the housing was designed using Design for AM techniques, and this made it possible to increase propellant storage capacity by minimizing support structures. The miniature propulsion nozzle, a key component of the propulsion system, was produced using micro-milling techniques to produce a full 3D converging-diverging profile.

A secondary objective of the project was to validate this unique approach by conducting in-space validation experiments to determine the viability of AM in the development of space propulsion applications. Work is currently on-going in the assembly and integration of the proof-of-concept propulsion payload into a 1U Cubesat, where it will serve as the primary payload. This Cubesat mission features a secondary payload which is a commercial off-the-shelf imaging sensor with M12 ruggedized lens that will be tasked with space imaging applications. The current plan is to launch the Cubesat from the International Space Station using the J-SSOD module.

The project was carried out by a multi-disciplinary staff/student team comprising faculty members with domain expertise in aerospace, additive manufacturing, avionics/electronics, advanced machining, quality assurance and mechanical testing. The faculty members were responsible for the design, development, and integration of the proof-of-concept propulsion and imaging payloads. The project also provided valuable opportunities for our students to gain hands-on experience in space and satellite engineering. The students hail from the diplomas in aerospace, aviation systems and advanced & digital manufacturing. They were co-located within the Assembly, Integration and Testing lab which features a class 10,000 clean booth. The students supported Cubesat and payload development and integration as well as mechanical testing.

Keywords
AlSi10Mg, Additive Manufacturing, Design for AM (DfAM), Direct Metal Laser Sintering (DMLS), Space Propulsion

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Acronyms/Abbreviations

AM	*Additive Manufacturing*
AIT	*Assembly, Integration & Testing*
CAD	*Computer-Aided Design*
COTS	*Commercial of the Shelf*
DEIC	*Digital Engineering Innovation Centre*
DfAM	*Design for Additive Manufacturing*
DMLS	*Direct Metal Laser Sintering*
EASA	*European Aviation Safety Agency*
EOS	*Electro-Optical Systems GmbH*
FEA	*Finite Element Analysis*
ISS	*International Space Station*
JEM	*Japanese Experimental Module*
J-SSOD	*JEM-Small Satellite Orbital Deployer*
POC	*Proof of Concept*
QA	*Quality Assurance*
NYP	*Nanyang Polytechnic*
SEG	*School of Engineering*
SSA	*Space situational awareness*
TPL	*Third party liability*

1. Introduction

In recent years, there has been a surge in interest in nanosatellites within the space community. In a report prepared by the global space consultancy company Spaceworks [1], it was shown that the nano/microsatellite segment has grown 10x over the last 10 years from 2010 to 2019, and it is projected that as many as 2,400 nano/microsatellites will require launch over the next 5 years. This is driven in part by the rapid evolution of miniaturized devices, which has redefined space technology, making possible the most ambitious interplanetary missions and near-Earth space exploration. Small, unmanned satellites are now being launched in hundreds at a time [2], forming constellations of powerful small satellites capable of providing platforms that serves as enabling technologies for global communication [3], navigation, ubiquitous data mining, Earth observation, and many other functions.

For smallsats to take advantage of these new opportunities, the presence of an onboard propulsion capability is necessary. The propulsion functions that are required on these smallsat missions include attitude control, orbit maintenance and manoeuvring [4]. However, by definition, nanosatellites are mass and volume constrained [5]. Therefore, it can be challenging for smallsat propulsion systems to fulfil these requirements adequately.

Additive manufacturing is an emerging manufacturing technology, that in the context of spacecraft propulsion, can potentially enable the designer to utilize space more effectively within the spacecraft structure. In addition, rather than just using AM to print specific components, this project also looked at using AM to fabricate an integrated system in which other functions of the propulsion sub-systems are integrated into the main structure.

This project also has important educational objectives on top of its technology demonstration objectives. Final year students are engaged in the project to provide them with valuable on-the-job training, and they work together with their supervising lecturers in a multi-disciplinary setting to support the assembly, integration and testing at system and sub-system levels. The students were also introduced to the rigorous procedures of screening and selection of materials for space applications.

One of the secondary objectives of the project was to establish a ground-station for mission control of the Cubesat during the space segment. This will be integrated with data analytics capability of the Digital Engineering Innovation Centre (DEIC) to explore the possibility of deriving deeper insights using some of the analytics tools. However, this portion of the project was not carried out as there were some issues faced which led to the Cubesat not being launched. The issues and follow-up actions are addressed in Sections 8 (Discussion) and 9 (Conclusion).

2. AM for Space Applications

Additive Manufacturing is a process of joining materials to make objects from 3D model data, usually layer upon layer. The AM process traditionally begins with the creation of a three-dimensional (3D) model using computer-aided design (CAD) software. The CAD model is then sliced into individual layers, which are collectively sent as instructions to the AM machine, which then re-creates the object by adding layers of material, one on top of the other, until the physical object is created.

DOI: 10.5821/conference-9788419184405.101

2.1. *Applications of AM for Space Propulsion*

Some advantages of the AM process compared to conventional manufacturing processes in the context of space propulsion system are:

- Part consolidation
- Design flexibility
- Design freedom

2.1.1. *Part consolidation*

Using AM techniques, conventional assemblies can be redesigned and consolidated into a single complex structure encompassing the functions of the propulsion sub-components: propellant storage, manifold, piping. This greatly simplifies the assembly process and reduces errors due to tolerance stack-ups.

2.1.2. *Maximizing design flexibility*

AM enables the manufacture of complex and intricate geometries without many of the constraints imposed by traditional manufacturing techniques. This is beneficial as the propulsion system can be designed to conform to the internal space of the Cubesat without comprising on structural requirements. This maximises the propellant storage capacity and improves the Cubesat's lifetime in orbit.

2.1.3. *Design freedom*

Another important benefit of using AM to build the propellant tank is that it can be built in one piece, without the need for welding two shells together as in the case of a conventional tank. This eliminates the joining/welding process that can be costly to inspect and qualify, as well as eliminating the possibility of leaks. With careful design and planning, the internal propellant storage spaces can be maximised without the need for support structures that is typical of the AM process.

3. Design Approach

A novel gas propulsion system for Cubesat application is proposed based on AM techniques. The concept of operation for this system is illustrated in Figure 1.

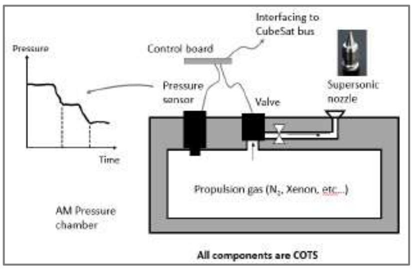

Figure 1. Schematic of gas propulsion system with integral propellant flow channels

The main housing for the propulsion is designed to store the propellant under pressure as well as to serve as a manifold structure with integrated ports and flow channels. This concept is illustrated in Figure 2, which shows the CT-Scan model of an earlier design. The internal flow channels and ports can be seen are integrated within the main structure. The structure also had to match the footprint of the Cubesat standard PC-104 board. This included mounting support for four threaded rods that spanned the full length of the spacecraft. The material chosen for the main structure is AlSi10Mg. This material was chosen as it is strong and yet lightweight, and it is a widely used and well-understood material for AM machine.

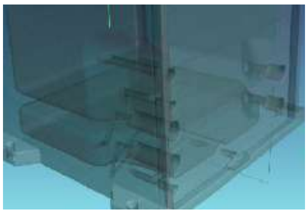

Figure 2. CT-scan of an earlier prototype showing internal flow channels and ports integrated into the main structure

Ports for sensors, solenoid valve, check valve and gas screens are also printed into the main structure together with the flow channels. The result is a very compact and integrated propulsion main structure, which conforms almost perfectly to the internal outline of the Cubesat structure. This maximises the available volume for storing the propellant gas, thereby improving the propulsion capacity.

The pressure sensor, solenoid valve and micro-nozzle will be mounted to the main structure using O-ring seals. To ensure leak-free connections, and to ensure proper operation in the harsh space environment, the seals will have to be carefully selected and evaluated for operation in the harsh space environment that is characterized by a wide operating temperature range, ultra-high vacuum, and radiation.

3.1. *CAD modeling design*

The 3D CAD software Creo was used in the modelling of the structure. A top-down design approach was taken whereby the propulsion structure was modelled in the context of the Cubesat assembly (Figure 3). This ensures that the propulsion structure maximises the available space within the strict confines of the Cubesat assembly, whilst also ensuring all the components can be assembled without any interferences.

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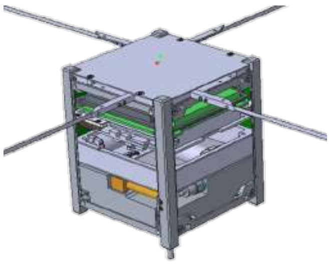

Figure 3. CAD modeling of propulsion structure within the context of the Cubesat assembly

Two variants of the propulsion structure were designed: (1) AM-ready variant, and (2) as-designed variant (Figure 4). The AM-ready variant includes the part geometry that will be produced by the AM process, and includes excess materials distributed strategically over the model which will be subsequently removed by machining and threading operations. The as-designed variant represents the final desired part that will be derived after all the post-build machining processes have been completed.

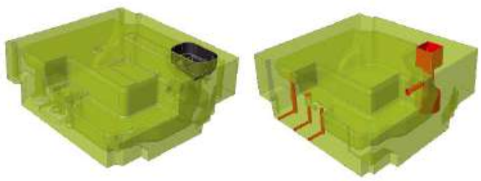

Figure 4. Simplified representations of the CAD model showing the two variants

The Simplified Representation functionality was employed to enable the programmatic regeneration of features based on a single master model to generate two variants This ensures that both the as-designed and AM-ready models share the same baseline features, whilst at the same time, are properly pre-processed for the AM operations downstream. This improves modelling efficiency and reduces errors, thereby ensuring the high quality of the final part.

3.2. AM Build Simulation

The AM build simulation software Magics from Materialise was used to prepare the CAD model for AM operations. The necessary features were designed into the model to ensure that the part can be built properly and efficiently. In summary, Magics allows for:

- Optimization of AM build to reduce unnecessary support structures
- Reduction of warpage by the strategic placement of support structures, ensuring build success

4. Fabrication of Propulsion Structure

4.1. AM Build Process

The part was printed using the M290 direct metal laser sintering (DMLS) machine from Electro-Optical Systems GmbH (EOS). This machine was previously qualified for aerospace applications by the European Aviation Safety Agency (EASA). The AM powder used in the project was AlSi10Mg, which has comparable mechanical properties to AL2024.

The novelty of the project is that the part was strategically oriented within the build platform such that the propellant cavity can be built without any support structures, as can be seen in the CT-scan (Figure 6).

Figure 5. Printed parts, with support structures removed

4.2. Post-AM Build Inspection

The AM parts were then inspected using non-destructive CT technology. The results of the scan (Figure 6) revealed that all the designed features were successfully built. The internal chamber for propellant gas storage was built successfully without any support structures. The air flow channels were also successfully built without any closures or blockages.

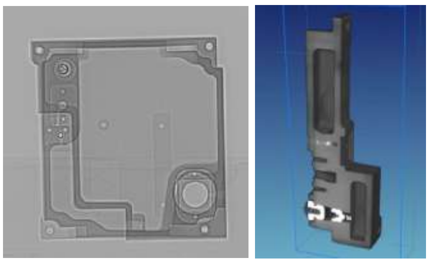

Figure 6: CT-Scan post-processing showing internal features of housing (left) and valves and fittings (right)

4.3. Quality assurance of AM-built propulsion housing

The quality and accuracy of the parts produced by the additive manufacturing process is dependent upon many parameters (AM process, powder, post-processing, environment, etc.), which must be carefully monitored and controlled to achieve consistency and repeatability. In this project, the

EOS M290 DMLS machine has previously undergone successful quality control audit by a major Singapore-based aerospace company. This shows that the processes and workflow of the M290 AM machine is highly reliable and can therefore be relied upon to print the propulsion structure with the desired level of quality and accuracy.

4.4. Post-Processing

Although AM technology has improved tremendously, it has not reached the level of accuracy and dimensional tolerances required for high-precision work. The propulsion structure will be required to interface with valves, fittings, sensors, etc. and it is necessary to produce a high-quality surface finish to prevent leakages. Therefore, the R_a for these mating surfaces were specified at 3.2 μm or better. In addition, the machining datums were chosen using the appropriate part features to correspond to the AM-ready variant so that the final part can be produced. Ports were also reamed into the part so that check valves and plug fittings can be assembled. Threads also were machined into the part for accepting the M12 lens, pressure sensor (M5), and plug fitting. Finally, the post-build machined part was then sent for chromate conversion for anti-corrosion protection. The final completed part is shown in Figure 7.

Figure 7. Post-machined propulsion housing with surface treatment for corrosion protection

4.5. Micro-machining of de Laval nozzle

The role of the converging-diverging nozzle (or a de Laval nozzle) is to produce thrust by efficiently converting the pressure/internal energy of inlet gases into kinetic energy. The profile of the nozzle adopted the 80% bell contour as proposed by Rao [6]. The nozzle throat diameter was minimised as much as possible to achieve the lowest "minimum impulse bit". In this project, it was possible to achieve a throat diameter 0.4 mm for the full 3D converging-diverging nozzle profile. The micro-nozzle was fabricated using high speed ultra-precision micro-milling technique on the multi-axis Mikron HSU 00U.

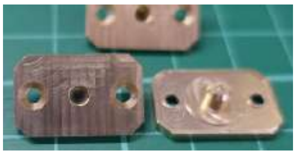

Figure 8. Machined propulsion nozzles

5. Assembly and integration of sub-systems

The assembly and integration of the propulsion payload sub-system was carried out within the clean booth that was setup for this project within the DEIC lab. In addition to the propulsion function, the structure also accepts a COTS imaging sensor with a ruggedized M12 lens for space imaging application.

5.1. COTS imaging system

The imaging sensor system used in this project is the OpenMV H7. This sensor board was chosen for its simplicity and ease of integration. The team has implemented the multiple functions for the OpenMV camera including photo shooting, video shooting and resetting.

The assembled sub-system is shown in Figure 9, where the solenoid valve, pressure sensor and imaging sensor are shown assembled.

Figure 9. Assembled payload sub-system

6. Testing

The assembled propulsion sub-system was then subjected to leak testing. Nitrogen gas (99.99% purity) was pumped into structure and the internal chamber pressure was monitored using the pressure sensor connected to PicoTech ADC-24. The monitoring was conducted over a period of more than 24 hours, and the results show that the pressure remains virtually unchanged.

The sub-system also underwent thermal-cycling testing with a temperature range between -15 degrees Celsius to +35 degrees Celsius over several hours. The result of the thermal cycling test proved that the COTS sensors and camera were able to function as per normal during and after the test. Additionally, there was no leak from the sub-system.

7. Involvement of students

An important aspect of this project was the involvement of the final year project students. The multi-disciplinary team comprises students from the aerospace, aviation systems and advanced & digital manufacturing diplomas. They were co-located within the DEIC lab, and they supported the assembly, integration and testing of the payload sub-system (Figure 10). For example, they helped to produce mock-ups of the 1U Cubesat using plastic 3D printing for fit checking the payload sub-system. They also helped to screen and select suitable adhesive systems for the staking of the fasteners. There was also industry exposure via visits to local space companies and thermal cycling testing at external test house.

Figure 10: Students supporting cleanroom AIT (left) and component testing (right)

8. Discussion

In exploring launch options for the deployment of the Cubesat for the space segment, there were some issues uncovered. One of these issues relates to the launch and post-launch in-space operations of the Cubesat.

A key requirement of the project is to reduce our overall risk exposure, and to procure insurance where risk exposure cannot be avoided. However, in-orbit TPL insurance products for Cubesats are not readily available. In addition, to minimize risk exposure, it is imperative that in-space operations be conducted in a safe and sustainable manner. However, these guidelines are not yet well-defined. As a result, the launch procurement was suspended pending the outcome of the review.

After consultations with industry experts, the recommended approach for risk minimization was to:

1. Adopt the launch option provided by ISS (J-SSOD)
2. Establish space traffic conjunction warning and alert capability, possibly with Space Situational Awareness (SSA) capabilities, to support in-space operations.

Both approaches are currently undergoing review for implementation feasibility.

9. Conclusions

In this project, a propulsion sub-system with integrated COTS imaging was successfully designed and developed using metallic AM techniques. The sub-system has been successfully tested in the labs and the next steps involve integration with the Cubesat flight model. The project was led by faculty staff members and supported by a multi-disciplinary team of final year project students.

Some issues were encountered which led to a review of the launch options and post-launch Cubesat operations to minimize risk exposure. Although the review has not been completed, initial findings suggest that the next steps of the project involve the establishment of a SSA platform to support the Cubesat operations, and to deploy the Cubesat using the J-SSOD option from the ISS. This will enable the operations to be conducted in a safe and sustainable manner, thereby reducing the risk exposure.

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Ice Moon Research – A phenomenon called plume

Mario Andre Zuegner[1]

Abstract
Based on the observations of the Cassini-Huygens space exploration mission, Saturn's moon Enceladus was found to be a very promising subject in the solar system for further exploration and follow-up research, especially focusing on the potential of extraterrestrial life and its origin. Near its South Pole, fountains, specified plumes, consisting mostly of water vapor and small salt-rich ice grains with intermittent activity were observed at the surface. With supersonic speed the water vapor is exiting the trenches known as Tiger Stripes. The driving force of these plumes are not completely understood yet. In current models, Enceladus is expected to consist of a rocky core, surrounded by an ocean of liquid water and covered by a layer of ice. The observed phenomenon is assumed to be caused by the tidal forces that act upon Enceladus. However, several models try to describe the underlying physical processes. Various investigations have recognized the astrobiological potential of Enceladus, even proposed a concept for a sample return for further research in relation to the subsurface ocean. Cassini´s existing analysis already identified CH4, CO, CO2, simple and complex organics at an altitude of approximately 190 km which allow the assumption of supersonic speeds.

That said, the goal of our experiment is to gain further indices/evidence to support the current models of the plumes. Our experiment takes place on a sounding rocket which gives access to a stable vacuum and microgravity in addition. The achieved altitude with its physical environment provides almost the conditions at Enceladus related to the gravitation.
The rocket module contains a pressurized and heated water reservoir which is connected via an injection system with the evaporation chamber. On the top a convergent-divergent nozzle is welded. Furthermore a nozzle cover system and a locking mechanism are integrated. At apogee, the nozzle shall be opened and the fluid stream (assumingly made up of ice, water droplets and vapor) shall exit the module at about Mach 2. The necessary fluid-dynamic data is gathered by multiple temperature and pressure measurements at different points on the module. So, the vapor stream shall be compared to the expectations based on the models.

Finally it is to mention that our project is still running and waiting for its launch. Caused through the Corona crisis and the Ukraine war the launch cycle was canceled two years in succession. With much luck the rocket will launch in March 2023.

Keywords
Enceladus, Icemoon, Plume

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1. Introduction

The µMoon student team consists of about 19 students from two universities in Aachen, the University of Applied Sciences (UAS) and the Rhine Westphalia Technical University (RWTH). The project is allocated at the facilities of the Faculty of Aerospace Engineering at UAS.

A Master Thesis [2] at Technical University (TU) Delft set the foundation for our experiment approach. The thesis provides the basic fluid-dynamical model and a summary of the explorative knowledge on the topic. Mr. Becx simulated the plumes by creating artificial ice trenches in a vacuum chamber. Although his experiment setup was close to the original, the tests failed due to the limitation of the vacuum chamber. In the past various research and study projects from FH Aachen UAS like "IceMole", "Enceladus Explorer (EnEx)" and currently "Enceladus Explorer – Environmental Experimental Testing (EnEx-nExT)" already broached the issue of the ice moon research. µMoon will tie in at this state of work by approaching the scientific observations with space engineering methods.

1.1. Mission Statement

Our mission is to simulate Enceladus' plumes and to characterize the uncharted fluid-mechanical behavior within the Rocket Experiments for Students (REXUS) program. The experiment data shall assist validating current hypothesis on the mechanisms of the plumes and further to break down the characteristics of the subsurface oceans. µMoon is committed to identify new possible insights about the solar system and to create a small steppingstone for further follow-up research.

1.2. Experiment Objectives

The mission statement described above translates into several experiment objectives that have to be achieved by µMoon.
The primary objectives are:

- Obj.A1: Fluid-mechanical recreation of an Enceladus-like plume
- Obj.A2: Characterization of the created plume

The secondary objectives are:

- Obj.B1: Storage of acquired data related to evaporation of water in space

The tertiary objectives are:

- Obj.C1: Analysis of residuals in the reservoir after landing

1.3. Experiment Concept

To recreate natural evaporation and expansion of water due to pressure difference, the experiment will be positioned in an environment close to Enceladus wit. It is designed starting with an injection system, containing a water mixture with a similar composition to Enceladus´ ocean. This liquid is injected from a hydraulic accumulator with lowly pressurized nitrogen into the evaporation chamber during flight, just before reaching the maximum altitude. A convergent-divergent nozzle is connected to the evaporation chamber. The nozzle is further covered by a movable cover system (Nozzle Cover System (NCS)). When the nozzle's outlet is opened up in the residual atmosphere, the natural evaporation of the liquid water into the vacuum leads to a pressure difference between nozzle intake and exhaust sections that will expand the vapor into space. Pressure and temperature sensors will measure the flow parameters to characterize the flow at any time during the experiment run. A camera will observe the visual development of the plume. This data will be sent to the ground station for post-flight analysis.

2. Experiment Description

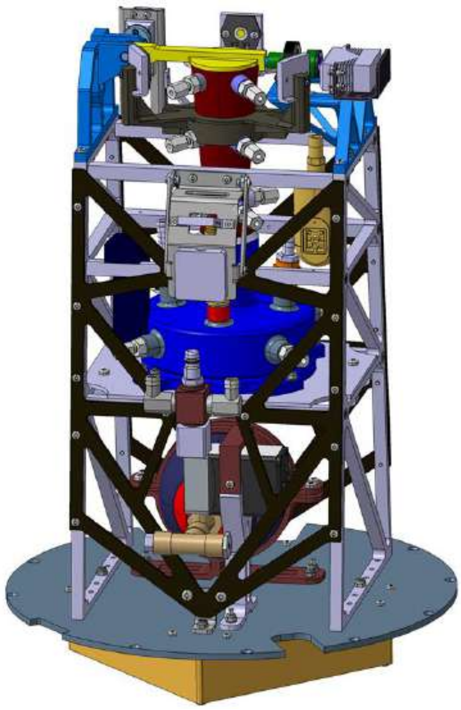

Figure 1.1.: Entire Setup

DOI: 10.5821/conference-9788419184405.102

In order to fulfill the requirements and to achieve all objectives of the µMoon project, the experiment must ensure mechanical and structural safety and requires an unusual effort in fluid-mechanical design considerations and measurement technology.

The experiment setup is divided into 4 subsystems, the Flow System Assembly (FSA), the Structure Mount Assembly (SMA), the Injection System (IS) and the NCS. Additionally, the hang-on parts (HoP) are attached on all subsystems.

2.1.1. Mechanics

Flow System Assembly

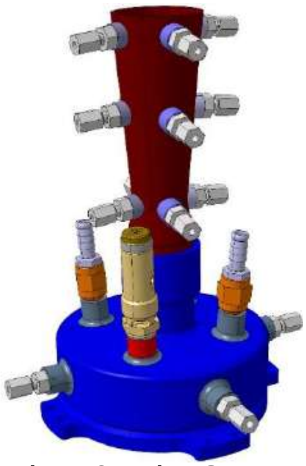

Figure 2.1. Flow System Assembly

This subsystem is designed to generate the plume and serves as a storage for residual water for further analysis. It is made up of an evaporation chamber, a nozzle, fittings for sensors, a pressure relief valve and three check valves which are responsible for the water injection. The heart of the experiment, the nozzle, is linked to the evaporation chamber. The nozzle offers fittings which serve as mountings for temperature and pressure sensors. During rocket ascent a pressure relief valve that is connected to the fitting of the evaporation chamber reduces the internal pressure to 30:000 Pa. Three check valves of the IS are also connected to the fittings. Through these check valves water is injected. Because of this injection the internal pressure increases temporary to 50:000 Pa. The nozzle cover of the NCS is placed on the top of the nozzle sealing up the FSA against an unintended pressure loss. By opening the nozzle cover the experiment starts. During the sudden pressure drop the water begins to boil and the emerging vapor exhausts through the nozzle. To end the experiment the nozzle cover gets closed again.

Structure Mount Assembly

The Structure Mount Assembly has a Primary Structure (PS) and a Secondary Structure (SecS) with Hop´s attached. The PS carries the main flight loads and defines the overall stiffness whereas the SecS is only attached to the PS and has negligible participation in the main load transfer and overall stiffness. Two A-beams of the primary structure are mounted on the Nose Cone Adapter Plate (NCAP) and are connected via struts. The beams and struts are also linked by the Evaporation Chamber Mounting Plate ECMP) to enhance the stiffness and stabilize the FSA. Furthermore the IS is attached onto the NCAP via two clamp brackets. Each side Carbon Fibre Reinforced Plastic plates were added to support lateral stability. The secondary structure consists of a camera mounting, brackets for lighting, bearings for the NCS and sensor brackets for pressure and temperature sensors detecting ambient condition data. A plumb pad, which absorbs water from possible leakages, is placed above the NCAP to protect the located project beneath against damage. As the last part the housing for electronic parts is positioned underneath the NCAP.

Figure 2.2: Structure Mount Assembly

Injection System Assembly

This system consists of 4 main parts:

- Hydraulic Accumulator
- Pivoted Armature Valve
- Cross Manifold
- Check Valves (3x)

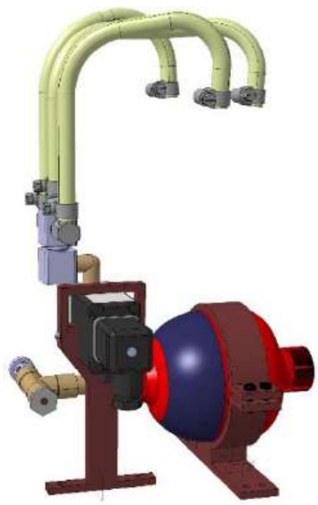

Figure 2.3: Injection

A hydraulic accumulator is separated into two filling volumes by a diaphragm. The first sector filled with gas and has an overpressure compared to the second sector that will be filled with water. The second sector is connected to the pipeline system which shall be permanently flooded. The first connected part to the hydraulic accumulator is a T-fitting, connected by a reducing adapter. It is connected to the pivoted armature valve and a second T-fitting which provides an appliance for the temperature sensor 0 and serves as a device for water refill and venting. By release of the pivoted armature valve the water is enabled to flow through the pipe elbow to the cross manifold.
Latter distributes the fluid to the three check valves, via hoses. Due to the pressure difference which is based on the low pressure in the evaporation chamber, the force applied on the diaphragm pushes the water into the evaporation chamber.

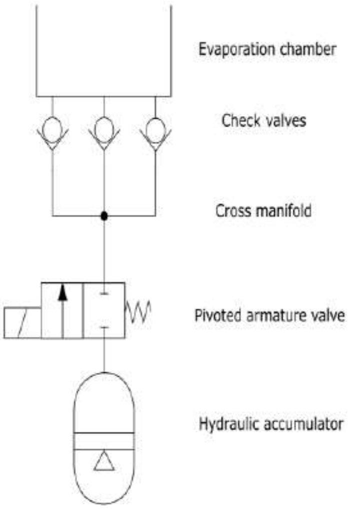

Figure 2.4: Schematic: Injection System

Nozzle Cover System Assembly


Figure 2.5 :Nozzle Cover

There are two fundamental mechanisms that activate and deactivate the experiment. NCS and locking mechanism (LM) depend on each other and work in sequence. The nozzle cover is closed when the locking pin is blocked by the rotating sleeve. To initiate
the opening mechanism a small servo drive spins the rotating sleeve by 90°, so that the locking pin is able to exit the apparatus. A shaft driven by a stronger, second servo drive, is linked to the lever arm of the Nozzle Cover. This shaft is pivot mounted via sleeve bearings and is connected to the servo drive by a force transmission wheel. The transmission wheel is screwed on the servo drive shaft. When the nozzle cover is fully opened, and the experiment time has ended, the closing process is initiated. Driven by servo drive 2, the shaft moves in opposite direction to shut the nozzle cover. Finally, the rotating sleeve turns once again into starting position to lock the Nozzle Cover as before.


Figure 2.6: Locking Mechanism

2.1.2. *Sensors and Instrumentation*

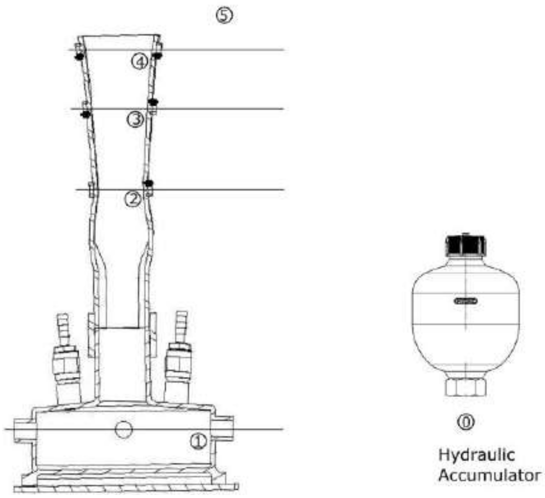

Figure 2.7: Measurments Location

The measurement sections are shown in the picture above. Point 0 is inside the hydraulic accumulator. Point 1 is inside the evaporation chamber. Point 2 is in the throat area. Points 3 and 4 are in the divergent section of the nozzle. Point 5 is attached at the top on the PS. The behavior of the plume is described by three different flow characteristics: pressure, temperature and velocity. There is a temperature measurement at Point 0. So, monitoring the temperature development in the hydraulic accumulator is mandatory, as the water shall be externally heated to ensure that it remains at 70 °C. At point 1 there are temperature and pressure sensors. Later it shall be referred to these measured values as temperature and pressure at rest. They are important for subsequent calculations. The temperature and pressure sensors at points 2, 3 and 4 there will provide information about the local flow characteristics. At point 5 there are temperature and pressure sensor installed which will measure the ambient conductions.

There are also a camera and LEDs attached to the SecS in order to perform an optical analysis of the advancing experiment. There will be no direct velocity measurement, but the local Mach Number at points 2,3 and 4 shall be calculated with the isentropic relation between temperature and pressure at rest and the local values of pressure and temperature:

$$p/p0 = f(M) \quad (1)$$

$$T/T_0 = f(M) \quad (2)$$

Both calculations should provide appropriate values for the local Mach Number.
So with respect to redundancy there shall be four equal values for each measuring point. Velocity itself cannot be calculated because calculations for sonic speed only work with ideal gases which cannot be assumed for water vapor.

2.1.3. Electronic

The complete electronic system is realized by one big PCB mounted in the electronic housing below the experiment construction. It supplies all components with the appropriate voltage and receives signals from the RXSM. Placed on it are all sensor systems, naming the Temperature Measurement System (TMS) 1 and 2, the MPR Sensors and the Analog-to-digital converter (ADC) to readout the TPR Sensors. The TMS 1 and 2 provide the digital conversion of the temperature sensors placed in different parts of the experiment. The two servo motors that are used to open and close the NCS are powered and controlled by the Mainboard as well. The valve is activated (and thereby opened) by a voltage supply that is also placed on the Mainboard. The camera gets it power from a DCDC converter on the Mainboard while the set of three LEDs is powered by a constant current LED driver which can be turned on and off by the mainboard as well. All digital control and recording of the data are realized by a Raspberry Pi Compute Module Version 4 (CM4). It acts as the “brain” of the experiment, receives the status links from the service module and controls every actor and sensor. There will be an external heating foil to condition the water before lift-off. This setup is separated from the main electronics design and will be supplied with an external power line which will be shared.

3. Fluid Dynamic Design

To ensure an Enceladus-like plume with supersonic flow, the nozzle shall provide an exhaust Mach number of 2. In the experiment the used nozzle is a convergent-divergent nozzle. The geometry of the nozzle, particularly throat diameter and nozzle length, will be designed according to the parameters in table.
According to the phase diagram of water (compare figure 4.58), liquid water will evaporate at a temperature of 373:15K at sea level on Earth in a standard atmosphere. With decreasing ambient pressure, the boiling temperature of water will also decrease. During RGP in flight, the outside pressure will be around 100 Pa (ICAO n.d.), where no liquid water exists (below triple point pressure of 611 Pa). As the phase change from liquid to gaseous shall be used to provide a sufficient pressure difference between reservoir and ambient, the formation of solid water (ice) must be avoided. To be sure that the water will evaporate, it is heated up to reach a safer position in the vapor area of the state diagram of water. The given diagram is only for a first short overview about the behavior of water in different pressure environments. It does
not show the µMoon water composition.
Anyway, the formation of ice due temperature variations caused by compressible flow effects **cannot be ruled out.**

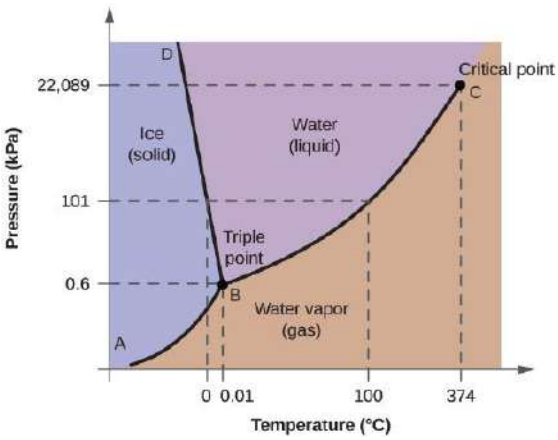

Figure 3.1: State of Diagram of Water

In the first scientific test three different temperatures were tested and a final water temperature is chosen to 328K. At that temperature the stored energy is high enough to evaporate the water.

3.1. Experiment Water Composition

To leave out salts and other pH value altering agents, it was decided to put a mixture of water and silicates into use. The water composition for the µMoon experiment shall contain 2:5 g of silicates (0.8 µm) to 100 ml of distilled water.

4. Conclusion

Finally it is to mention that our project is still running and waiting for its launch. Caused through the Corona crisis and the Ukraine war the launch cycle was canceled two years in succession. With much luck the rocket will launch in March 2023. I really want to give thanks to all my team members and professors who supported us during the project. Especially huge thanks to the REXUS program, the Swedish Space Company (SSC) Kiruna Sweden, the German Aerospace Center (DLR), the European Space Agency (ESA) and all other participants.

Nomenclature

T_0	*Ambient Temperature*
T	*Temperature*
p_0	*Ambient Pressure*
p	*Pressure*
M	*Mach*

Acronyms/Abbreviations

DLR	*German Aerospace Centre*
EnEx	*Enceladus Explorer*
EnEx-nExT	*Environmental Experimental Testing (EnEx-nExT)*
ESA	*European Space Agency*
FSA	*Flow System Assembly*
HoP	*Hang-on part*
IS	*Injection System*
LM	*Locking Mechanism*
NCS	*Nozzle Cover System*
NCAP	*Nose Cone Adapter Plate*
REXUS	*Rocket Experiments for Students*
RXSM	*Rexus Service Modulator*
RWTH	*Rhine Westphalia Technical University*
SMA	*Structure Mount Assembly*
TU	*Technical University*
UAS	*University of Applied Science*
PS	*Primary Structure*
SecS	*Secondary Structure*
SSC	*Swedish Space Company*

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Design and Development of the Re-Entry Sensor System for the CubeSat Mission SOURCE

Hendrik Kuhm [1], Hendrik Fischer [2] Lars Blümler [2], Emily Seeberg [2], Vincent Kirchner [2],

Daniel Galla [2], Sabine Klinkner [3]

Abstract

With the number of man-made objects being launched into orbit steadily increasing, space debris is one of the big challenges for future space flight. In order to better assess the danger to humans on Earth’s surface, re-entry should be researched in more detail. SOURCE serves as a 3U+ satellite platform designed and developed by the small satellite student society (KSat e.V.) and the Institute of Space Systems (IRS) at the University of Stuttgart. It was selected by ESA in 2020 to be part of the ‘Fly your Satellite’ program, has successfully completed the CDR and is currently preparing for the MRR. SOURCE’s objectives are education, verification of several cost-saving, not yet space-proven technologies for orbital use, capturing images of meteoroids entering Earth's atmosphere and documenting its own demise during re-entry by analysing atomic oxygen, heat flux- and pressure data. In order to receive data for as long as possible during re-entry, the satellite switches from S-band to Iridium (inter-satellite link) communication at an altitude below 200 km.

For the in-situ measurement during the re-entry, SOURCE is equipped with two Flux-Phi-Probe (FIPEX) sensors for the measurement of atomic oxygen and five additional sensor arrays. Each array contains one pressure sensor and two heat flux sensors, one commercial and one developed by the IRS. The arrays are placed at five positions in-line across the satellite to reduce effects of tumbling during the re-entry and to allow for the measurement of gradients.

For a first estimation of the expected value ranges, simulations were performed with the software PICLas, developed by the IRS and the Institute of Aero-and Gas Dynamics (IAG) at the University of Stuttgart. In an iterative process, the collected data will be used to further improve this simulation software after the re-entry of the SOURCE satellite.

The aim of this paper is to describe the design philosophy and development process of the sensor readout electronics. The tests carried out are presented and the first results are presented.

Keywords

Re-Entry, CubeSat, Sensors, Tests

Acronyms/Abbreviations

ADC	*Analog Digital Converter*
COTS	*Commercial Off-the-Shelf*
DLR	*German Aerospace Center*
FIPEX	*Flux Phi Probe Experiment*
IRS	*Institute for Space Systems*
KSat e.V.	*Small Satellite Student Society*
MCU	*Microcontroller-Unit*
OBC	*On-Board Computer*
PCB	*Printed Circuit Board*
RTD	*Resistance Temperature Detector*
SOURCE	*Stuttgart Operated, University Research CubeSat for Evaluation and Education*
SPI	*Serial Peripheral Interface*
SSEA	*Symposium on Space Educational Activities*

1. Introduction

The amount of space debris in Earth's Orbit is steadily increasing [1]. Collisions in Orbit, the destruction of two satellites by China and India further amplify this problem, as can be seen in Figure 1. The increasing popularity of Small Satellites and new Satellite Constellations such as Starlink are also responsible for an increasing amount of objects in orbit. Another factor for the increase of objects in orbit are the so called "CubeSats", as this standard also allows small companies and educational institutions to build and launch their own satellites.

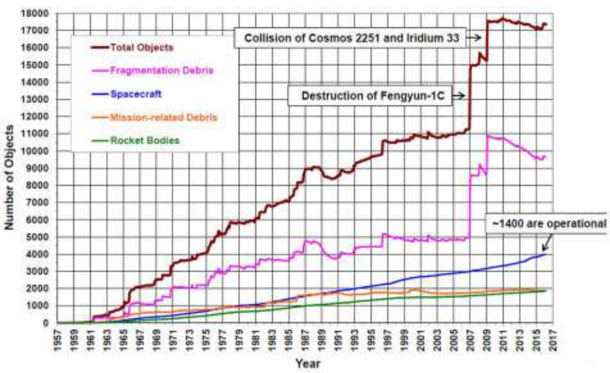

Figure 1. Number of Objects in Earth's Orbit over time [2]

Due to the increasing number of objects in orbit, the number of re-entering objects also increases. Despite this trend, the behaviour of re-entering objects is still not sufficiently investigated.

Although CubeSats are part of the problem, they can help with re-entry research by performing in-situ measurements. This is one of the reasons why the 3U+ CubeSat SOURCE is currently being developed: To gather in-situ data during the re-entry of the satellite.
SOURCE is an abbreviation for Stuttgart Operated University Research CubeSat for Evaluation and Education. Additionally to the re-entry sensor setup, SOURCE features a camera system for meteor observation and star tracking, as well as multiple payloads by DLR, Airbus and Fraunhofer IPA for technology demonstration [3].

The mission scenario can be divided into two parts. In the first mission phase begins after the deployment of the satellite. In this phase, meteors are observed and the suitability of the camera system as a startracker is examined. The technology demonstrations will also be tested. As soon as the satellite altitude decreases below 200km, the re-entry sensor system is activated and data is gathered until contact with the satellite is lost. This approach is illustrated in the Mission Scenario in Figure 2.

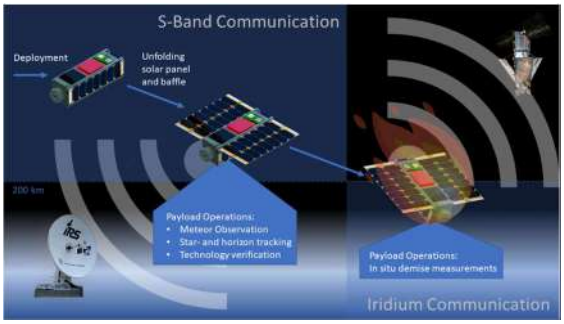

Figure 2. Mission Scenario of SOURCE. Mission Scenario of SOURCE

During the first Phase of the Mission, S-Band is used for communication. During the re-entry phase, communication is switched to Iridium. By using this inter-satellite communication, continuous data transmission can be achieved during the satellite's re-entry phase without the need for a S-Band connection to a specific ground station.

SOURCE is primarily developed and build by students. It is organized by members of the small satellite Student Society (KSat e.V.) and the Institute of Space Systems (IRS) at the University of Stuttgart. Each Subsystem is organized by a student group lead and a PhD supervisor from the institute.

This way, the institute's know-how can be accessed during the development. This know-how results from the small satellite "Flying Laptop", which was launched 2017 and is still in operation [4], as well as from the 6U CubeSat EIVE [5], which is being developed in parallel to SOURCE at the Institute.

Additional support has come from ESA since SOURCE was accepted into the Fly-Your-Satellite programme in 2020.

This paper focusses on the development, build-up and testing of the sensor system for in-situ design measurements.

2. Design of Sensor PCBs

The SOURCE satellite's sensor system is equipped with 17 sensors for re-entry science. Two Flux Phi Probe Experiment (FIPEX) sensors, located on the front and back of the satellite, determine the amount of atomic oxygen in the upper atmosphere by measuring the electric current caused by the flow of oxygen ions over an electrolyte [6]. They are controlled by three small circular printed circuit boards (PCBs) in the front of the satellite. These PCBs are designed and built by the IRS and tested by the student team.

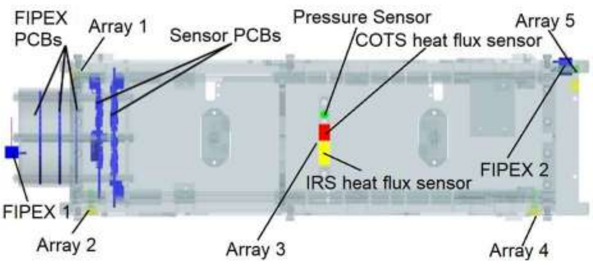

Figure 3. Sensor placement on SOURCE

The remaining 15 sensors are grouped into five arrays shown in Figure 3. Each array consists of one Posifa PVC1000 vacuum pressure sensor, one commercially available Wuntronic FM120-K heat flux sensor, and one heat flux sensor developed by IRS. Each IRS Heat Flux sensor consists of two PT1000 resistance temperature detectors (RTD), whose resistance changes according to their temperature. The RTDs are coated with materials of different catalytic properties, which will result in different recombination rates of dissociated molecules in the hot plasma during re-entry and therefore produce different temperatures [7]. To determine the resistance of the RTDs, a Wheatstone bridge converts their resistance to a differential voltage which is subsequently amplified by an instrumentation amplifier and digitized via an ADC. The heat flux can then be calculated from these temperature measurements. To improve the accuracy of the measurement, the supply voltage of the Wheatstone bridge is also measured via an ADC. The commercial FM-120K heat flux sensors consist of a thermocouple and a thermopile. A thermopile produces a voltage which is directly proportional to the temperature difference of the sensors top and bottom side. This voltage is then amplified by an instrumentation amplifier and digitized via an ADC. Because the thermal conductivity of the sensor is known, the heat flux can be easily derived from the temperature difference. The thermocouple measures the temperature. The PVC1000 pressure sensors operate according to the Pirani measuring principle [8],[9]: A heated measurement resistor is exposed to the atmosphere and supplied with a constant heating current. As the pressure of a low-pressure gas changes proportionally to its thermal conductivity, the temperature of this resistor will change as well according to its surrounding pressure. This will affect the sensor's resistance, which is calculated by measuring the voltage via Ohm 's law. The accuracy of the constant current source is the single most important factor for the accuracy of the pressure measurements.

The control electronics of these 15 sensors are housed on two 4-layer PCBs located behind the FIPEX-PCBs. Due to space constraints, both sides of both PCBs contain components. As only one side of a PCB can be reflow-soldered at the KSat workshop, the second side was hand-soldered. Components which were deemed exceedingly difficult to hand-solder were therefore placed on the front side. Due to concerns about tin whisker growth in the space environment [10], lead-based solder was chosen.

A radiation-hardened VA10820 microcontroller communicates via an SPI bus with 8 ADS8343E Analog-to-Digital-Converters. An RS485 bus receives and sends data from and to the On-board Computer (OBC) of the satellite and a JTAG-Bus is used to program the VA10820. This JTAG-bus will be connected to the maintenance port of the satellite and will therefore allow for testing and debugging of the re-entry sensor system on the assembled satellite even if the OBC is off or not working.

3. Test Preparations

Fundamental to verifying the design and functionality of the sensors and their respective systems in space conditions is a thermal-vacuum-test. This is because the test simulates key conditions of a space environment, such as vacuum-level pressure and cycling through significant temperature ranges, however not realistic radiation conditions. It is the first time the system is subjected to realistic operating conditions. Functional and thermal-cycle tests were conducted for two tested systems: one being the FIPEX sensors with a PIC24 microcontroller-unit (MCU) and the second being the re-entry sensors combined with their Vorago microcontroller, both MCUs on respective PCBs. The chamber used for the tests was the IRS thermal-vacuum-chamber, depicted in Figure 4.

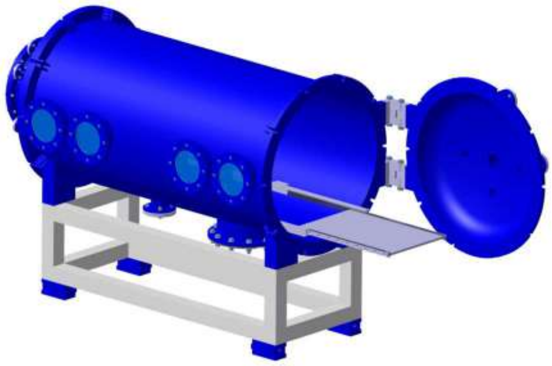

Figure 4. Representation of the thermal-vacuum-chamber at IRS

To enable the communication between the computer and the MCU, the FIPEX system used a custom RS422 to USB board and the software “HTerm”. The PIC24 uses a fixed list of pre-programmed 6-byte commands, which are used to either set a specified sensor to a certain temperature or request the current read-out of data, for which the PIC24 returns a string of 27 bytes.

After initial issues, the connection of the Vorago Payload MCU could be successfully established using a JLink debugging probe. The setup in the chamber led to further problems as the JTag connection only allows cable lengths under 30 cm. This was solved by putting the debugging probe inside the chamber. In the flight setup, the main communication will be handled through RS485, which supports longer cable lengths.

The chamber itself is a tubular chamber that can be opened at one end. The external circulation thermostat “Lauda Proline RP855” brings the mounting plate to the desired temperature via a cooling cycle using the coolant Kryo 51. Through two successively activated pumps a pressure in the lower 10^{-5} mbar range can be achieved.

4. Test Execution

The tests for the FIPEX system and the re-entry sensors on the payload PCBs were carried out separately, as will be their description in this section.

The first tests conducted were the thermal cycles. The thermal simulation for SOURCE predicts temperatures between 1°C and 15°C with uncertainties of ±10°C. The storage temperature ranges of the components are between -40°C and 85°C. The operational temperature of the payload PCBs is -40°C to 80°C, for FIPEX it is -30°C to 60°C. With the component temperature ranges much broader than the expected temperature range, these were the values used for the temperature cycle. The thermal plate must be set to a higher or lower temperature to reach the desired values. This difference comes from the compensation necessary for balancing the thermal radiation from the chamber from which the experiment cannot be shielded completely. In vacuum, there is no heat transfer via convection, meaning the system needs some time to dwell to reach a uniform temperature. The dwell times were up to 12 hours to ensure an even temperature distribution. The thermal cycles were performed in accordance with ESA standards [11].

The thermal cycle for the payload PCBs started with a functional test at room temperature inside the thermal vacuum chamber at a pressure of approximately 10^{-5} mbar. The PCBs were then heated to the maximum operational temperature and the maximum storage temperature. At the maximum operational temperature, a functional test was performed. The first functional test at minimum temperature was conducted a few degrees above -40°C, as the required temperature of the cooling plate was miscalculated. This was corrected for the following cycles. All in all, the cycle of the operational temperature range was executed three times with functional tests at the peaks. The functional test worked as expected. Figure 5 below shows the temperature of the two PCBs during the thermal cycle as measured by Pt1000 sensors glued to the PCBs.

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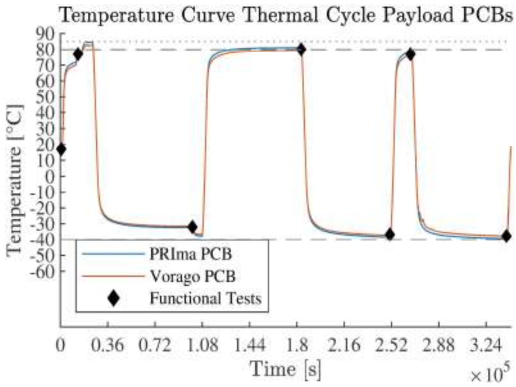

Figure 5. Temperature Curve Thermal Cycle

FIPEX' thermal cycle test consisted of 7 cycles ranging from -40°C to +85°C. To achieve the extreme temperature on all components, the thermal plate was determined in the first cycle to be having to be cooled to -70°C and heated to +100°C respectively. With a narrower operational temperature range, functional tests were conducted during the first cycle at -30°C, room temperature and +60°C. The graph of the temperature profile can be depicted similarly to that of the Payload PCBs.

After completion of the cycles, further functional tests with varying voltages were conducted on the FIPEX system. During the last test, the measurement was run for a total of 30 mins to confirm long-term measurements to be possible. The system passed all tests as functional. However, FIPEX requires a significant amount of power due to the heating of the sensors during measurement. The power consumption measured during each of the functional tests revealed a much higher power consumption than expected during the design phase.

The long-term test for the payload PCBs was also performed. During re-entry, the payload PCB has to run for six to twelve hours. At this time, the microcontroller will continuously read the sensor outputs. For the test, the MCU ran for over 15 hours inside the chamber.

The calibration of the re-entry sensors was also part of the tests. As the pressure sensor of the chamber is not exact enough, a MicroPirani 905 was ordered to be the reference sensor. Communication was established, but it could not be used as it had to be zeroed at a pressure below 10^{-5} mbar. This was not possible because the pressure sensor of the chamber was not exact enough to ensure this value. An alternative setup is under design to zero the reference sensor. When this is concluded, further calibrations for the pressure sensor can be conducted.

The commercial heat flux sensor, a Wuntronic FM-120-K, can measure bidirectional heat flux as well as temperature. To calibrate the temperature, we used a dry-well calibrator. The heat flux calibration was conducted by gluing Pt1000 temperature sensors to both sides of the heat flux sensor. One temperature sensor was also attached to the cooling plate. With different temperatures and different temperature gradients, measured by the Pt1000 and the known transfer surface area, the heat flux can be calculated, and the sensor calibrated. The setup is shown in Figure 6.

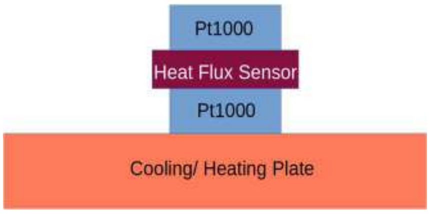

Figure 6. Heat Flux Sensor Setup

The heat flux sensor by the IRS consists mainly of two Pt1000 temperature sensors. These were also calibrated using the dry-well calibrator and the cooling plate.

The analysis of the calibration results is ongoing.

5. Discussion

5.1. PCB Design

Although great care was taken in the selection of components with regard to radiation tolerance and flight heritage, not all parts could be selected according to these criteria.

For instance, some of the voltage converters installed are without radiation tolerance or flight heritage. Here, there were simply no components found that fulfilled these criteria.

As SOURCE is a student project, testing components for radiation tolerance or resorting to radiation-hard parts is not feasible.

For this reason, risks must be taken in this regard. These risks are attempted to be reduced by implementing redundancies.

5.2. Test Results

The qualification tests, the thermal cycle and the long-term test, of the payload PCBs were concluded successfully. Further long-term tests will be performed to ensure reliability and to

DOI: 10.5821/conference-9788419184405.103

investigate power requirements and heating of the PCBs in more detail.

The results of the calibration tests are less stringent. The calibration of the pressure sensor is still to be done. The commercial heat flux sensor shows the same heat flux curves as the calibration data, only the amplification seems to be a bit off. It will be examined, whether this is due to the calibration data or the amplification of the sensor. The temperature values of the commercial sensor are of now not coherent, further calibrations will be conducted with the dry-well calibrator. As the vacuum chamber is not needed for this, this test can be performed very easily.

6. Conclusion

The PCB design for the atmospheric re-entry sensors is now almost complete. Initial functional tests show the functionality of the system, even under vacuum conditions. Flight heritage or radiation hardness was considered in the selection of the components used, but this could not always be taken into account.

It is quite likely that the system will survive the two-year stay in space, but this cannot be said with certainty.

The thermal-vacuum tests, even though there were obstacles to overcome, proved successful. Both the Payload PCBs and sensor arrays as well as the FIPEX system could be confirmed to withstand both the vacuum and thermal conditions expected for them during operations.

FIPEX’ excess of its initially expected power consumption now needs to be assessed and taken into consideration for the power budget of the satellite in different operating modes. It is unlikely to prohibit use of the sensors however it may affect simultaneous operation with other power-hungry systems.

The only thing missing now for the re-entry sensors is the software for communication with the OBC and the production of the flight model. The FIPEX and the pressure sensors also still need to be calibrated. This step is set to take place in August 2022, closer to the date of launch.

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3D printed telescopes: an interesting tool for teaching Astronomy, Science and Technology

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Abstract

3D printing technologies experienced a huge evolution both in techniques and applications since its invention in the early 1980s. Fused Deposition Modelling (FDM) was the first term used to describe an additive manufacturing technique and from that point on, many different ways of 3D printing have been developed to fulfil a variety of needs.

Nowadays, 3D printing has become more accessible to the general public because of the big drop in prices caused by the big technical developments. As a result of that, a community of "makers" has been taking shape internationally making access to designs and advice easier.

3D printing is without a doubt one of the key developments of the last decades and covers from highly technical research fields (like medicine-related investigations) to individual makers or even educational programs to encourage young people to create.

As a result of that, it can be seen daily that the so-called 3D printing has gained a big amount of fame between fabrication processes for its accessibility and ease of use, it only takes a computer, a 3D printer and time. On behalf of that, an idea for a final degree thesis was proposed: designing and printing using fused deposition modelling a telescope for astronomical and educational purposes.

The main goal of the project is to, first check the capabilities of the 3D printing technology to build telescopes for amateur astronomers, comparing its performance with the current commercial products, and secondly, to develop a set of educational resources that permit the easy construction of low-cost custom instruments for the teaching and diffusion of Astronomy and Space Science. The set of resources derived from this project will be an interesting tool for Astronomy beginners, Engineering and Science students, teachers, and makers.

In this work, we summarise the current status of the project and the results obtained with the first built prototype, as well as the design and choices made to fulfil our needs in a practical and feasible way. Last but not least, a list of possible educational activities to be carried out with the developed resources will be exposed.

Keywords
3D printer, Additive manufacturing, Astronomy, Education, Telescope

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Acronyms/Abbreviations

CAD *Computed Aided Design*

FDM *Fused Deployment Modelling*

FFF *Fused Filament Fabrication*

SLA *Stereolithography*

1. Introduction

3D printing is a technology that has been around us for more than four decades [1].

The pioneering 3D printing works date from 1981 and were carried on by the Japanese automobile designer Hideo Kodama.

Kodama invented a new manufacturing technique that consisted of the addition of layers using resin polymerized under UV light irradiation. However, Kodama's invention did not fit the requirements for patent claiming, and he was not officially recognized as the inventor of the procedure.

In 1986, a group of French investigators failed to file a patent for a monomer curing system by means of a laser. That same year, a patent for SLA by Charles Hull, who was searching for a fabrication technique that let him build small parts for furniture in an easy way, was published. Hull's technique consisted of a system that cured resin by exposing it to UV light, layer by layer.

Later on, in 1988, Charles Hull founded the enterprise 3DSystems [2], a company dedicated to the development of 3D printers and related technology.

At that same time, the first iteration of the most famous 3D printing method was patented. Scott Grump submitted the patent for Fused Deposition Modelling (FDM) or Fused Filament Fabrication (FFF), which was a printing method that consisted of extruding material through a pre-heated nozzle in order to melt it.

During the 1990 decade, the industry benefited from the emerging different CAD software, increasing the ability of both individuals and companies to mass-produce designs that could be easily exportable to 3D printing formats that existed at that time.

Later on, in the first decade of the 2000s, two major milestones of 3D printing were achieved. The first of them, achieved in 2005 being the creation of the RepRap Project [3], which consisted in designing an OpenSource printer that could be mainly built using pieces previously printed with another 3D printer, basically a "self-replicating manufacturing machine" (as told by RepRap themselves). This, in fact, opened the doors of amateur 3D printing by enabling the general public to print their own print farms.

The second major accomplishment of this technology was achieved in 2008 when the first fully printed prosthetic leg was unveiled giving 3D printing a big media coverage and helping it expand all over the world.

Since then, 3D printing has done nothing less than keep expanding through the globe and becoming key in technological developments in fields such as medicine, fabrication methods or even in the aerospace industry with the design and fabrication of new rockets with many of its components 3D printed.

As an example, a recent work [4] has shown the possibilities of the practical implementation of 3D print optomechanical hardware with high-performance rates and with a cost much lower than if conventional commercial hardware was bought. This reference is an illustrative example (among many others) on how 3D printing technologies can be a game-changer in research and development in many areas of the optical industry.

2. Contextualization of the project: Amateur Astronomy

Amateur Astronomy is a field in which different technical skills and needs converge. The amateur astronomical community is formed by thousands of motivated people that want to know more about the Cosmos and to transmit that knowledge. Furthermore, a huge fraction of that community is also interested in do-it-yourself projects

This section summarises the different designs of telescopes commonly used by the amateur community and the different approaches in which, as far as the authors know, several members of the community have been made with 3D printing technology.

2.1. Types of telescopes

Telescopes are basically divided into three types: refractors, reflectors and catadioptric.

In this subsection, the three main types of telescopes used by amateur astronomers are briefly introduced and described.

2.1.1. Refractors

This type of telescope is based on the use of refracting elements (lenses). The main design known as Keplerian telescope is compound by two positive (i.e, converging) lenses (the objective and the eyepiece), and it is the principal design used nowadays (despite optical corrections such as the use of achromatic doublets or inversors for the case of terrestrial telescopes). Another common design is the Galilean telescope, which uses a negative (divergent) lens as eyepiece. An example of a Keplerian telescope is shown in Figure 1a).

Refractors need little to no maintenance because of their lenses being static and fixed to the tube. This kind of telescope provides superb colour contrast and are generally compact.

Even though its simplicity, refractors suffer from chromatic aberration, a phenomenon caused by the different focus points that light can have when changing the refractivity index of the environment depending on the wavelength of the light.

2.1.2. Reflectors

A reflector's working principle is based on reflection instead of refraction. In the most common design, parallel beams of light enter the tube by the top opening and travel through the whole telescope until they reach the bottom, where a parabolic (or spherical) mirror reflects the light to a secondary flat mirror mounted on the spider at the top of the telescope. This secondary mirror reflects light to the side eyepiece in which the focal point of the primary mirror is re-sended to the infinity. This design is commonly known as Newtonian telescope and it is one of the most popular reflecting systems used by amateur astronomers. The basic scheme of this type of telescope is shown in Figure 1b).

In comparison to refractor telescopes, reflectors do have the need of some maintenance, due to the fact that they use two (or more) mirrors and these need to be aligned, a process called *collimation* — which consists in the alignment of the two mirrors — must be done from time to time. Furthermore, eventual dust deposition over the primary mirror could occur, leading to a reflectivity loss, which affects the final quality image.

2.1.3. Catadioptric

Catadioptric telescopes are a combination of the characteristics of both refractors and reflectors because they combine the benefits of lenses and mirrors at the same time.

This type of telescope works by applying a correction to avoid aberrations to the beam of light which then is reflected by the primary spherical mirror that can be found at the bottom of the tube. The beam then travels to the secondary mirror which finally reflects it to the eyepiece. It is for this reason that catadioptric telescopes are much more compact than refractors or reflectors.

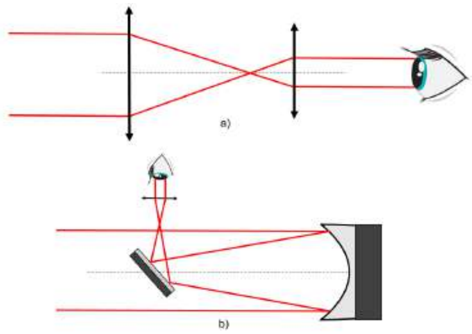

Figure 1. Working principle of a refracting (a)) and reflecting (b)) telescope. [5] [6] [7] [8]

2.2. Amateur 3D printed telescopes

3D printed telescopes are starting to gain popularity among the maker community. By looking at 3D printing websites like Thingiverse [9], many different projects with full guidelines to print and build a telescope using a 3D printer can be found.

As an example, one of the most popular projects is the *Pikon telescope* [10], a reflector telescope that uses a Raspberry Pi [11] to capture images of the observed objects. A picture of the telescope is shown below.

Figure 2. PiKon telescope, extracted from PiKon Website. [10]

3. Design and specifications

For this project, a Newtonian design was chosen. For the optical specifications of the system, a 152 mm (6 inches) aperture was chosen. Since a 762 mm focal length concave mirror with such aperture diameter was available, thus, an F5 Newtonian telescope design was finally proposed.

With these main characteristics set, the next step is to begin designing the pieces needed to build the telescope using CAD. In our case, SolidWorks [12], a software developed by Dassault Systems was used. After some

DOI: 10.5821/conference-9788419184405.104

iterations and a complete assembly of all the pieces, the CAD design resulted in the solid shown in Figure 3.

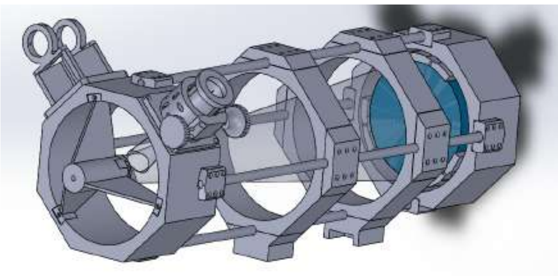

Figure 3. Telescope CAD.

Four parts of the design can be differentiated in Figure 3: the top cap —to the left—, the middle rings —the two rings at the centre of the assembly—, the bottom cap —to the right— and finally the bars that form the truss and unite all the pieces together. We will now go into further detail about each part.

3.1. Top Cap

The top cap is composed of five pieces itself: the top ring, the eyepiece holder (which in this case it is a Crayford focuser designed specifically for this telescope), the searcher support, the spider and the secondary mirror cell.

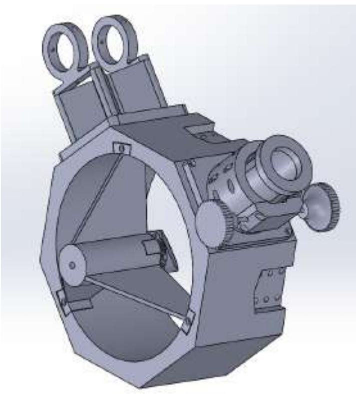

Figure 4. Top cap image with all the parts visible.

The most important piece of this part is the spider —centrepiece attached to the top cap—, which is basic for holding the secondary mirror cell to the body of the telescope. The design of the spider has to be done with special care, because it is required that it occupies the least amount of aperture possible, maximising the amount of photons that arrive at the primary mirror. All the pieces are fixed to the top ring with DIN912 M3 (different length depending on usage) screws that screw into inserts that are coupled to the ring using heat.

It can also be seen that both the eyepiece and searcher holders have many screw holes. That is to ensure the integrity of the system in case the final user would like to strap a camera to take pictures through the eyepiece.

3.2. Middle rings

The main purpose of the middle rings is to act as interfaces between the truss and the equatorial mount that will be used to point the telescope to the sky.

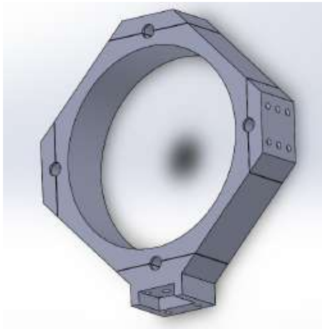

Figure 5. Middle ring, used as the interface between the mount and the telescope.

As it is shown in Figure 5, the middle ring's design presents three plates that screw into the main ring to ensure a perfect attachment to the truss of the telescope and a fourth plate which is different, that is used for fastening the telescope to the mount with the centre hole. Again, all screws fit into inserts put on the piece using heat.

3.3. Bottom cap

The bottom cap is the most intricate part to design because it contains moving pieces that will be used to collimate the main mirror.

Between the pieces that compose it, we can find the main mirror cell, the levers that compose the collimation system and the bottom cap which is the container of all the previous pieces.

This is a key part for the correct performance of the whole telescope because it contains the main part of the optical system as well as the alignment components.

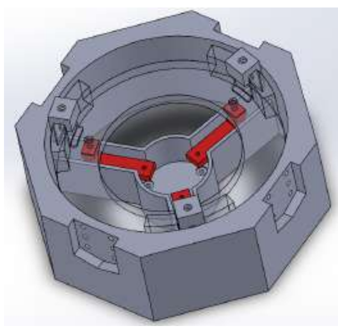

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Figure 6. Bottom cap image. Main mirror cell is transparent so the collimation system can be visible.

As illustrated in the previous figure, the cell is supported by the red mechanisms. These form the collimation system as well as provide attachment to the main mirror cell both radial and longitudinally. These work as levers and are preloaded with a spring (not visible in the CAD - Figure 6 -). Figure 7 shows an image of a prototype of the collimation system.

Figure 7. Prototype of the collimation system, intended to test structural integrity.

The *whiffletree* [13] (lever) is spring-loaded and acts the left arm of the lever when the screw on the right arm is actioned. This allows the main mirror cell to move upwards and downwards because of the flexibility given by the flexors.

Figure 6 shows how the levers are located inside guides, to ensure the structure is stiff enough to support the loads produced by the collimation system.

3.4. Truss bars

Figure 8. Truss bar with the interfaces to attach it to both the top and bottom caps.

The truss is composed of two different pieces, the bars and the interfaces to connect the top and bottom caps.

For the bars, 12 mm aluminium hollow bars are used, since aluminium gives rigidity to the truss and avoids overweight problems because of its lightness.

The interfaces are also 3D printed parts and are the key backbone of the structure. These are glued together with the aluminium bars using epoxy glue.

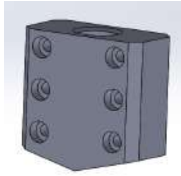

Figure 9. The interface of the truss in detail.

4. Educational applications

One of the aims of this project is mainly to introduce students of all ages into cosmos exploration, optical design of telescopes basis, and to provide a hands-on experience with 3D printing technologies, by means of building a telescope and testing its capabilities. This project is adequate both for upper course students, amateur astronomers and makers motivated with Astronomy. Focused on more experienced engineering students. For doing so, a proposal of activities is given.

Students could involve themselves in building the actual telescope by following the guidelines provided. The majority of the telescope is built by 3D printing the pieces and the non-3D printed materials are easily bought on the internet.

In addition to telescope fabrication and building, an introductory course into optics should be done in order to ensure a better understanding of the physics behind the telescope.

Moreover, as an extra activity, a space observation workshop using the telescope could be conducted.

The application of this project for different dissemination and educational activities, and the design of a workshop activity is a current ongoing work. At the final stage of the project, a complete free manual and theoretical background will be provided.

5. Results

At this point, the telescope has been built ensuring each piece was perfectly printed and everything fits together precisely and without critical loads. The final assembly is shown below.

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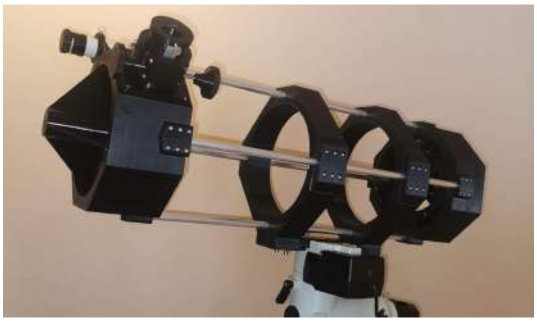

Figure 10. Final assembly of the telescope.

A commercial equivalent system is available thanks to COSMOS Mataró (an amateur Astronomy Association) to perform a comparison between the commercial and the custom 3D printed design. A preliminary comparison between both telescopes is shown in Figure 11. Authors are currently waiting for an optimal observation night, to obtain full results of the telescope's real resolution and capabilities.

Figure 11. Image of a telecommunication tower obtained with the Meade LXD75 telescope (a)) from COSMOS Mataró, and with the 3D printed F5 Newtonian (b)). Both images were obtained using the same equatorial mount.

Acknowledgements

This project has been partially funded by the Escola d'Enginyeria de Telecomunicacions i Aeroespacial de Castelldefels (EETAC) and the Physics Department of the Universitat Politècnica de Catalunya.

The authors acknowledge Diego Rodríguez from COSMOS Mataró for providing the commercial Meade telescope.

The corresponding author also wants to acknowledge his closest friends and family. Especially his brother, who has always been one of his biggest supports. And his fathers for always supporting him without ever losing their faith as well as for raising him as they did.

Also his uncle, Joan, to whom has always admired. For he served as an inspiration and encouraged him to become a great engineer as well as a better human.

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Simulating Atmospheric Turbulence: Code Development and Educational Applications

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Abstract
Earth atmosphere turbulence affects many areas of interest related with Space studies, such as optical communications or Astronomy. In fact, it is a key topic for such applications and, thus, it is important for students in aerospace and aeronavigation studies to get some knowledge of the basis of such phenomena, and how to compensate for it. The phenomenon of turbulence is tangent to many areas such as Optics, Meteorology, Fluid Dynamics, Astronomy, Space Science and Telecommunications, among others. To properly understand the effect of such phenomena on the propagation of an optical signal is imprescindible to properly evaluate and implement the corrections introduced with Adaptive Optics [1] and for understanding the limitations of optical free-space communications channels. The simulation of optical propagation through turbulence constitutes an intuitive and powerful tool for visualizing and understanding such phenomena. Within those ideas, a Final Degree Project, based on the development of simulation tools of atmospheric turbulence is carried out in the Escola d'Enginyeria de Telecomunicacions i Aeroespacial de Castelldefels (EETAC) of the Universitat Politècnica de Catalunya (UPC). In this communication the development of an application, written in MATLAB®, for the simulation of optical propagation through turbulent mediums is presented.

The project consists of the development of a software based on scalar diffraction theory [2] and Kolmogorov's turbulence theory for the generation of turbulent phases under specific meteorological conditions and the simulation of the propagation of an electromagnetic signal through them. With this tool, different applications are going to be analysed.

As an example of application, at the moment this communication is presented, the code is capable of performing the reconstruction of the generated phase in terms of Zernike coefficients [3], providing key information for the understanding of the aberrations introduced by the turbulence and also for correcting them with a proper design. The communication first describes the main basis of the problem, in terms of scalar diffraction theory, and the structure of the application. Later, some results are presented and discussed. Finally, the application of the tool for adaptive optics, optical free-space communications and as an educational application for aeronavigation and aerospace students is discussed, with emphasis in the context of the different degrees, courses and subjects taught in the EETAC.

Keywords
Turbulence, Propagation, Application

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1. Introduction.

The atmospheric variations due to fluctuation of the different meteorological parameters (pressure and temperature) affects the refractive index of air, thus modifying the propagation of optical rays in the atmosphere.
Those variations on the trajectory of the rays have a great impact in several applications, such as Observational Astronomy and optical telecommunications.
Being aware of how critical is that impact on those two fields, and the fact that both Astronomy and telecommunications markets are growing significantly in the last years, aiming the necessity of enlarge the recruitment of new engineers, and the fact that, typically, atmospheric turbulence is poorly analyzed in the academic formation of such future engineers, a MATLAB®-based application has been developed and a computational workshop has been designed in order to introduce this topic to Telecommunication Engineering students.

This paper summarizes how a scenario of optical propagation through a turbulent medium is simulated in MATLAB® programming software tool, describing how the corresponding application is designed and presents the final designed software, proposing a hands-on learning activity for Telecommunication Engineers in the framework of the Telecommunication Engineering at the Escola d'Enginyeria de Telecomunicacions i Aeroespacial de Castelldefels (EETAC) with the Universitat Politècnica de Catalunya (UPC).
The paper is structured as follows: first, the theoretical background required, and the development of the application are presented; second, the application is shown and described, and two different interesting applications in the fields of Astronomy and telecommunications are presented; finally, a learning activity is proposed and contextualized in the studies taught at the EETAC.

2. Methodology and theoretical background.

This section describes the theoretical basis of the project, the diffraction theory of light, a fundamental theory for describing the propagation of light and the turbulent phase generation.

2.1. Diffraction theory: Optical propagation.

The diffraction theory of light provides the theoretical mathematical basis for describing the propagation of an optical signal (usually a two-dimensional signal which propagates in the third dimension) [1]. As is deeply described in the existing literature, diffraction is, by definition, the deflection of waves around the corners of an obstacle or through the aperture in the region of a geometrical shadow of the obstacle. Thanks to Huygens principle, the diffracting object or slit effectively becomes a secondary source of the propagating wave. This framework is useful for describing two-dimensional light sources and the propagation of its corresponding radiation between different planes.
One of the first to analyse the concept mathematically was Augustin Fresnel (1788 – 1825), who described the propagation of the complex amplitude field $U(x,y)$ between different planes by means of diffraction. Thus, when propagating the optical complex field $U_1(x,y)$ of an emitting source from a plane 1 to a plane 2 located at a certain distance z, the resulting diffracted (i.e., propagated) complex field $U_2(x,y)$ can be computed as follows:

$$U(x_2,y_2) = \\ = \frac{e^{ik\Delta z}}{i\lambda\Delta z}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} U(x_1,y_1)e^{i\frac{k}{2\Delta z}((x_1-x_2)^2+(y_1-y_2)^2)}dx_1dy_1 \quad (1)$$

However, this expression is only valid for short propagating distances. For the case of long distances (which is the typical situation in Telecommunications and Astronomy), the Fraunhoffer theory is used (see equation (2)).

$$U(x_2,y_2) = \\ = \frac{e^{ik\Delta z}}{i\lambda\Delta z}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} U(x_1,y_1)e^{i\frac{k}{2\Delta z}(x_1x_2+y_1y_2)}dx_1dy_1 \quad (2)$$

2.2. Turbulent phase generation.

The variability of atmospheric parameters generates a turbulent phase that can be described by means of Kolmogorov's theory, which permits the combination with diffraction theory of light for the analysis of the propagation of the optical signal through such media [2].

This dependence on the atmospheric physical parameters provides the necessity of defining the turbulence scales. On the one hand, the external scale L_0 is defined as the dimension where the large vortices of the phase are generated (typically on the scale of 100 m), whereas the smallest diameters are governed by the internal scale l_0 which is on the order of 0.01 m.

Furthermore, the intensity of the phase is related to the so-called Fried parameter r_0, which determines how strongly the turbulence acts over the optical signal when it crosses the turbulence region. The Fried parameter depends on the so-called turbulence structure parameter $\mathrm{Cn2}$, which comprises all the variability introduced in the refractive index by the change on the meteorological conditions. The Fried parameter is then computed using the following mathematical expression:

$$r_0 = (0.423 \cdot k^2 \cdot Cn2 \cdot Z)^{\left(-\frac{3}{5}\right)} \qquad (3)$$

This formula permits the generation of a turbulence phase $\phi(\rho)$ at a certain plane and the propagation of an optical signal through that plane by simply using the following relation:

$$U_2 = U_1 \cdot e^{(2j\pi\phi(\rho))} \qquad (4)$$

A simple scheme illustrating this procedure is shown in Figure 1.

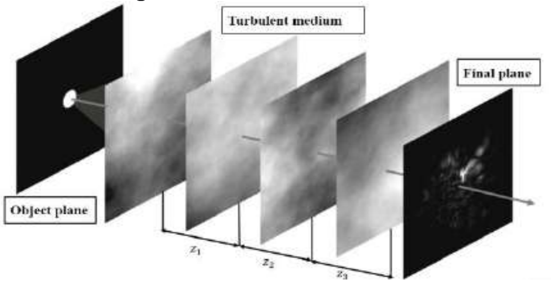


Figure 1: Propagation of an optical signal through a turbulent medium. First, an emitting object in 2D is defined (in this example, a circular emitting source). Later, the different phases screens corresponding to several turbulent planes are generated at the corresponding distances z_i from the original plane (the object plane). Finally, the resulting amplitude in the final plane is obtained from equation (4). This working scheme is valid for both the analysis of the effects of the turbulence on the optical quality of an astronomical observation and for the case of a communication between an optical emitter and its corresponding receiver.

3. Description of the software

This section describes the developed software and the two main applications.

3.1. The software application.

The main window of the application developed is shown in Figure 2.

Figure 2: Software main window.

The idea of the application is to incorporate the two basic ideas explained above into practical scenarios of current interest. It is intended to introduce the interested party to the world of Zernike polynomials, and how they are capable of reconstructing turbulent phases for subsequent compensation, introducing great improvements in large telescopes. A second application aims to understand how atmospheric attenuations interact in the channels connecting ground stations and satellites, with special emphasis on the tracking of suitable areas for optical propagation.

The following subsection describe and show the results of the two applications studied with the developed program.

DOI: 10.5821/conference-9788419184405.105

3.2. *Application on Observational Astronomy and Mechanical Engineering of Large Telescopes: wavefront reconstruction under turbulence conditions.*

This application is focused on performing a practical introduction to the field of Adaptive Optics. The main characteristic of this application is the reconstruction of the aberrated wavefront that arrives to the primary mirror of a telescope. Knowing how the atmosphere has affected the original wavefront, it is possible to design an Adaptive or Active Optics system to correct such aberration.
To do that, the Zernike polynomials are commonly used. This set of polynomials permit the reconstruction of the wavefront by adding some weight (i.e., coefficient) to each component (polynomial). Thus, the aberrated phase can be described in terms of Zernike polynomials as follows:

$$\phi(\rho) = \sum_{j=1}^{N} a_j Z_j(\rho) \tag{5}$$

Where $Z_j(\rho)$ represents the polynomial and a_j the corresponding coefficient.
For a deeper discussion on these polynomials, the interested reader is referred to [3] and [4].

Using equation (5), the software developed for this project provides the Zernike coefficients, which are commonly used by Mechanical Engineers when designing primary mirrors for large telescopes and to perform corrections and provide optical error budgets for Adaptive and Active Optics. An example of the reconstruction done by the software is shown in Figure 3.

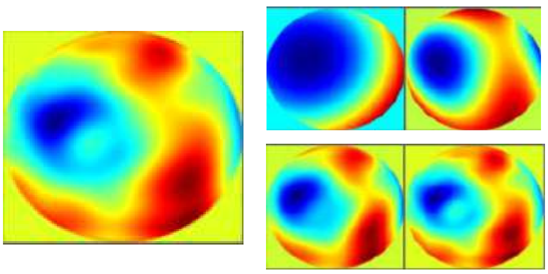


Figure 3: Real, and 5, 20, 70, 105 modes reconstruction.

From this simulation, the required coefficients for optomechanical analysis can be extracted. Furthermore, the different obtained phases (both reconstructed and the corresponding simulation for correction) can be compared using the MALTAB® SSIM function [5].

3.3. *Application on Optical communications.*

The other application explored in this project is the simulation and modelling of the atmospheric attenuation losses in an optical channel for Optical Communications.
Using the same framework described above, an optical emitter is generated and then, using the Kolmogorov's theory for generating the turbulent phases, the propagation between receiver and emitter is performed. By analyzing the resulting two-dimensional pattern which reaches the receiver (the so-called far-field Point-Spread Function, PSF), the losses introduced by the atmospheric turbulent phases can be obtained by counting the number of photons that has arrived at the receptors collecting area.
Furthermore, the developed code is not only able to determine the attenuation of the channel, but also of reading turbulent phases to track the areas of the sky in which the propagation of the optical signal is optimal (i.e., the path which performs a minimization of the losses), which will led to an optimized communication link between the emitter (either an optical ground station or a satellite) and the receiver (which also can be a satellite or an optical ground station).
In this application, the atmospheric channel is modelled with a collapse of atmospheric layers (as illustrated in Figure 1), considering a few kilometres, concentrated in the area where clouds form. Finally, reception is based on the mathematical principle of a photodetector. This can transform the light, i.e., optical, information into a mathematical intensity value that can provide us with the essential information. Thus, the attenuation L_p is defined as follows:

$$L_p[\text{dB}] = 10\log\left(\frac{\sum_{i,j}\text{PSF}_{\text{emitter}_{i,j}}}{\sum_{i,j}\text{PSF}_{\text{receiver}_{i,j}}}\right) \tag{6}$$

Where the i, j indices correspond to the pixel indices of the emitter and receiver PSF images. For this application, the results window shows how the image is distorted in the case of propagating the light without any angle or optimization of propagation. Also, the code analyzes the areas of lowest attenuation and providing the firing angles.

As an illustrative example of this application, a simulation is presented in Figure 4. For this simulation, the emitting source is a 5.1 cm diameter laser diode emitting at 800 nm.

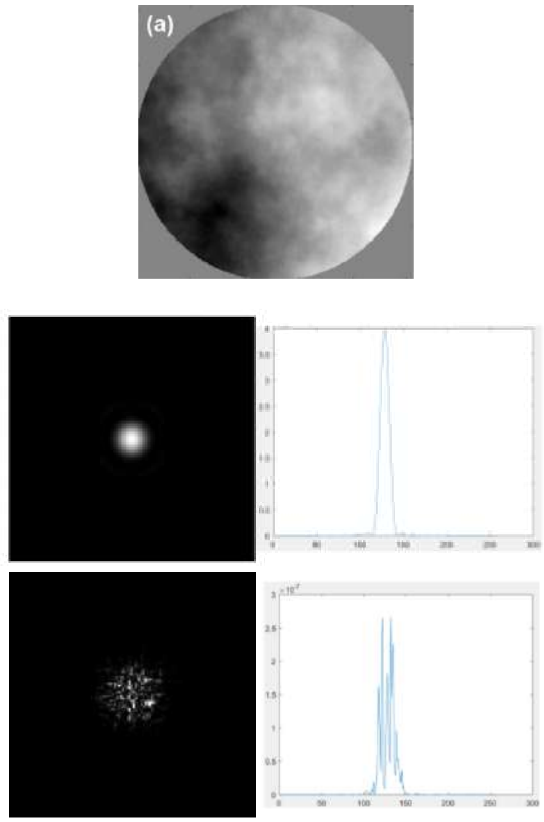


Figure 4: Simulation of a propagation trough a turbulent phase screen (a), where the PSF shows the distortion of the image.

This illustrative example shows how the distortions introduced by the atmospheric turbulence to the optical channel are.
For a deeper discussion on the mathematical models of atmosphere [6], and for optical communications in satellites, the interested reader is referred to [7].

4. Educational interest and applications of the software

In this work, the results current of an on-going engineering student's Final Degree Project are shown. As above exposed, the two applications are of the interest for both Mechanical and Aerospace Engineering students, and in the Telecommunication Engineering studies.
In the context of the EETAC, which is the UPC school in which this project is been carried out, there are several subjects which cover topics that are related to the areas analyzed with the software presented in this work.
The authors are currently designing a workshop in which students will use the beta-version of the application for generating and analyzing several scenarios and situations with the two applications shown in this work. The proposed workshop consists of the use of a guide which introduces the main topics described in this paper, and the basic functionalities of the beta-version of the code. Using the guide, students will be driven to the simulation of different situations and then questions regarding such simulations should be answered. A sample of Telecommunication Engineering Degree students will perform this workshop during the next weeks, and the results and a detailed explanation on the workshop will be presented in the conference.

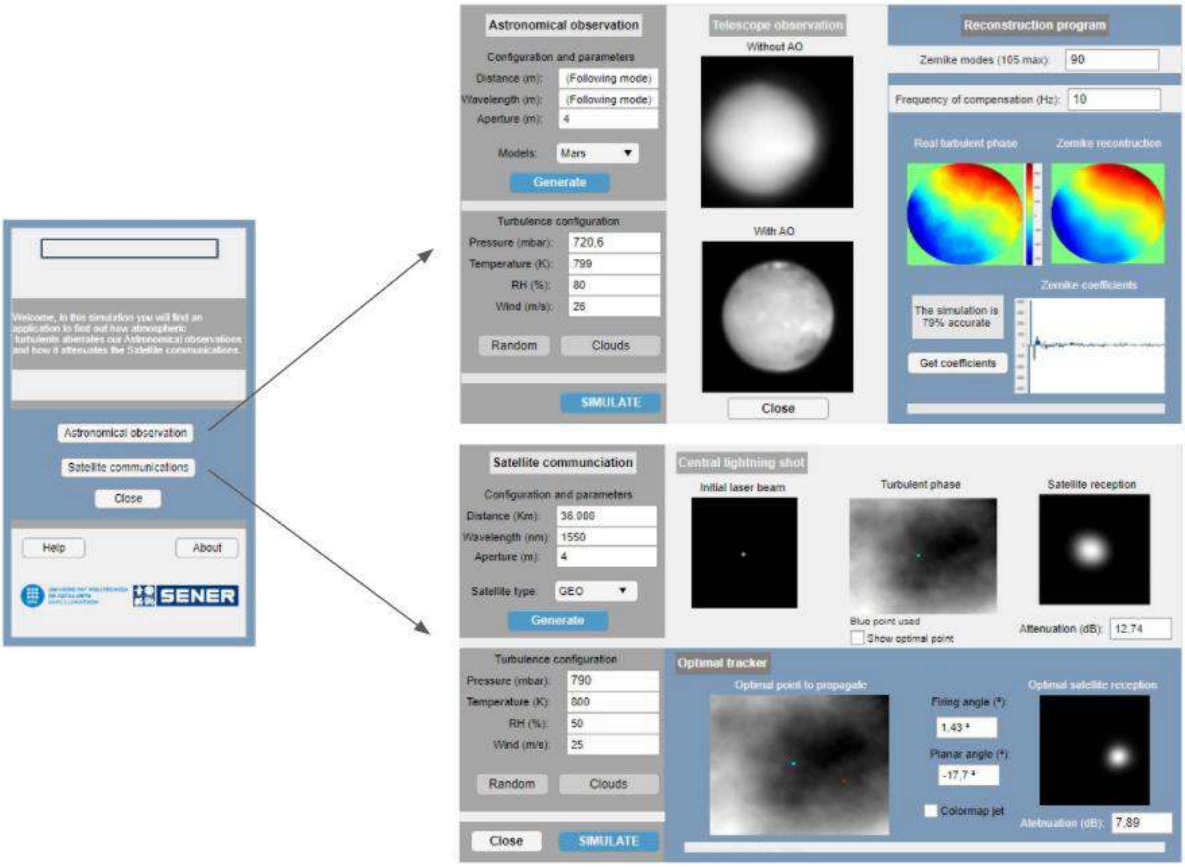
5. Conclusions

Adaptive Optics and Optical Communications are two key technological topics that will provide technical challenges in the next years that will need high-qualified professionals to be solve. Both areas are affected by the fluctuations of the atmosphere, thus, introducing students that in their academic formation to this topic will provide a more warned professionals in the future. To push in that direction, this work presents the development of an application that can perform simulations of the effects of atmospheric turbulence in both applications.
At the current stage, the developed code is a helpful tool for both academics and engineers for a better understanding of such phenomena and effects and has been used in research projects. Furthermore, the authors are designing a workshop to use this application for teaching purposes, and first results with students and the analysis of the impact of the workshop on their learning curves are expected in next months.

Acknowledgements

This project has been partially funded by the EETAC and the Physics Department of the UPC.
The authors want to acknowledge Dr. Joan Bas from CTTC for fruitful discussion and providing interesting information and bibliography for the telecommunications application.

Appendix



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Development of Commercial-Off-The-Shelf Imaging Payload for Cloud Coverage Monitoring

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Abstract

Locana Bhumi payload is one of the selected payloads in The 2nd GRSS Student Grand Challenge, and it will be installed in a 3U Cube Satellite. Its main mission is to monitor cloud coverage in several regions such as Indonesia, United Arab Emirates, Oman, and Australia. Clouds have a role in climate change, they are able to reflect infrared light and cool the surface of the earth that is covered by clouds. At the same time, clouds are also able to trap heat, as a result, they warm the earth. By monitoring cloud coverage over the selected areas, it is expected that we will be able to study how cloud coverage could affect the climate system on the earth. In order to monitor the cloud coverage, the Locana payload will capture cloud images by using a small serial camera that is equipped with a low voltage ¼-inch 5-megapixel OV5642 image sensor. This camera also employs a 4.14 mm focal length fixed-infrared-cut-filter lens. This camera is able to capture 500 x 375 km^2 of the area from about 575 km above the earth's surface, with that area observation, the cloud coverage is expected to be easier to observe. In terms of image storage, this payload is integrated with a 1 Gigabit memory. This memory is also used for saving the payload housekeeping data. To prevent the payload from overcurrent situations, the payload system is integrated with an Over Current Protection module. Moreover, an alloy-based enclosure has been designed to protect the component from outer space radiation. The material used for the enclosure is aluminum alloy 7075. The payload has a compact dimension, which fits in 0.5U of Cube Satellite size. Currently, the development of this payload has reached the Critical Design Review stage and it is expected to be ready in Quartal-1 2022.

Keywords

Climate change, cloud coverage, Cube Satellite, RGB camera

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Acronyms/Abbreviations

CDR *Critical Design Review*

CubeSat *Cube Satellite*

Gb *Gigabit*

OCP *Overcurrent Protection*

PCB *Printed Circuit Board*

PDR *Preliminary Design Review*

RGB *Red Green Blue*

1. Introduction

Climate change is one of the climate systems phenomena that could change the condition of the earth. Climate change can be detected by observing one of the few things, one of them is clouds. Clouds strongly affect the climate system on the earth in many ways. Clouds could warm the earth by trapping some heat in the atmosphere. At the same time, clouds are also able to cool down the earth by radiating infrared light to space [1]. Climate scientists have been studying how clouds could change the daily weather, the seasonal cycle, and even climate system changes from year to year [2]. However, further research and observation are still needed in order to predict the future climate. The satellite with cloud observation mission-related may help the climate scientists to study more about how clouds could change the climate system or even predict future climate by providing the clouds data that are needed.

Locana Bhumi payload is one of three selected remote sensing payloads in The 2nd GRSS Student Grand Challenge developed by a student team from Telkom University, Indonesia. The mission of the Locana Bhumi payload is to monitor cloud coverage in Bandung and North Sumatera in Indonesia, United Arab Emirates, Oman, and New South Wales in Australia. In order to achieve that goal, this payload will take pictures of the clouds that cover those selected areas using a COTS RGB Camera. Previous research regarding the usage of that camera has been done by [3]. The Preliminary design of this research payload has been done [4]. By developing this payload, it is expected that the images taken could be used to study more about how clouds could affect the climate system or even predict future climate.

This research result is an engineering model of a remote sensing payload that employs a Commercial-Off-The-Shelf RGB Camera which is able to capture low and high-resolution images. This camera is controlled by a low-power ARM Cortex M0 microcontroller. A NOR memory is used to store the images. In order to manage the memory allocation, memory management is applied.

2. Payload System

The challenge of this project is to develop a payload that fits into a 3U CubeSat. There are three payloads that will be carried by this 3U CubeSat, therefore each of the payloads should be fit into less than 1U spaces inside the CubeSat. Besides that, the payload should consume the amount of powers as small as possible. The payloads also have to be able to perform from 575 km above the earth.

The mission of the Locana Bhumi payload is to monitor cloud coverage by taking images of clouds from time to time. In order to meet the requirements, the Locana payload uses a mini serial camera that only needs 0.5U CubeSat, a low-power microcontroller unit, and other instruments with only 3.3 Voltage level power consumption respectively.

2.1. Payload Instruments

There are three main instruments that are used in the Locana Bhumi payload, they are RGB Camera, Microcontroller, and Memory.

Figure 1. OV5642 RGB Camera [5]

In order to take pictures of clouds, the camera used in the Locana payload is a low-power ¼-inch OV5642 RGB sensor camera module from Arducam. This camera provides resolution options from QVGA to 5MP [5]. Due to the limited size of data that the Locana payload may transfer, the resolutions that will be used are only QVGA to VGA. However, those resolutions have fit the requirement in the cloud imagery case.

Figure 2. ATSAMD21G18 Microprocessor [6]

DOI: 10.5821/conference-9788419184405.106

The microprocessor used for the microcontroller is a low-power ATSAMD21G18. The microprocessor is integrated with a 32 kHz oscillator and other components to form the 32-bit microcontroller. It has 256 kb of flash memory and 32 kb of RAM [6]. It is chosen because it is compatible with the OV5642 camera, and it has the lowest power consumption compared to other microcontrollers.

Figure 3. MT25QL01GB NOR Flash Memory [7]

The memory used to store the captured images and taken housekeeping data is NOR Flash Memory MT25QL01GB. It has 133 MHz maximum clock frequency, 1 Gb memory size, and uses SPI peripheral [7].

To monitor the health conditions of the payload, this payload also carried an analog temperature sensor LM335D to monitor the temperature around it. To prevent the payload from overcurrent condition, the power lines of the payload are connected to the Over Current Protection LTC4361 module.

2.2. Block Diagram

The integration of all instruments that are used in the Locana Bhumi payload could be seen in figure 4 below.

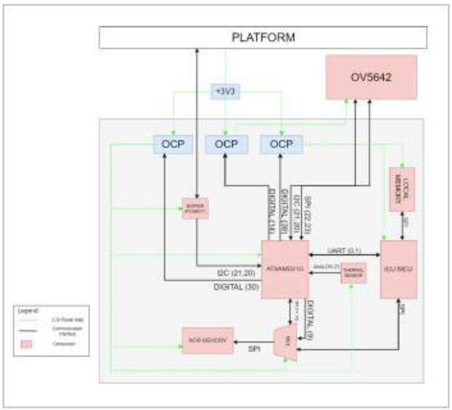

Figure 4. Payload Block Diagram

Locana payload will be given 3.3 Voltage level power from the platform. Before all instruments are supplied, the supply will go to the OCP module to prevent an overcurrent supply that could damage the payload. If there is an overcurrent detected by the OCP, then it will cut the power lines automatically. The OCP also could be used as a controller to turn on or off the load. In this case, it will be controlled by the microcontroller. The power lines between the camera and other instruments are using different OCPs, so when the camera is supposed to be turned off, other instruments are not going to turn off as well.

2.3. Operational Mode

The payload itself has two operational modes, they are mission and calibration mode.

a. Mission Mode
In this mode, the payload (i.e. the camera) will work for the mission. The used camera will capture the picture of the cloud in certain target areas. The target areas we will use are North Sumatera and Bandung in Indonesia, New South Wales in Australia, Uni Emirates Arab, and Oman.

b. Calibration Mode
In this calibration mode, the camera will take a picture of Mount Bromo in Indonesia and Alice Spring in Australia. The purpose of this mode is to check the color correction (i.e., radiometric calibration) of the camera and its functionality. The pictures taken in every calibration will be compared from time to time.

3. Payload Design

3.1. Printed Circuit Board

The PCB has a dimension of 89.22 mm x 89.10 mm and consists of four layers. The interface that is used to communicate with other payloads is the UART interface, while to communicate with the onboard computer is using the I^2C interface. Also, the board consists of headers, OCPs, a microcontroller, a sensor, a multiplexer for sharing the connection between payload from top to bottom layers, and a NOR Flash Memory.

Figure 5. Engineering Model Circuit Board

3.2. Mechanical Design

In this section, the mechanical structure of the Locana payload will be explained. The Locana payload mechanical structure consists of a bracket that has several separate parts. These brackets are used to hold overall components in the payload such as cameras and PCB boards.

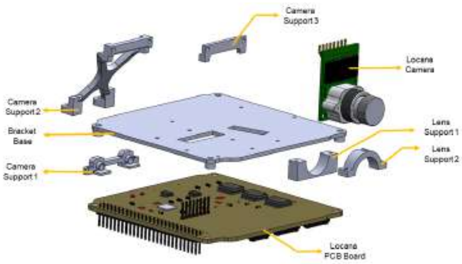

Figure 6. Locana CAD

Brackets are designed with several separate parts for the purpose of simplifying the assembly process so that the supported components can stand firmly. To be able to support the components in order to withstand shocks at the launch stage, the bracket is made of aluminum alloy 7075 with the addition of an anodized layer on the surface.

The selection of 7075 aluminum alloy material is based on the structure of the material that can operate in extreme conditions [8]. On the outer layer of the bracket is given a clear anodize layer to increase high emissivity and low absorptivity that lead to the efficient radiative heat transfer in the space environment [9].

4. Testing and Simulation Result

Several camera testing that should be carried out are RGB quality testing, focus lens testing, and camera endurance testing.

4.1. RGB Quality Testing

To prevent the captured images from infrared light in the atmosphere that could distort the images, the RGB Camera employs an infrared-cut filter lens. Several experiments are needed to make sure this filter lens will not affect the camera in taking RGB colors.

Figure 7. RGB quality testing result

The RGB quality test is done by giving a colorful object, then the RGB camera takes a picture out of it. The sensor of the camera shall differentiate the RGB colors. The picture above is the result of the RGB quality testing. It is shown that the camera could differentiate the RGB colors and produce colorful images well.

4.2. Focus Lens Testing

The Locana Bhumi payload will perform from 575 km above the earth. Therefore, the focus lens of the camera should be set to infinity, so that the camera will be able to capture the clouds as far as possible.

Figure 8. Focus lens testing result using QVGA resolution

Figure 9. Focus lens testing result using VGA resolution

Figure 8 and figure 9 shows the camera is able to take images of clouds clearly with the focus lens set up to infinity.

4.3. RGB Camera Endurance Testing

After the CubeSat is launched, the payload will be operating from month to month, even from year to year, as well as the camera. It is important to make sure the payload, especially the camera, is able to perform for a long time. Therefore, an endurance test needs to be conducted.

Figure 10. The image was taken right after the camera turns on

Figure 11. The image was taken after the camera turns on for 6 hours

As shown in figure 11, there is color degradation compared to figure 10. Therefore, it is important to turn off the camera before the payload takes pictures to prevent color degradation.

4.4. Memory Management

As mentioned previously, the IC to save the captured images and housekeeping data is NOR Flash Memory MT25QL01GB which has 1 Gb of memory size. Below is the memory management table that mapped the use of the NOR Flash Memory.

Table 1. Memory Management

Allocation	Length (KB)	Start Address	End Address
Image 1	256	0000 0000	0000 3FFF
…	…	…	…
Image 200	256	031C 0000	031F FFFF
Padding	64	0320 0000	0320 FFFF
Internal	64	0321 0000	0321 FFFF
Image Status Data	64	0322 0000	0322 FFFF
Housekeeping Data	64	0323 0000	0323 FFFF
Test Connection NOR	64	0324 0000	0324 FFFF
Camera Setting	64	0325 0000	0325 FFFF

4.5. Mechanical simulation on structure

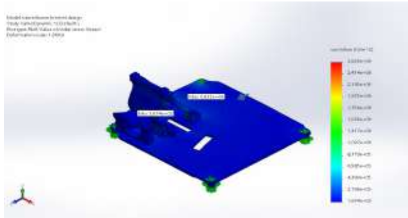

Figure 12. Structure Simulation

We perform a mechanical simulation to determine the toughness of the structure that we have. According to the needs of the space environment, the simulations carried out include random vibration which is carried out vertically and horizontally, and thermal simulations. The simulation results can be seen in Tables 2, Table 3, and Table 4.

Table 2. Horizontal random vibration simulation

Simulation	Type	Min	Max
Stress	Von: von mises stress	1,674e+02 N/m^2	2,633e+06 N/m^2
Displacement	URES: Resultant Displacement	1,000e-24 nm	8,773e+03 nm
Strain	SEDENS: Strain Energy Destiny	7,168e-07 N.m/m^3	4,575e+02 N.m/m^3

Table 3. Vertical random vibration simulation

Simulation	Type	Min	Max
Stress	Von: von mises stress	2,410e+02 N/m^2	9,739e+06 N/m^2
Displacement	URES: Resultant Displacement	1,000e-24 nm	1,683e+04 nm
Strain	SEDENS: Strain Energy Destiny	7,591e-07 N.m/m^3	1,978e+03 N.m/m^3

Table 4. Thermal simulation

Simulation	Type	Min	Max
Thermal	TEMP: Temperature	-3,000e+ ^{o}C	6,500e+01 ^{o}C

Figure 13. Fitting test result

We have manufactured the engineering model of the structure. As can be seen in figure 13, the payload structure fits the engineering model of the PCB. Based on the result of payload experiments, the result of the mechanical structure simulation, and the CDR, the Locana Bhumi payload is ready to manufacture its flight model.

5. Conclusion

The Locana Bhumi payload engineering model has been developed in this research. Some test to capture images has been done to validate the camera image quality, focus, and its endurance when it is operated for a long time. Based on the experiments that have been carried out, it is proven that a COTS mini serial RGB camera could be used as an instrument for the CubeSat imagery payload. Structure simulation analysis has also been done to check the strength of this payload. In the future, environmental test will be conducted to validate the actual payload vulnerability.

Acknowledgment

We would like to thank the IEEE GRSS and NSSTC, the organizer of the 2nd GRSS Student Grand Challenge, for supporting this research. We would also like to thank the ICU Team from the Kyushu Institute of Technology, and the RITA Team from Universitat Politècnica De Catalunya for the teamwork. Last but not least, we would like to thank Telkom University and Nanosatellite Division Satcomradar Laboratory members for supporting this activity.

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How to Manage a Rocketry student project in full quarantine

Júlio Santos[1], Jeremy Silva[2], Henrique Neves[3]

Abstract

The Fénix Project was created by a multidisciplinary team of forty students that aims to design and build a rocket totally Student Researched and Developed (SRAD), capable of reaching three thousand metres of altitude to participate in universitary rocket launch competitions in Europe. It was born from the will of students at the University of Beira Interior (UBI) and the University of Coimbra (UC) who in 2022 have the goal to participate in the European Rocketry Challenge (EuRoC), organised by the Portuguese Space Agency, and to present a high powered solid rocket. In the desired category, students have to develop a motor from scratch and produce its solid fuel.

Due to the current pandemic situation it was impossible, on the one hand, to hold face-to-face meetings regarding teamwork and, on the other hand, to organise fundraising events. In this way, the team was forced to develop teleworking solutions and look for other ways to get some monetary sponsorship. For this, tools such as Discord, Trello, Google Drive and Google Meets were used.

The hardest thing to control on a team of so many people in a full quarantine is precisely the pace. For that, this project was based on an Agile methodology - Scrum approach - which encourages teams to learn through experience, reflecting on their own achievements and difficulties during work sprints of fifteen days, promoting continuous improvement and causing there to be a constant concern in complying with the initially defined timeline. To reward the effort allocated by students on the project, points were given to the several teams. Being compliant with the applicable standards of the European Cooperation for Space Standardisation (ECSS) also gave students a great sense of responsibility and endeavour, due to the proximity of the tasks that are performed in huge space agencies, such as the European Space Agency (ESA).

With the right approach, COVID-19 effects can be mitigated without ever losing the main focus, which is facilitating the acquisition of soft-skills and hard-skills by students who want to participate and be a part of this fascinating sector.

Keywords

Agile Methodologies, Education, Project Management, Remote, Rocket

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Acronyms/Abbreviations

All used acronyms and abbreviations should be listed in alphabetical order, as follows:

AR *Acceptance Review*

CAD *Computer Aided Design*

CDR *Critical Design Review*

MDR *Mission Definition Review*

PDR *Preliminary Design Review*

PRR *Preliminary Requirements Review*

SSEA *Symposium on Space Educational Activities*

SRAD *Student Researched and Developed*

SRR *System Requirements Review*

UBI *University of Beira Interior*

UC *University of Coimbra*

1. Introduction

COVID-19 has been severely affecting the entire space sector and this long-lasting pandemic will have consequences for years to come. It is threatening the economic viability of companies, jobs and working conditions [1]. But in plain lockdown there was a project rising from the ashes.

Created in March 2021, Fénix is a partnership between the University of Beira Interior (UBI) and the University of Coimbra (UC) that aims to develop a rocket capable of participating in university rocket launch competitions in Europe and other events that encourage university students to design, build and launch their own vehicles. At a time when the importance of diversity is increasingly recognized in the world, Fénix is proud to present a group formed by a mix of experience with youth, with forty students from the University of Beira Interior and University of Coimbra, some without any connection to the space area, and others with major projects such as Stratospolca participating in Balloon Experiment for University Students (BEXUS) - collaboration with the European Space Agency (ESA) - in their curriculum. This project's ultimate goal is to prove that learning Rocket Science/Engineering is for anyone, opening up horizons for space lovers and future professionals in this fascinating area.

2. Objectives

2.1. Technical Objectives

Fénix's mission consists in the building of an unguided Student Researched and Developed (SRAD) Solid Propulsion Rocket capable of reaching an apogee of 3,000 metres. Additionally, it shall employ internal electrical and software subsystems and must have a dual-stage parachute as a mandatory condition to ensure the rocket is successfully recovered, and can be reusable. The functionality of the payload is also a key detail in this project, as well as the portability of its Launch System and Ground Segment.

2.2. Non-Technical Objectives

One of the major objectives with this initiative is to provide students a space for creativity and self-development, thus facilitating the acquisition of soft-skills and hard-skills. Every member should individually acquire knowledge of the respective subsystem in which they are working, as well as an overview of how a space project is managed and planned.

The project is intended to reach a wide audience, being mentioned in national and international newspapers and media. As the space sector is booming in Portugal [2] and more and more students from Faculties of Engineering want to participate and be part of this fascinating sector, we hope that this project will promote UBI and UC as being at the forefront of the Portuguese Space Sector, and that it is maintained for many years, with the foundations being created for new patents to be developed and for this to become a profitable business, if the next generations of students/professors wishes to do so.

Figure 1. Mission Patch

DOI: 10.5821/conference-9788419184405.107

3. Project Management Approach

There are several constraints to this project on a management level. Firstly, since it is composed only by students, it requires from them the ability to excel in discipline and time management in order to conciliate their work with the ever so important academic career, as well as other extracurricular activities they may have and their free time. Also, the two hundred kilometres that separate the two universities participating in this project complicate the possibility of face-to-face work and regular meetings/team-buildings. However, and as this paper will try to prove, teams can develop exceptional communication and relationships by bringing their work cultures to the virtual space.

3.1. Organisation

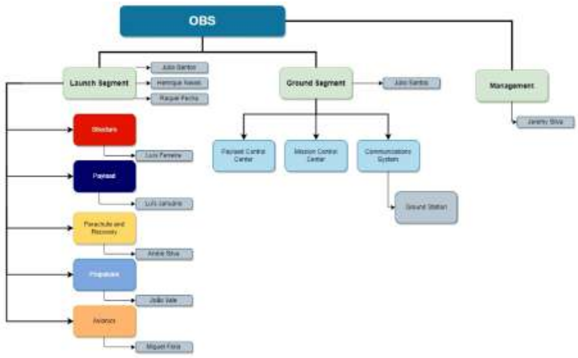

Figure 2. Organisational Breakdown Structure

The leadership of the project is in charge of the Team Leader. Together with the Project Manager, they supervise all the work and guarantee that every member knows their job description and what authority they have.

The rest of the team is divided into several working groups (subsystems), inside two segments: Ground and Flight. The latter is divided into Avionics, Propulsion, Structure, Parachute & Recovery and Payload, as seen in the Figure above.

Each working group has a coordinator, who is responsible for managing and motivating every group member, reporting the information to the Team Leader and Project Manager, who also has the task of leading the Management team, ensuring all the communication with stakeholders, documentation and promotion of the project. Their range of responsibilities also includes travel logistics for testing, as well as monitoring the financial aspects. This organisation offers the framework for the project's execution.

The team has also three System Engineers who assess every system and ensure that all the parts function as a whole, determining problems, providing solutions to issues that arise, designing, upgrading and maintaining systems, while also brainstorming possible improvements that can be made to a system in the future. They assume the functions of an "Operations Director", tracking and reviewing every team's work. Finally, they are in charge of the validation and verification tests necessary until the final decision to launch.

3.2. Agile Methodology

On a team of so many people, the pace is hard to control. That is why this project was based on an Agile methodology (Scrum approach) which encourages teams to learn through experience, reflecting on their own achievements and difficulties, making retrospectives and reviews. The team works in sprints of fifteen days where after each one there is a meeting to review every task, causing there to be a constant concern in complying with the initially defined timeline.

This adaptable and effective framework was implemented using three main softwares: Google Drive, where important documents, excel sheets and budgets are stored; Discord, used for communication, containing individual voice and text channels for all the teams; and Trello, where the Scrum approach is deployed on three columns ("To Do" - tasks that needs to be performed in fifteen days; "Doing" - tasks that are being done during the current sprint, and "Done" - tasks that are finished).

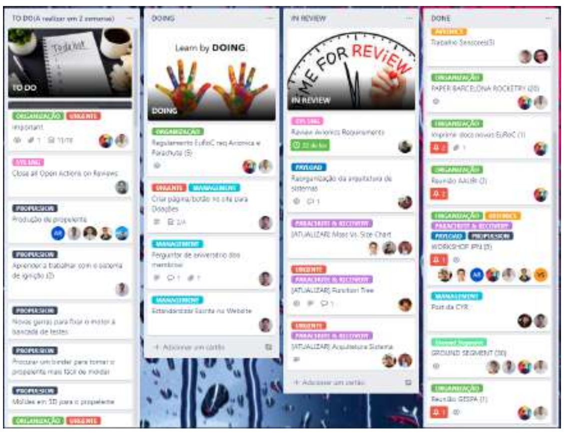

Figure 3. Trello Board in Use

DOI: 10.5821/conference-9788419184405.107

3.3. Cost Management

Cost is usually one of the first aspects that come up in any project, but when it comes to a universitary project, it can be challenging to forecast and manage costs effectively. In fact, there is news every day about projects going over budget and time, yet this is avoidable with strong cost management.

For the project to have its desired success, it was necessary to resort to the support of entities willing to dispense some type of collaboration, mainly national and international companies to which the project was aligned with their strategic plan and activities, many of them offering materials that the company had, rather than money. Funding was also acquired through other sources, such as raffle tickets.

The cost estimate for this project started out as a rough figure and got more refined, as the project work and materials were defined in one Google Sheets document, where every team has a particular budget associated with their monetary expenses.

Registration fees of the competitions are also important to take into consideration, as they round up to 100€ per person.

3.4. Schedule

Project scheduling is just as important as cost budgeting, as it determines the timeline, resources needed, and reality of the delivery of the project. Once an overall schedule is set, using a consensus-driven estimation method the project manager is responsible for monitoring the progress of the project and revising the schedule if needed. This must be done in consultation with project team members who are doing the work. It is essential for the project manager to keep all participants informed as to current schedule status.

Figure 4. Management timeline of the project

As well as the cost budget, the schedule estimate for this project started out as a rough figure and got more refined, as the project deadlines were defined in a Gantt Chart.

3.4.1. Deliverables

The desire was to be as compliant as possible with the applicable standards of the European Cooperation for Space Standardisation (ECSS). Making regular technical meetings and elaborating system engineering reviews gives students a great sense of responsibility and endeavour. The reviews that need to be performed are:

- Mission Definition Review (MDR)
- Preliminary Requirement Review (PRR)
- System Requirement Review (SRR)
- Preliminary Design Review (PDR)
- Critical Design Review (CDR)
- Acceptance Review (AR)

The usage of Reviews as Milestones serves the very useful function of allowing users to have “snapshots” of the various phases of the project and providing a formal approval for the start of the next phase. This has allowed the team to identify and mitigate problems early on in the design phases and not allows for the mistakes to propagate throughout the project, such as the usage of materials or components not acceptable for the performance requirement of the system.

Two major ECSS Standards that are being followed in this project are Project Planning Implementation [3], and System Engineering General Requirements [4]. These guides provide important rules for space projects.

Figure 5. ECSS Standards [3] and [4]

DOI: 10.5821/conference-9788419184405.107

3.5. Requirements

The first activity in a space project is, obviously, to define its requirements. In Fénix this is not an exception. High-level requirements were first defined, and then subsystem requirements were also defined. Collaborative documents were used to host all the requirements, making use of an ID to identify the requirement itself and adding a third column to explain the rationale behind it. Also, a Change Log was created to store the major changes in the project, and register the affected subsystems.

3.6. Risk Management

Risk management is the practice of identifying, evaluating, and preventing or mitigating risks to a project that have the potential to impact the desired outcomes.

As the team cannot predict the future with certainty, it was essential that everyone brainstormed about what failure modes their subsystem could have and in which phases of the project they would tend to happen. Once the risks were identified by every team, they were analysed by the Systems Engineers to identify the qualitative and quantitative impact of the risk on Fénix so that appropriate steps can be taken to mitigate them. To do that, the probability and severity of each occurrence were pointed and the criticality was calculated by multiplying the two. Finally, a mitigation measure was defined for every failure mode.

ID	Type	Failure Mode	Mission Phase	Probability	Severity	Criticality	Mitigation Measures

Figure 6. Risk Matrix of the project

3.7. Promotion

The advertising of this project is done through the Fénix website - http://fenixrocket.pt/, where it is possible to find information about the rocket, including reports on its development and future announcements - and in social networks. There is currently a Facebook and LinkedIn page, and an Instagram account (@fenixrocket) - where news about the project is being published and the experience is presented to the general public. This is the way of attracting sponsors and partners to finance Fénix.

4. COVID-19 and its Mitigation

Fénix's project started officially in March 2021, during a full quarantine situation in Portugal, at a time where on average the number of new infections was decreasing every day and about 3% to 4% of the population was vaccinated [5].

However, with still more than one thousand cases of COVID-19 diagnosed daily in the country, new risk-mitigation strategies needed to be implemented.

During the first months, every meeting was online and new teleworking solutions were found, such as AnyDesk, a powerful Remote Support Software that enabled students to use the university's supercomputers processing power from any physical location, thus facilitating every structural and thermal test, as well as the Computer Aided Design (CAD) drawings.

In fact, the first two-thousand hours of work were all done at distance, which demonstrates the perseverance of the group. To reward the effort allocated by the students on the project, points and prizes were given to the several teams according to the number of hours spent on a given task, thus creating a healthy competition between different working areas.

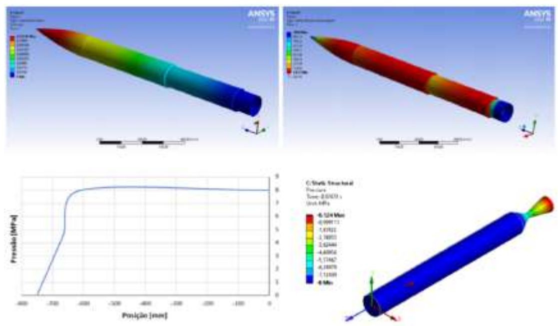

Figure 7. Structural Tests to the Shell of the Rocket

The Management team also organised a raffle draw, sending every raffle book via post to each students' home and collecting the money via a service of instantaneous banking transfers, with the sortition being done online. To keep everyone motivated, prizes such as hotel vouchers were given to the students who could sell the most raffles.

DOI: 10.5821/conference-9788419184405.107

Team building was also a concern, especially among students from two different universities who had never seen each other, as this could lead to feelings of loneliness and alienation from other coworkers, lowering productivity. Therefore, virtual activities were arranged to dynamize the team and make sure everyone felt comfortable and capable of communicating openly, solving difficulties, and collaborating effectively.

When restrictions were lifted and face-to-face work started, it was required to implement new physical distancing measures, as well as increased hygiene (with mandatory masks and the use of disinfectant), and other safeguards to prepare students for a safe return to the university.

5. Lessons Learned

Several lessons from the one-year duration of this project were taken, such as:

Requirements are a responsibility of everyone - Never accept requirements without discussing them. It is dangerous when the requirements come from a so-called intelligent student, because no one questions them. They shall be discussed by everyone in the team. There are no stupid opinions.

Requirement Identification is a fingerprint - To avoid confusion, never change the ID of a requirement. Most of the time, if an ID is changed, the requirements will be confused in other documents. Instead, write “Deleted” in the requirement text.

Holidays are to rest - Never plan a review on holidays. Students need the appropriate schedule to perform a final review, and this takes time. Plan in advance and look at the student’s exams calendar.

Unforeseen events really happen - Account on delays in the delivery of pieces from companies, because most of the time they have their machines in use and university projects are not their priority.

6. Conclusions

Despite the distance that separated the team members, one of the most powerful ways to unite people is to make everyone work with a common goal. The outcome of the learning experience of managing a project within the special context of Fénix is that, with work ethics a logical organisation of the work, thorough coordination, and bespoke motivation, teams can overcome the hardships. Future work to be done comprises the need to move from a totally web-based team to a hands-on team, cooperating from different sites, but building a system that interfaces correctly between each of its subsystems.

COVID-19 has taught us to expect the unexpected. But hopefully, this project proves that even in the worst situations, no student should stand still or fail to chase his/her dream.

Acknowledgements

We would like to thank the Portuguese Space Agency for organising EuRoC (a competition available to every european student), to Dr. Abílio Silva, Dr. Anna Guerman, Dr. Francisco Brójo and Dr. Pedro Gamboa for the availability and full cooperation. We would also like to express our very great appreciation to our sponsors Spaceway, Fundaço, Penedo da Saudade and M. Xavier da Costa, Lda, and our partners Frezite High Performance, Instituto de Soldadura e Qualidade, Comércio Ibérico de Rolamentos Lda - CYR, RatRig, Nova Forma and the Portuguese Army, whose collaboration is essential to the success of the project.

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The Structural Analysis of AlainSat-1: An Earth Observation 3U CubeSat

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Abstract

This paper presents the structural analysis of a remote sensing CubeSat planned for launch in Q4 2022. AlainSat-1 is a collaborative endeavour between the IEEE Geoscience and Remote Sensing Society and the National Space Science and Technology Center at United Arab Emirates University. To ensure that the conceptual design of the satellite satisfies design requirements Quasi-Static Analysis, Modal Analysis and Random Vibration Analysis are conducted using SIEMENS NX. These analyses identify the satellite's fundamental frequencies along with measuring the resulting deformations and stresses it experiences as a response to both the static and dynamic loads exerted by SpaceX's Falcon 9 launch vehicle. Modal Analysis results show that the satellite's lowest fundamental frequency 120.405Hz, complies with standards set by the QB50 Project and both Quasi-Static and Random Vibration analysis indicated that stress values are within safe limits. Issues detected during the various phases of the analyses such as occurrence of unusually high concentrated stresses and discrepancies between different element stress results are highlighted and the subsequent approach towards overcoming them are explained. Future work will involve validating obtained results experimentally using a vibration shaker test equipment on the actual AlainSat-1 structure.

Keywords

3U CubeSat, Finite Element Analysis, Modal Analysis, Structural Analysis, Vibration

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DOI: 10.5821/conference-9788419184405.108

Nomenclature

The nomenclature for symbols used in this paper are as follows:

f_0	*Fundamental frequency*
FS	*Factor of Safety*
G	*Launcher Load Factors*
g	*Gravitational Acceleration (m/s²)*
K_L	*Load Factor*
K_M	*Modelling Factor*
K_{MT}	*Material Factor*
m	*mass*
MS_U	*Margin of Safety*
P_u	*Ultimate Yield Stress*
P	*Stress obtained from analysis*
σ_{Max}	*Maximum Von-Mises Stress*

Acronyms/Abbreviations

All used acronyms and abbreviations in this paper are as follows:

ADCS	*Attitude Determination and Control System*
AL6061	*Aluminum 6061*
FR-4	*Flame Retardant-4*
GRSS	*Geoscience and Remote Sensing Society*
NSSTC	*National Space Science and Technology Center*
PCBs	*Printed Circuit Boards*
PSD	*Power Spectral Density*
RBEs	*Rigid Body Elements*
UAEU	*United Arab Emirates University*

1. Introduction

AlainSat-1 is a collaborative endeavour between the IEEE Geoscience and Remote Sensing Society (GRSS) and the National Space Science and Technology Center (NSSTC) at United Arab Emirates University (UAEU). Its main earth observation payloads are developed by three separate international universities which are Universitat Politechnica De Catalunya (Spain), Telkom University (Indonesia) and Kyutech Institute of Technology (Japan).

The dimensions of this 3U CubeSat are 100mm x 100 mm x 300mm and its maximum mass is limited to 4 kg. It is scheduled for launch on SpaceX's Falcon 9 sometime in Q4 2022 and its sun-synchronous orbit will be at an altitude of 550 km inclined at 97.6 degrees with an estimated orbital period of 95.55 mins. Figure 1 shows the configuration of the satellite (a) with panels and (b) without panels.

(a) (b)

Figure 1. AlainSat-1 (a) with panels and (b) without panels

The satellite must be designed to meet structural requirements which ensures survivability throughout its mission profile. In this paper, Siemens NX is used to carry out the modal, quasi-static and random vibrations analysis of AlainSat-1's main structure and its subsystems. These provide the designers with an indication that design requirements are met prior to undergoing testing to further validate the theoretical results.

The remainder of this paper is organized as follows. Section 2 explains the process of building the meshed model of AlainSat-1. Section 3 details the three structural analyses that are conducted on the meshed model while their respective results and encountered issues during analysis are subsequently discussed in Section 4. Concluding remarks along with planned future work are provided in Section 5.

2. Modelling

AlainSat-1's main structural body consists of frames and ribs made entirely from Aluminum 6061 (AL6061) alloy. Its subsystems contain various combinations of different materials such as Flame Retardant-4 epoxy laminate (FR-4) for printed circuit boards (PCBs), Polycarbonates for any plastic brackets and stainless steel (AISI-304) for bolt connectors or screws.

The mechanical properties of the materials stated in the above paragraph such as AL6061, Polycarbonates and AISI-304 are obtained from the material library available in NX while those for FR-4 are acquired from [1].

2.1. Parts Idealization and Meshing

During parts idealization; all blends; rounded corners and holes less than 2 mm in diameter are removed when possible.

A combination of element types is used to mesh the satellite. The suggested element sizes for the meshes by NX are initially used but further refined to ensure an acceptable percentage of high-quality elements. Table 1 lists sample parts of the model that are meshed and their corresponding element type. Note that bolts, screws, and connector rods are modelled as 1D Rigid Body Elements (RBEs) while complex structures which are assumed to have little influence on structural integrity such as the satellite's Attitude Determination and Control System (ADCS) CubeWheels and camera components are modelled as lumped masses.

Table 1. List of modelled part samples with their respective element types and material

Modelled Parts	Element Type	Material
Side Frames	3D	AL6061
Ribs	3D	AL6061
PCBs	2D	FR-4
Bolts, Screws and Rods	1D (RBE2)	AISI-304
PCB Stack Rods	1D (RBE3)	AL6061
Lumped Masses	0D	-

3. Structural Analysis

To ensure the structure meets its design requirements; Modal Analysis, Quasi-static Analysis and Random Vibrations Analysis are conducted under assumed boundary conditions that best represents the satellite's actual mission environment.

3.1. Modal Analysis

Resonant vibrations can occur between the satellite and its launcher causing amplification of the dynamic loads acting on the satellite. It is thus important to identify these fundamental frequencies and their corresponding mode shapes to enable design decisions that limits the impact of amplification if it occurs.

To simulate satellite conditions in the P-Pod, fixed constraints are applied at each end of the satellite to prevent axial translation while constraints located on the railings only prevent lateral translations [2]. As required in Falcon 9's mechanical testing guide [3], a frequency range of 20-2000Hz is observed for this analysis.

3.2. Quasi-Static Analysis

During launch the satellite experiences dynamic acceleration loads which can be assumed to be static [4]. Via this analysis, designers are able identify the magnitude and location of significant deformations and Von-Mises stresses due to these loads.

Similar constraints to those found in Modal Analysis is used in addition to declaring forces acting on the structure in all main axes. The magnitude of the forces is determined by Eq. 1.

$$F = m \times \mathrm{G} \times \mathrm{g} \times \mathrm{FS} \tag{1}$$

where FS is given by Eq. 2 below:

$$FS = K_M \times K_{MT} \times K_L \tag{2}$$

Both axial and lateral forces are respectively obtained by using the respective maximum load factors during launch in Eq. 1 as stated in [3]. While values for the factors in Eq. 2 are selected by the satellite's structural engineers and shown in Table 2.

Table 2. List of factors used to determine Factor of safety

Factor	Value
$\mathbf{K_M}$	1.25
$\mathbf{K_{MT}}$	1.25
$\mathbf{K_L}$	1.0
$\boldsymbol{FS}$ **(from Eq. 2)**	1.56

As a useful parameter to summarize structural performance [5], the Margin of Safety against yielding failure is defined in Eq. 3.

$$MS_u = \left(\frac{P_u}{P * FS}\right) - 1 \tag{3}$$

Note that based on the above equation, a negative MS_u means that the structure does not have the strength to handle the applied loads.

3.3. Random Vibration Analysis

Using statistical measures of structural responses to the varying exerted loads by the launch vehicle (LV) during the launching phase; the magnitude and location of the resultant deformations and Von-Mises stresses can be determined as in Quasi-Static Analysis.

For this analysis, an enforced motion location from which to apply input vibrations is added to the model. In terms of constraints, only the axis in the direction of the enforced motion is allowed to be free and lastly a value of 2% for both hysteretic and viscous damping is declared [6].

Figure 2 shows an example of the enforced motion location and direction. While Table 3 shows the random vibration test profile or Power Spectral Density (PSD) values expressed in terms of acceleration as a function of frequency in the range of 20-2000 Hz [3].

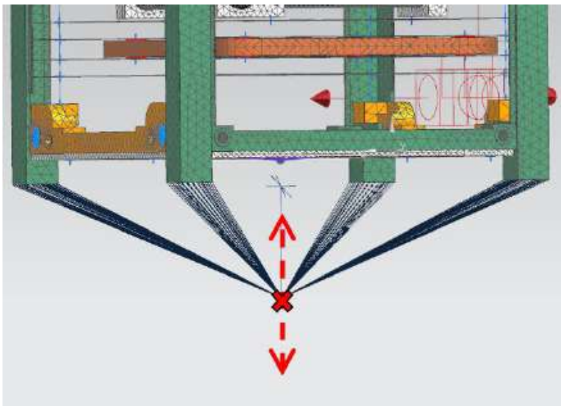


Figure 2. Enforced Motion Location and Direction.

Table 3. Power Spectral Density profile for Random Vibration [3]

Frequency (Hz)	Amplitude (g^2/Hz)
20	0.0088
100	0.0088
300	0.02
700	0.02
800	0.06
925	0.06
2000	0.01288

4. Results and Discussion

Here the meshed model and results of the analyses are presented and discussed. Additionally, issues encountered and how they are dealt with during modelling and analysis are highlighted and explained.

4.1. Modelling Results

Meshing AlainSat-1 resulted in a meshed model containing 345478 elements. Using the Element Quality Check capability in NX, shows that only 152 elements failed to meet the default standards set in the software. Figure 3 shows (a) original structure and (b) meshed model side by side for comparison.

With the current model, analyses running on a system using Windows 10 Enterprise OS, 3.10 GHz Intel Core i9-9900 and 8 GB RAM; required on average around 3-4 hours to be completed; with the longest being Random Vibration Analysis. This result can mainly be attributed to the large number of elements.

Element quality check shows 99.96% of the total number of elements meets the default element quality standards in NX. This should indicate that the analyst has the freedom to be less conservative towards element sizes when meshing. Using a coarser mesh is particularly useful when reducing processing time is desired rather than improved accuracy.

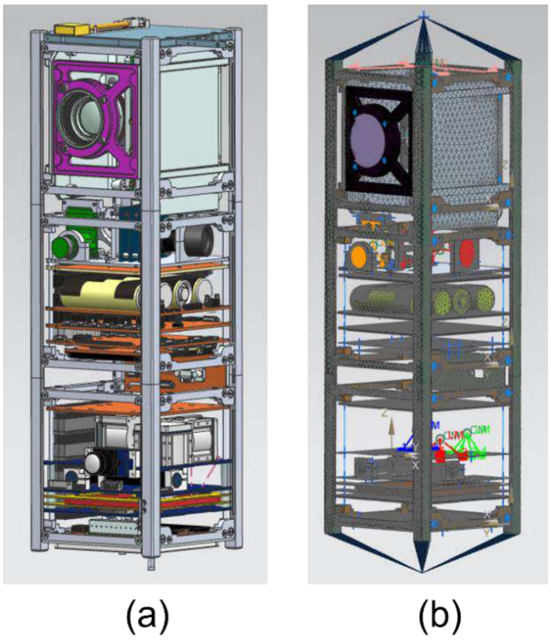


Figure 3. (a) Original Structure and (b) Meshed Model shown next to each other.

4.2. Modal Analysis Results

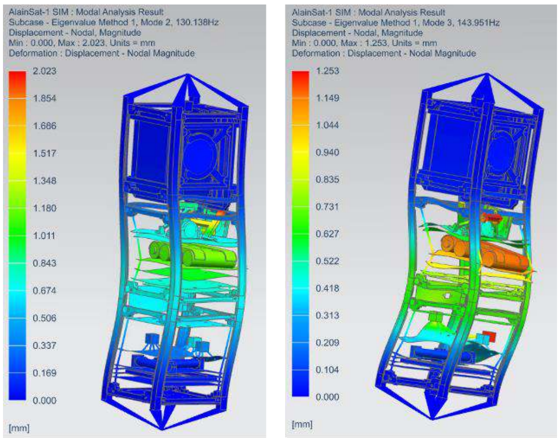
A total of 151 fundamental frequencies, f_0 and their corresponding mode shapes are identified in this analysis. The first 5 detected modes are listed in Table 4 while the sample mode shapes for (a) mode 2 and (b) mode 3 are displayed in Figure 4.

Results in Table 4 shows that the detected fundamental frequencies are greater than the minimum 90Hz [7] required to avoid resonance with the LV.

In this analysis constraints meant to simulate the satellite in a P-POD dispenser should be properly defined as it influences the values of detected fundamental frequencies. In this paper, constraints found in [2] are used. However, it is possible that experience with a similar structural setup can be used to justify a different constraint configuration such as the one found in [8, 9].

Table 4. First 5 detected fundamental frequencies

Mode	f_0 (Hz)
1	120.405
2	130.138
3	143.951
4	151.861
5	179.097



(a) (b)

Figure 4. Sample Mode Shapes for (a) Mode 2 and (b) Mode 3

4.3. Quasi-Static Analysis Results

The following Table 5 shows the maximum stress found in each axis after this specific analysis. These high stresses are mostly found at the edges of the holes of the PCBs where the 2D elements are attached to 1D connector elements. (See Figure 5).

Table 5. Maximum stress found in each axis

Axis	σ_{Max} (MPa)	Material	$\mathrm{MS_U}$
x	23.78	FR-4	7.43
y	87.64	FR-4	2.02
z	116.86	FR-4	1.51

While it is relatively low for this case and does provide a positive margin of safety; it is possible that these values can be unrealistically high due to the RBEs of the connector introducing artificial stiffness [10, 11]. According to accepted practice when dealing with this issue [12], the analyst must decide if stresses occurring in those areas are vital to their analysis or it can outright be ignored. If it is the former, then it is better to model the connector with proper elements rather than replacing it with RBEs. While for the latter, the analyst could group the affected elements using NX and prevent it from being considered by the solver or ignore any resulting stress values associated to areas where RBEs are found.

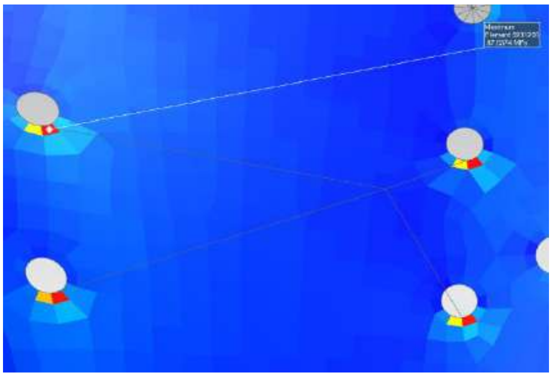


Figure 5. High stresses (red) concentrated at the points where 1D elements connect to 2D elements.

Also there exists some discrepancy between results for elemental stress and those for elemental nodal stress. Ideally both results should be similar but any discrepancies could be an indicator to the analyst that a finer mesh is required at the affected area [13, 14]. Potentially this can increase computational cost and therefore the analyst will need to decide if elemental stress results is sufficient for their analysis or if additional accuracy from a finer mesh justifies the added cost to processing time.

4.4. Random Vibrations Analysis Results

For Random Vibration Analysis, the 3 highest stress values and their corresponding locations can be found in Table 6. The positive values of Margin of Safety indicates that AlainSat-1's main structure along with its subsystems have the capability to withstand the dynamic loads exerted by the LV.

Initial results from this analysis resulted in very high and unrealistic stress values throughout the structure. It is unlike the phenomenon that occurred for Quasi-Static analysis where the high stresses could be attributed to utilizing RBEs to model connections. Instead, these are due to not defining a damping effect on the model resulting in undamped amplified loads causing very high stress values on the structure. Introducing a factor of 2% for both hysteretic and viscous damping is enough to bring the stress values to within expected results. The software can determine damping values from the meshed model but will require damping elements to be defined first prior to running the analysis.

DOI: 10.5821/conference-9788419184405.108

Table 6. Random Vibration Analysis Maximum Stress Values and Location

No	σ_{Max} (MPa)	Location	Material	MS_U
1	36.56	ADCS Board	FR-4	3.84
2	26.43	Battery Board	FR-4	5.69
3	14.29	Side Frames	AL6061	11.38

5. Conclusions

5.1. Provisional Conclusion

After building the building the meshed model of AlainSat-1, a total of 3 analyses are conducted: Modal, Quasi-Static and Random Vibrations. The general setup of each analysis is explained, and results shows that structurally the satellite and its subsystems is capable to handle the applied dynamic loads. Additionally, this paper highlighted issues specific to each activity and recommend a course of action that might best overcome it.

5.2. Future Works

The next step in this process is to validate the simulation results by conducting experimental tests on the actual AlainSat-1 structure using a vibration shaker. Comparing these results together will help to substantiate any assumptions made and provides a basis to refine constraints and meshes. In addition to structural analysis, thermal analysis will also be conducted on the satellite to ensure the structure and its subsystems are able to operate in extreme temperature environments.

Acknowledgements

This research was conducted and supervised utilizing resources from the National Space Science and Technology Centre, UAEU.

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Developing low-cost, reusable solar observation platforms to advance sustainable heliophysics research

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Abstract
The objective of this paper is to describe a methodology for cheaper solar observation, which would make it available to research institutions of all sizes. This is done through the use of low cost, reusable components, innovative manufacturing and by using high altitude balloons to transport the payload. The aims of the project are to produce clear, sharp images of the solar chromosphere. This proves that it is possible to produce research-grade images without the need for expensive alternatives such as adaptive optics on ground telescopes or satellites. As well as discussing the technical points of the project, the paper will discuss the technical hurdles encountered before this design iteration and how these have been overcome. The other aims of the project are to facilitate students introduction to the space industry and allow them to practice their skills in a practical manner. This is very different from the work done theoretically in the classroom and exposes students to the challenges of working in industrial teams.

Keywords
Heliophysics, Reusable, Low-Cost

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Acronyms/Abbreviations

CME	Coronal Mass Ejection
FEA	Finite Element Analysis
HASP	High Altitude Student Platform
ROS	Robot Operating System
RPi	Raspberry Pi
SBC	Single Board Computers
SSD	Solid State Disk
ZPB	Zero Pressure Balloons

1. Introduction

Solar observation is a important method of research in heliophysics, which allows for the observation and modelling of solar behaviour and how that impacts objects throughout the heliosphere [1]. The models developed from our sun allow us to make predictions about the behaviour of other stars and what might exist in their own solar system [2].

Since the earth is located within the heliosphere and is relatively close to the sun, earth is exposed to a variety of solar activity, which keeps our planet warm, whilst bombarding us with charged particles, known as solar wind. Though mostly harmless, as we are shielded by the earths magnetosphere and atmosphere, solar wind can become dangerous when emitted as a Coronal Mass Ejections (CME). Which upon contact with earth can induce large electric currents though magnetic coupling. Before the electrification of the planet this was not a significant issue and large storms have hit before [3]. Now though, a repeat CME strike could cause incalculable damage to modern communications and navigation systems [4].

Cheaper solar observation methodologies would lower the cost of failure and encourage innovation in the field, potentially increasing the number of novel observation methods proposed and modernising the equipment used through shorter development cycles. This would open up primary data collection to small and medium sized research institutions, or hobbyists, who would then be able to capture sharp and informative images of the solar chromosphere or corona for research purposes. The Solar observation platform discussed in this paper, SunbYte, is intended to act as a proof of concept for this approach to research. This is why SunbYte is capturing in Hα, a region of the solar spectrum visible though earths atmosphere, in order to compare high altitude observation with a ground based approach.

2. Requirements

In order to reach the reusable targets of the project, the various subsystems of SunbYte must be robust enough to survive multiple high altitude flights weathering harsh, variable, conditions whilst minimising the amount of repair work needed.

The environmental conditions at 35km, the highest point the Zero Pressure Balloon will reach, experience a pressure minimum of 5mb [5] and a temperature of -40 ^oC / 233 K. Because of the temperature inversion caused by ozone heating, the harshest temperature conditions are experienced when transiting though the atmosphere, with minimums of -71 ^oC / 221 K. These conditions were calculated for September launch, above 60 ^oN, and will vary by time of year and position [6]. The environment within the stratosphere has not changed significantly from 1980, with variation of up to 1 K depending upon its height [7]. Changes of 1 K, are not significant enough to impact on the platforms design, permitting the values to be used as reference. At 35 km, SunbYte would rest above the majority of the atmosphere and ozone layer [8], allowing for clear astronomical observation, free of large atmospheric distortion or absorbance. This position exposes the external surfaces of SunbYte to unobstructed Infrared and UV light, leading to heating on metallic surfaces and potential damage to optics not shielded with UV blocks.

Unlike a balloon launch, a rocket subjects payloads to large axial and lateral accelerations exceeding 7.5 and 2 g respectively as well as high frequency shock, vibrations and acoustic profiles [9]. The noise alone can be loud enough to cause damage to poorly designed or unlucky payloads. This means that the threshold for a successful design and launch is significantly higher, pushing costs up even before the launch itself. The physical requirements for a balloon flight are lower, as the largest acceleration shocks occur when the parachute deploys and when the gondola, the part under the balloon where experiments are typically attached, hits the ground. The deceleration experienced on impact can be up to 35 g. This means that balloon flights, while still technically challenging to design and build for, have fewer challenges that those designing rocket lifted payloads. Fewer challenges can encourage smaller teams to produce novel or sensitive designs, producing more affordable solar observation. Though balloons are more environmentally friendly than rockets producing fewer emissions, they may not be more sustainable. ZPB's use helium for lift, an expensive non-renewable natural resource [10], and the balloon envelopes are not reused between flights. Meaning though an experiment may be reusable, part of the process of capturing data might is not.

3. Structural and Thermal

In order to withstand the instantaneous impact forces and velocity changes during ascent and decent, the mounting and base plates were constructed out of steel. Plate thickness was determined though Finite Element Analysis (FEA), instantaneous forces were applied to the mounting points to test fracture and torsional resistance. Based on these results and a factor of safety of 2, a plate thickness of 3 mm was chosen.

Due to the loading mechanisms experienced by SunbYte, which are predominantly axial, the primary failure mode is buckling. Due to the bracing provided by the battery box, the thickness and material of the side planes can be reduced to 3 mm aluminium. The telescope is placed between the plates, mounted on a machined steel crossbar to prevent bucking that would damage the telescope pivot, and provide extra support between the plates.

The other, non structural elements of SunbYte are comprised of bent and mounted aluminium plates which act as an environmental shield. These structures should not be airtight, to avoid becoming pressurised containers, and consequently expose internal components to external atmospheric conditions. This could potentially reduce the temperature of critical electronic components below their operating limits, preventing them from working as expected. In order to prevent this from happening, heaters will be added to keep the critical electronics and batteries warm. Due to the high surface temperatures of these heaters when turned on, they cannot be placed directly onto the electronics and will instead be coupled indirectly to heatsinks. Lastly coupling the thermal mass of the electronics together captures wasted heat, allowing operating electronics to help maintain a steady temperature.

Due to the low external pressure environment, convective heat transfer is significantly reduced internally and externally. This presents problems when considering cooling electronics and batteries. One solution would be to connect the internal thermal mass to an external radiator, placed at the back to prevent contact with direct sunlight. This method would require heaters to function continuously in order to prevent external exposure from damaging the electronics. To limit the complexity of the thermal system, a smaller external radiator was chosen to provide the internals with adequate cooling if required. This reduces the power and heaters required to maintain an internal temperature allowing for greater thermal control. For this method to work effectively, the internal components of SunbYte will be insulated from its external walls through the use of air gaps and thermoplastics. This helps isolate from both extreme cold, but also heat, as in operation certain parts of SunbYte are permanently aligned with the sun. The affects of this external heating could be reduced by painting the external surfaces with white on the front, to prevent absorption and black on the back to promote emission.

4. Electrical

In order to reduce the cost and development time of SunbYte, the decision was made to use off the shelf components including Single Board Computers (SBC), like the Raspberry Pi (RPi), and DC converters. These components often require previous expertise to design and can be costly to manufacture in small quantities; by using this method SunbYte can benefit from external design experience and the economies of scale felt by those manufacturers. In future flights, without a preestablished communications link or though novel design, where it is necessary to have radio transceivers onboard, the use of premade and certified modules would be the most cost effective method of gaining regulatory and flight approval.

The electronics subsystem is further divided into separate boards stacked on top of each other to reduce heating requirements. Each board contains a separable subsystem, power supply and management, thermal control, motor control and processing. The processing capacities are maintained throughout the flight using a separate, smaller, reserve $LiFePO_4$ battery. This allows communications and remote activation of the payload to commence during the flight to conserve power. The primary $LiFePO_4$ battery can therefore be connected and disconnected remotely, and once connected provides power to all electronics sub-systems and charges the reserve battery. Switching can occur at any time during the flight, and will likely be needed before tracking operations commence to maintain a

DOI: 10.5821/conference-9788419184405.109

stable internal temperature.

The RPis do not switch high current loads directly, instead charging and discharging MOSFETTs though gate drivers to avoid potentially damaging current spikes. The same is true for the stepper motors, which use dual H bridges to control and record motor positions, whilst coupled to encoders to ensure there is no slippage.

5. Software

In order to reduce development time, SunbYte will use open source software within it's codebase. This drastically reduces development time and allows the project to benefit from software expertise that it would be unable to find otherwise. The solar tracking and observation system is developed on top of OpenCV. Using a low resolution primary camera to align the main telescope with the solar plane, before capturing and saving high resolution images onto a Solid State Disk (SSD). Real time operations are important prompting the use of either, Robot Operating System (ROS) or Real time Scheduling on Linux.

In order to take advantage of HEMERA's existing communications stack, which is RF, Ethernet, IP between the gondola and ground station, TCP packets were chosen to ensure delivery. Due to the bandwidth limits imposed, down linking high resolution images would be difficult requiring them to be stored locally for collection. Since communications between SunbYte and the ground is limited, operations should be semi-autonomous once main power is connected. Though in order to assess payload health, all sensor data should be down linked, and the option of manual operator control should be available.

The computers on board SunbYte the RPi are not incredibly powerful devices, so in order to perform all the necessary operations, they will be run in parallel. In the same way the electronics onboard is divided by subsystem, so are the RPis. With each one devoted to a series of tasks, depending on the computing power required. Communications will be performed over I2C links, with each task specific communicating with a coordinator which reports to ground.

A modular software design reduces future redesign time, if the mission changes scope and increases code reusablity by reducing the size of each tasks code base. This design methodology would benefit the separation of tasks, as each RPi would be only running necessary operations; reducing the chance of software crashes or bugs. This would be achieved though a kernel like approach, where core operations are always running, but specific modules for large tasks can be loaded, or compiled in.

6. Optical

The telescope that was chosen for this project is William Optics Zenithstar 61 II APO Refractor OTA. It is a refractor telescope, meaning the front lens is used to form an image of an observed object. The perfect refractors for solar observing range in size between 60-80 mm, with this aperture being 71 mm. In order to reduce the chance of oversaturating or overexposing images and obtaining scientifically unusable data, a telescope with a short focal length 420 mm was chosen.

The refractor telescope is fast, having a low focal ratio of f/5.9. This allows lots of light into the telescope, allowing for faster shutter speeds. Faster shutter speeds mean that CMOS sensors with line scanning shutters can be used. The small aperture helps to reduce telescope weight, with it weighting in at 3 kg, 10% of the projects weight budget.

A monochrome, ZWO ASI183MM USB 3.0 Mono 4/3" CMOS Deep Sky Imaging camera was chosen as the primary scientific instrument. Its' very high quantum efficiency of 84%, alongside the low read noise of 1.6 e^{-} and high resolution will allow us to image the Sun in detail. Most importantly the fast, high quality CMOS sensor complements the refractor telescope design, producing short exposure images of high quality. The camera is also very compact and lightweight (0.80 kg), further minimising weight.

Lastly, to allow for ground testing and calibration SunbYte will be imaging in the $H-\alpha$ part of the spectrum (656.3 nm). At this wavelength it is possible to observe a lot of solar activity and this emission line allows for observation of different features such as granulation of the chromosphere, prominences and flares. The chosen eyepiece is a Daystar QUARK Hydrogen Alpha Solar Eyepiece with an integrated filter to simplify the build process.

7. Costs

There are various levels of costs to projects such as SunbYte, there is material cost, cost of equipment used in design and manufacture and cost of labour. Since SunbYte is being manufactured with volunteer student help, and with existing tools within university labs, the initial costing will be one of materials only.

Table 1: A summary of the various materials costs, per sub-team, over SunbYte 4.

Year Ending	2020	2021	2022	Total
Structures	£800	£1000	£300	£2000
Optical	£0	£0	£1644	£1644
Electronics	£600	£430	£130	£1180
Software	£0	£0	£0	£0
Total	£1400	£1430	£1994	£4824

It should be noted that though no software was purchase by us, it was provided for free though the university. Due to the closed nature of the licensing it would be difficult to cost, but discounts are available to research institutions and hobbyists. Table 1 places the cost of replicating SunbYte at £4824 from parts at their time of purchase. Had all these parts been purchased at once, rather than over 3 years, then accounting for inflation, the figure would be slightly higher. At the time of writing, the current highest estimate of parts costs is £$5,500$, within the budget of many hobbyists. Unlike hobbyist groups, or university students who are volunteering, staff at research institutions are paid workers, and thus the total project budget would be significantly higher. To date, over the last three years, students have recorded the approximate number of hours spent working on the project. Their reported working times are summarised below, broken down by year and position.

Year Ending	2020	2021	2022	Total
Leaders	112	173	220	505
Members	47	56	101	204

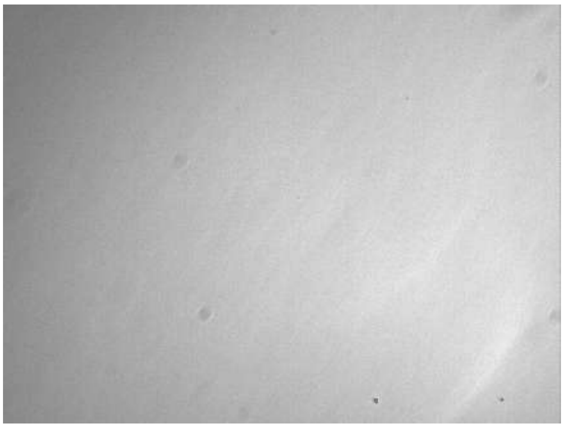
Table 2: The approximate number of working hours, per student, over the year broken down by position in the project.

The values for 2022 are still projections based on the number of working hours to date, extrapolated to the end of the academic year. They may increase as deadlines approach. Using the data provided in Table 2, and using the average team size over all 3 years, produces around 5080 labour hours. At national living wage produces a total cost of £$48,260$ for labour and a total project cost of £$53,760$, well within the three year budget of a small research institution.

8. Discussion

This iteration of the payload is the fourth, there have been many designs and challenges throughout the process. The previous three iterations have failed to capture viable images of the solar plane. The best image captured so far, on Sunbyte 3, is in Figure 1. Each failure has been different, and all have been small oversights in design or preparation. The first prototype of the experiment was supported by the REXUS/BEXUS programme and was launched from the Esrange Space Center in 2017. Subsequent re-flights were made in 2018 and 2019 with NASA, as part of the High Altitude Student Platform (HASP) program. The design has been significantly altered throughout the redesign process over the last three years, in the hope that any oversights have been fixed. SunbYte IV is set to launch in September 2022, from the Esrange Space Center in Sweden.

Figure 1: Image of the solar surface, captured by SunbYte 3.



The next big challenge after the successful capture of imagery, aside from expanding the scope of the project to capture alternative wavelengths, is to the limited number of open balloon launches each year. It is certainly possible, with the correct level of funding to buy and perform your own launches, especially as an institution with other payloads being flown. This would allow for optimised flight plans and altitudes for solar observation and would mean that observation experiments, especially novel designs, would not have to compete for space on the more general scientific flights performed by NASA or ESA. Using dedicated launches would allow for further reusable balloon development or research into recycling used helium.

SunbYte's other purpose is to introduce passionate students to the space industry and give them an experience of what higher-calibre space missions feel like. Our team is composed of mainly undergraduate students from the departments of Engineering, and Physics and Astronomy and is a sister project to a variety of other experiments such as SunRide and SunSat, who are developing rockets and cubesats.

9. Conclusions

Due to advancements made in manufacturing, low cost electronic components and open source software, it is certainly possible to manufacture a high altitude solar telescope. Though careful budgeting, manufacturing one is even within the grasp of hobbyists and small research institutions. These groups would likely have to launch with the help of a space agency, a private launch would only be within the reach of well funded groups. The next step, once solar images have been captured and their quality established, is to introduce a filter wheel into the design. This would allow for multi wavelength viewing of the Sun, further increasing the versatility of the system and allowing it to capture bandwidths which are not visible though the atmosphere.

Acknowledgements

A sincere thank you to the teams of students who have worked on design and manufacturing over the last two years: Ahmed Mahmoud Elhabushy, Ahmed Mosaad Abdalla, Aikaterini Mitsiou, Akhil Jayewardene, Ashraf Zahidi, Brett Pasquill, Chun Iao Tai, Edward Hutchins, Esperanza Pinazo Real, Faris Hamdy, Igor Panfil, Ioannis Papaioannou, Jakub Jasik, James Horn, James Mottershead, Joel Phillips, Leonardo Azzopardi, Lewis Spurgeon, Luke Dolman, Mabel Ubong, Maciej Ziolkowski, Maddy-May Sterland, Madhur Chandak, Paddy Smith, Palash Surana, Raquel Hernandez, Roch Dmitri Rahir, Saloni Hajare, Samuel Wege, Shamoil Khomosi, Swaraj Nikam, Trisha Digan, Vladimir Babenko, Zhenting Kong. Thanks to Lucy Flint, George Ashton and Ellie Ingram who helped proof this paper.

A special thanks to the University Staff who have patiently validated designs, approved risk assessments and proved general support to the authors as well as the wider team over the years: Viktor Fedun, Pete Mylon, Ryan Jones, Laura Mason, Jonathan Davidson and the ACSE Support Staff.

Many thanks to our charity sponsor, John Partridge of Sonardyne International, for a generous contribution to the project.

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LEOniDAS Drag Sail Experiment on the 2021 ESA Fly Your Thesis! Parabolic Flight Campaign

Zaria Serfontein[1], Lt. Marco Rigamonti[2], Edouard Demers[1], Gonzalo Temprano[1], Jennifer Kingston[1]

Abstract

Space engineering students and academics from Cranfield University have developed two space debris mitigation drag sail concepts and three sails are currently in orbit. The sails enable a reduced time to atmospheric re-entry by increasing the natural aerodynamic drag forces acting on the host satellite. Intended to be used on small, low Earth orbit satellites, these sails provide a low-cost solution to achieving compliance with the IADC target of removal from orbit within 25 years of end-of-mission.

The LEOniDAS team, comprising one PhD and three MSc students, submitted a proposal to the ESA Fly Your Thesis! parabolic flight campaign to perform microgravity deployment testing on a more scalable and adaptable hybrid design. The project aimed to qualify the new design, provide a better understanding of deployment behaviour in microgravity and allow for a deeper understanding of the effect of deployment on the host satellite. Participation in the programme provided significant educational benefits to the students involved, resulting in three Masters theses and a major input to a PhD thesis, as well as publications and outreach activities.

The experiment was presented by the students at the ESA Academy Gravity-Related Training week in January 2021. There followed extensive design, prototyping and assembly work, with regular review and input from ESA and Novespace, culminating in the two-week parabolic flight campaign in October 2021. The planned deployment experiments were successfully completed across all three flights, with the experimenters accumulating a total of more than 30 minutes of microgravity. Data on dynamics of the sail deployments was recorded via high-speed video cameras, accelerometers and torque sensors. This paper will highlight the key scientific and educational achievements of the project, and summarise the lessons learned for the benefit of future participants in this exceptional student opportunity.

Keywords

Space Debris, Deorbit Sail, Microgravity Testing

1. Introduction

The European Space Agency (ESA) released the 2021 Annual Space Environment Report [1] with the following analogy:

"Imagine driving down a road which has more broken cars, bikes and vans lining the street than functioning vehicles. This is the scene our satellites face in Earth orbit."

Space debris poses a problem for all current and future space missions by increasing the risk of involuntary collisions with operational satellites. If no action is taken to stabilise or decrease the debris population, the situation in low Earth orbit (LEO) could deteriorate well beyond the boundary where remediation is achievable with current resources [2].

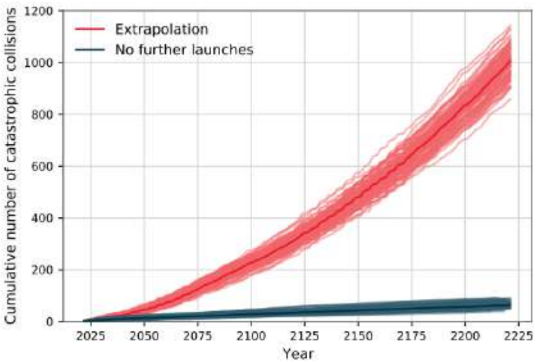

Figure 1: Long-term evolution of cumulative collisions in LEO in simulated scenarios [1]

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[2] Italian Air Force – Flight Test Wing, Italy

The trend of the current evolving use of orbits and launch traffic, coupled with fragmentation of space objects and limited post-mission disposal success rate, could lead to a cascade of collisions over the next centuries, as shown in . This overcrowding of LEO, as seen in Figure 2, already has significant immediate consequences, most clearly seen in the increased frequency of close approaches.

Space traffic is changing, fuelled by the deployment of large constellations of satellites and the miniaturisation of space systems. Constellations in LEO will greatly impact and shape the near-Earth space environment over the next decade. Mega-constellations are occupying new, lower orbits between 400 km and 600 km. This is further exacerbated by the deployment of small constellations in sun-synchronous orbits at similar altitudes, often utilising nano or small satellites.

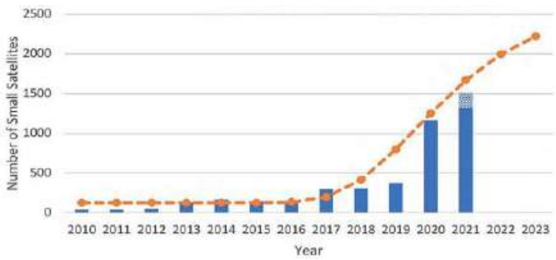

Figure 2: Trend in the number of small satellites launched (2010-2021) [3]

1.1. Cranfield University Drag Sails

Designing a satellite to comply with the regulations often increases the cost, mass and complexity of a mission. There are a number of approaches to removing a satellite from orbit at end-of-life (EOL), including active deorbit using propulsion, but amongst deorbit technologies, drag sails have emerged as a practical, low-cost solution to allow small satellites to comply with regulations and operate sustainably by accelerating the deorbit process.

A Drag Augmentation System (DAS) is employed at the satellite's EOL through the deployment of one or more sails, enlarging the effective area of the satellite, increasing its rate of orbital decay and allowing it to re-enter and burn up in the Earth's atmosphere.

Cranfield University has developed a family of drag sails for deorbiting small LEO satellites at end-of-mission [4]. The target market for these passive deorbit devices is microsatellites and minisatellites (10-500 kg) in LEO, particularly without on-board propulsion, but they could also be included as a back-up for larger satellites.

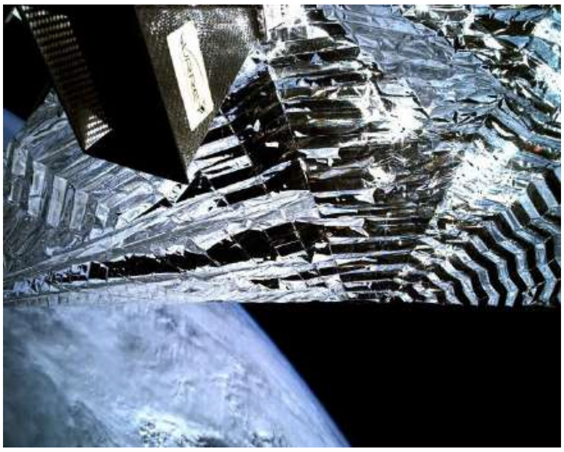

Figure 3: Image captured by TechDemoSat-1 post sail deployment (image courtesy of SSTL)

Cranfield has developed and qualified two systems: Icarus and De-Orbit Mechanism (DOM). They are low-mass, simple designs, intended to have a minimal impact on the host satellite. Deployment of the sails does not require a motor and is facilitated by the stored strain energy in copper beryllium booms, released by pyroelectric cord cutters activated by a brief current pulse. The size of the sail required depends on the mass of the satellite, its configuration and its orbital altitude. Three DAS are currently in orbit and two Icarus models have already successfully deployed their sails (see Figure 3). General DOM requirements are:

- ***Low-cost:*** essential for small satellite operators and important for a redundant solution for larger satellites.
- ***Simplicity:*** in terms of design of the device, integration to the host satellite and interfaces to the host satellite.
- ***Safety:*** no premature deployment or damage to the host satellite, and no additional debris production.
- ***Reliability:*** deployment success rate greater than 90%.
- ***Low-mass:*** should not exceed the mass of propellant required to deorbit.
- ***Scalability:*** should be compatible with a wide range of satellite platforms.
- ***Testability:*** in a 1 g environment.

1.2. ESA Fly Your Thesis! Programme

The ESA Education Office aims to motivate young students towards STEM subjects,

DOI: 10.5821/conference-9788419184405.110

ensuring a qualified workforce for the future European space sector. Amongst all the initiatives, Fly Your Thesis! allows student teams from ESA member states to design, build and test experiments in a simulated microgravity environment. Supported by technical staff from ESA and Novespace, students perform their experiments onboard the A310 ZERO-G aircraft through a series of three parabolic flights for a total of approximately 30 minutes of microgravity.

Figure 4: LEONiDAS team mission patch (left) and mascot Leo (right)

The Low Earth Orbit negligible impact Drag Augmentation Systems (LEONiDAS) team from Cranfield University aimed to qualify a new sail design (the hybrid design) for deployment in microgravity. This experiment lends credibility to the sails, further accelerating their maturation and commercialisation.

The qualification process requires reliably reproducible tests in an accurate analogue environment. Ground testing of larger sails is not possible and would be affected by external disturbance forces, which could yield significantly different results to actual in-orbit behaviour. Additionally, host satellites need to be passivated at EOL and it can be difficult to assess the performance of the sail from actual missions. The flights have sufficient deployment opportunities to qualify new design variables and observe the effects of deployment in a similar environment to in-orbit conditions.

The ESA Academy Gravity-Related Training week in January 2021 covered a range of topics to improve the teams' technical and soft skills. The project had continuous support from ESA, Novespace, and a European Low Gravity Research Association mentor.

2. Experiment Overview

Currently, when the design is tested in 1 g conditions in the laboratory, several adverse effects, such as blossoming[1], occur during the deployment process. By observing the deployment in microgravity, the team could assess whether these adverse effects were due to deployment in 1 g conditions or the limits of the design. Primary objectives:

- Qualify the improved hybrid drag sail for deployment in microgravity
- Compare deployment dynamics in microgravity with deployment in 1 g

Secondary objectives:

- Study and quantify the effects of sail deployment on the host satellite

The hybrid design was based on features of the DOM design, previously flown on-board the European Students Earth Orbiter, and it was assumed that the qualification process would be similar. Since the application of the technology is expected to be the same for the new hybrid design, the team used the same criteria to qualify the design; reliability of more than 90% across a minimum of 22 deployments.

2.1. Experiment Description and Set-Up

To achieve the project objectives, three sail configurations were fabricated (see Figure 5):

- ***Sail1 Control module*** – one sail quadrant of the original DOM module
- ***Sail2 Limiting module*** – one sail quadrant of the original DOM module with 0.75 m booms
- ***Sail3 Hybrid module*** – two DOM modules (containing only one boom each), with a sail cartridge containing a 1.5 m long rectangular sail

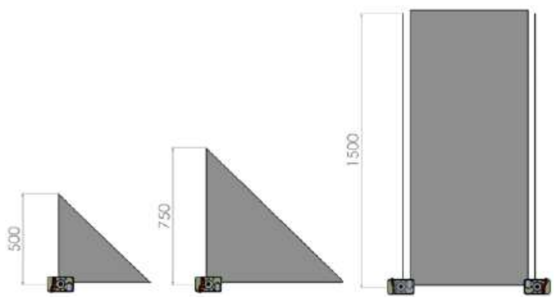

Figure 5: In order of appearance, Sail1, Sail2 and Sail3 (dimensions in mm)

[1] During deployment, the boom starts to uncoil within the deployment structure, causing the mechanism to jam (primarily caused by friction between layers and difficult to predict/simulate)

The length of the Sail2 booms (0.75 m) represent the limits of what is possible to test in 1 g conditions. Successful deployment in 1g is possible, but deployment is not reliable. By comparing deployment in microgravity to ground-based deployment, the team will be able to learn more about the deployment dynamics. The sail modules were attached to an experiment rack and the entire experiment was monitored by a series of sensors (see Figure 6).

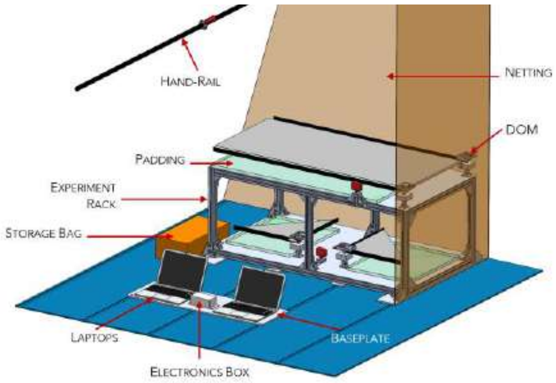

Figure 6: Overall experiment set-up with all the sail modules deployed

Although all the modules were designed to house copper beryllium booms, manufacturing difficulties restricted the team to 1 m long booms. For the hybrid module, the copper beryllium booms were substituted with tape measures. These have a higher modulus of elasticity, resulting in a stiffer extended configuration, but copper beryllium has a significantly higher tensile yield strength, allowing the booms to 'bounce-back' after a snap-through fail, hence why copper beryllium is preferred in the final design.

2.1.1. Modified De-Orbit Mechanism (DOM)

The current DOM sail is a self-contained unit (Figure 7). In the stowed configuration, booms are co-reeled with sail quadrants around a central spool, deforming their profile and adding spring energy to the system. The booms are held in position by Kevlar cords and deployment is activated by two CYPRES™ cord cutters.

For the experiment, a ratchet system was implemented to replace the cord cutters, to ensure the sails would not unfurl without being commanded to do so and to improve the ease of resetting the experiment and restowing the sails between parabolas. The system was actuated by ARM and FIRE commands; a signal activates a linear solenoid which releases the arm of the ratchet system restraining the spool from turning. With the spool free to rotate (~20 rev/sec), the stored strain energy in the booms is released and the sail, attached at the boom tip, is deployed to its final configuration.

Figure 7: De-Orbit Mechanism (DOM) Flight Model in Cleanroom at Cranfield University

A vertical hollow tube was screwed to the base of the DOM and fixed by a clamp on the experiment rack (see Figure 8). This mounting setup was chosen to enhance the torque measurement, limit the sensor noise, maximise the measured strain and withstand the emergency landing conditions.

2.1.2. Hybrid Design

The hybrid design was developed to improve the scalability and adaptability of the drag sails, allowing the devices to be tailored to a wider range of satellite configurations. By separating the boom and sail modules, the new modular design is no longer restricted to the size of the host satellite and the sail doesn't overlap with the host satellite body. On shared opportunity launches, smaller satellites need to comply with the orbital altitude requirements of the primary payload, which are subject to change before launch. If the secondary payloads no longer meet debris guidelines, a drag sail could be added. Given the versatility of the new hybrid design, the sail could be rapidly procured and fitted to an already mature satellite design.

2.1.3. Experiment Sensors

For the primary objectives, the team required visual evidence of successful deployments. Since the deployment takes place over a fraction of a second, high-speed cameras (240 fps) were obtained. Initially, a conventional smartphone was employed pre-flight, whereas several cost-effective GoPro HERO10 cameras were purchased for the flight.

For the secondary objective, torque was identified as the primary force related to sail deployment and was measured to quantify the

DOI: 10.5821/conference-9788419184405.110

impact of deployment on the host satellite. Two torque strain gauges in a Wheatstone bridge configuration (see Figure 8) were chosen due to their high accuracy and precision, and low intrinsic noise (±0.0006 Nm), and were coupled with a load cell amplifier. The experiment configuration was insensitive to external vibrations, increasing confidence in the results.

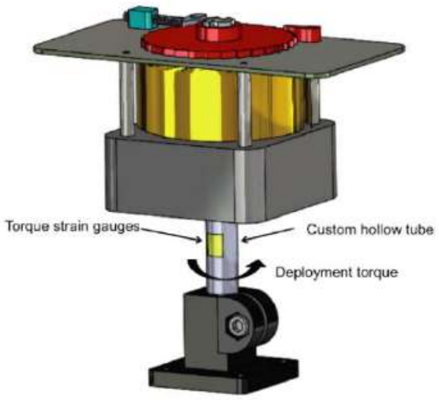

Figure 8: Strain gauge measurement setup

For further work, the vibration responses were measured in hopes that the results are repeatable and identifiable. A low-cost, high-precision accelerometer was implemented and equipped with a 14-bit analog-digital converter, offering a high sensitivity in the operational range required.

2.1.4. Supporting Structures

Ensuring the safety of the experiment, the supporting experiment rack was able to withstand emergency landing loads (up to +9 g).

3. Methodology

During the stowing process, the booms are rolled around the central spool of the DOM. In cases when friction levels increase dramatically (due to incorrect stowing processes or excessive deployment forces on the sail) the booms blossom or jam. Preliminary testing led to the inclusion of 8 PTFE rollers in a circular pattern around the central spool to reduce blossoming. Additionally, the rollers constrain the booms to deploy in the planned direction and ensure a smooth deployment.

The project allowed for the testing of the hybrid sail far exceeding the size of the previous DOM system. A 1.5 m long rectangular sail was rolled around a central bar which connected two mirrored DOM modules. Tests were performed to improve the interface between the DOM modules and the sail cartridge by reducing the friction of the system.

Preliminary testing revealed friction levels between the central spool and the housing were initially the main factor in failed deployments. To avoid this, PTFE bushings were tightly inserted in the top and base plates of the system to avoid lateral oscillation of the spool during the deployment, which has been shown to negatively impact deployment.

3.1. Parabolic Flight Experimental Procedure

Each parabolic flight had 6 series of parabolas, with 5 parabolas per series. At the start of a parabola, the aircraft would pitch up, shifting the vertical g-force from cruise conditions (1 g) to hypergravity (1.7 g) for 20 seconds. The same conditions were mirrored during the recovery phase. The experiments were performed during the microgravity phase (~22 seconds) between the two hypergravity phases. One sail was deployed per parabola. After deployment, the team had a maximum of 100 seconds to reset the experiment. Restowing was optimised to ensure the team would always be able to reset the experiment within the allocated time.

4. Results and Discussion

The primary objective of qualifying the improved hybrid drag sail for deployment in microgravity was achieved. Out of 36 deployments, Sail3 successfully deployed 34 times, exceeding the 90% reliability requirement. Additionally, when comparing deployment dynamics in microgravity with 1 g, it was clear that most blossoming and failed deployments were due to testing in 1 g and not the limits of the design itself. Sail2 deployments were less convincing and unreliable. Results showed the co-reeled sail and boom quadrants can only support a boom length of up to 0.75 m in the current configuration before the friction between the folded sail layers interferes with deployment.

The team was also able to achieve the secondary objective of studying and quantifying the effects of sail deployment on the host satellite. During the flights, the team had to resort to a manual, redundant deployment system. The dynamic response was therefore different to pre-flight measurements and it was difficult to detect the sinusoidal pattern and identify the maximum deployment torque. Nevertheless, when the spike in data due to the manual deployment was filtered out, the

DOI: 10.5821/conference-9788419184405.110

following spike in torque (see Figure 9) corresponded to the maximum response of the sail deployment. While testing the Sail1 control module in the laboratory, the maximum observed torque was approximately 0.3 Nm. During the flight, the maximum deployment torque of Sail2 peaked at 0.45 Nm.

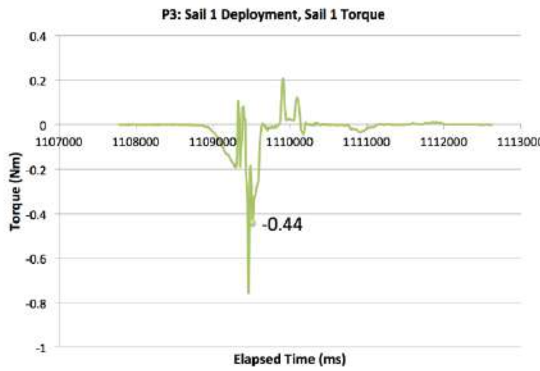

Figure 9: Deployment torque profile of Sail2

Since deployment of the hybrid sail takes place over several seconds, the sinusoidal pattern is clearly distinguishable. Every cycle corresponds to the sail being coiled around the central spool. The torque response differs from the other configurations, primarily due to the use of tape measures instead of copper beryllium booms. Figure 10 shows the torques of each hybrid DOM module; the difference in torque values is likely due to the manual manipulations during assembly.

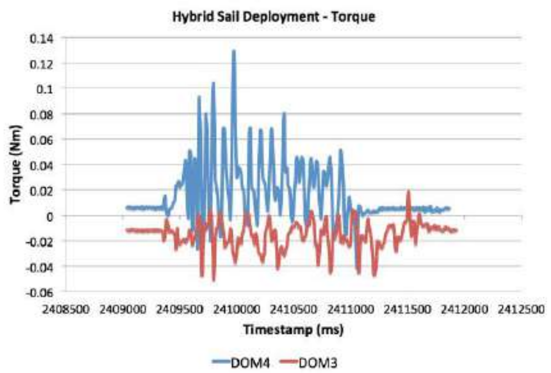

Figure 10: Deployment torque profile of Sail3

Finally, the team carried out a very successful outreach campaign, challenging over 850 Key Stage 2 primary school students, between the ages of 7 and 12, to describe how they would clean up space. The winners received a personalised Leo plush and the top 30 entries were published on the website and received UK Space Agency and ESA merchandise.

5. Conclusion

Fly Your Thesis! was an exceptional opportunity to improve the technical and soft skills of several postgraduate students, and it allowed for the further development of Cranfield's drag sails. Frontier Space Technologies, a spin-out start-up from Cranfield University, are currently in the process of commercialising the devices and have continued to benefit from the technology demonstration on-board the parabolic flights.

The key lessons learned from the experience were as follows; be adaptable, be aware of your resources and be aware of the complexity of procurement management. The experiment went through multiple iterations, many of those who provided valuable support to the project came from outside the team's university department, and procuring equipment was far more cumbersome and admin-dense than initially anticipated.

Research continues on the drag sails with the goal of offering the small satellite community a simple, low-cost device that will allow them to be compliant with space debris mitigation guidelines, assisting in the conservation of the space environment.

Acknowledgements

A special thanks to ESA and Novespace (Nigel Savage, Jeffrey Gorissen, Alexis Jolion), Cranfield University (Jennifer Kingston, Jarryd Braithwaite, the facilities team, the workshop team), and Staffan Persson for their invaluable support on this project.

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Lessons Learned when Developing a High Performance Attitude Controlled Platform to Achieve Microgravity for Low-Cost Experiments

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Abstract

Available Attitude Control Systems are often targeted at orbital flights, and therefore manoeuvre slowly. As such, these solutions are suboptimal for sounding rocket experiments, as experiments such as those conducted on free falling units have restricted flight times. Furthermore, current attitude control systems are usually aimed at projects with extensive funding, and are therefore out of the budget range of low-cost experiments. Taking these constraints into account, the objective of project ASTER is to design and test a low-cost, fast-acting solution, to stabilise and orientate a free-falling platform, which is capable of providing microgravity conditions for experiments. The proposed design utilises three reaction wheels, controlled by a closed loop system, to stabilise the Free Falling Unit within seconds. The platform will be able to perform predefined slewing manoeuvres, which can be adapted to a wide range of applications. The free falling unit is a cube weighing around 3kg with a side length of 150 x 150 x 180 mm, with a recovery parachute system included. Designed to act as a system platform for free falling units, it will be able to accommodate future experiments, providing an easily adaptable payload bay with dimensions up to 56 x 91 x 77 mm. Furthermore, the system will be recovered after the experiment has been concluded and the results obtained will be published on an open source basis to ensure its future availability to other student and low budget research projects, thereby allowing further improvement, optimisation, and customisation. The experiment development began in September 2019 and is scheduled to fly on a sounding rocket in March 2023. Team ASTER wants to contribute to the student community by sharing the experiences and lessons learned during the project development, which is what will be focused upon in this paper and accompanying presentation.

Keywords
Attitude Control System, Free Falling Unit, Learning Project, Microgravity, Sounding Rocket

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Acronyms/Abbreviations

ASTER	*Attitude STabilised free falling ExpeRiment*
ACS	*Attitude Control System*
CDR	*Attitude Control System*
GS	*Ground Station*
EAR	*Experiment Acceptance Review*
EPS	*Electronic Power System*
FFU	*Free Falling Unit*
IPR	*Integration Progress Review*
OBDH	*On-Board Datahandling*
PDR	*Preliminary Design Review*
REXUS	*Rocket EXperiment for University Students*
RMU	*Rocket Mounted Unit*
RW	*Reaction Wheels*
LTU	*Luleå University of Technology*
SED	*Student Experiment Document*

1. Introduction

Microgravity is an important field of research, which is vital for the efficient future utilisation of space and helps to develop new technologies both for space and ground applications. Microgravity experiments can be undertaken on-orbit, however, this is often well outside the available funding range of student and low-budget experiments. More economical alternatives are offered by drop towers and parabolic flights, but these are instead constrained to short periods of sustained microgravity conditions. Performing microgravity experiments on sounding rockets provides a more accessible solution, while still allowing for periods of microgravity in the order of minutes rather than seconds. However, unless entirely stabilised, such experiments cannot achieve true microgravity conditions due to residual external forces, such as the centrifugal force of the rocket's spin. A solution to eliminate the remaining forces acting on the experiment is ejecting the testing platform on a fully stabilised Free Falling Unit (FFU), but the costs and complexity of such systems can pose a significant barrier to entry. Attitude Control Systems (ACS) which are currently available are slow-acting and tend to have a significant price tag, which reduces their effectiveness on sounding rockets and places them out of the range of low-budget projects, such as student experiments.

The aim of the ASTER project [1][2] is to demonstrate the functionality of a high-performance, low cost and easy to integrate ACS platform for FFUs. This platform shall be capable of stabilising and performing rotation manoeuvres in FFU in a reduced gravity environment using three reaction wheels. This solution will be tested with a sounding rocket launch in which a FFU is ejected and subsequently performs slewing manoeuvres.

The primary objectives of the experiment are:

1. Develop an attitude controlled FFU to be ejected from a sounding rocket.
2. Demonstrate that the ACS is capable of stabilising the FFU.
3. Recover the system after the experiment has been concluded and the FFU has landed.

Additionally, the following secondary objectives have been defined:

4. Demonstrate that the ACS can perform slewing manoeuvres of the FFU with the desired accuracy.
5. Design an FFU which is able to accommodate payloads of future experiments.
6. Design and build an FFU, including the ACS, that is easy to integrate with future experiments.

The mission timeline can be divided into six stages, which can be seen in Figure 1. [1]:

1. Launch and flight prior to ejection.
2. Ejection of the FFU before apogee of the REXUS rocket.
3. Stabilisation of the ejected FFU using reaction wheels in reduced gravity.
4. Slewing manoeuvres of the ejected FFU using reaction wheels.
5. Parachute deployment and location transmission.
6. Recovery of the FFU.

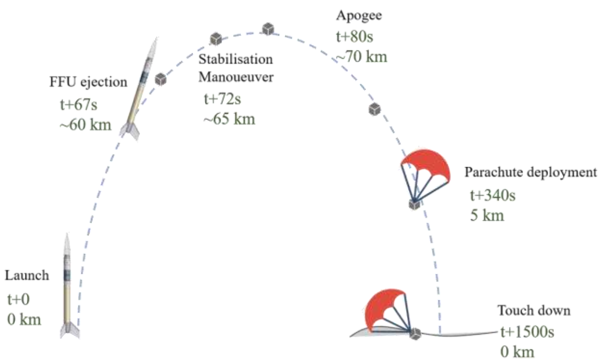

Figure 1. Timeline and altitudes of the ASTER mission stages

2. Platform Description

2.1. Project ASTER/definition

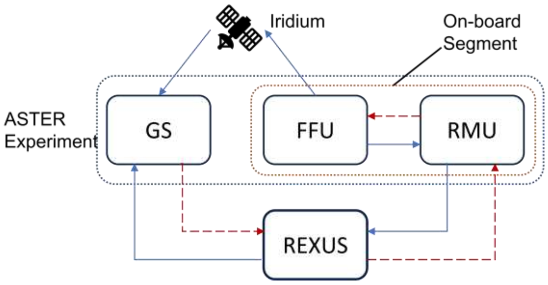

Figure 2. Overview of ASTER functional blocks and communication concept. The red dashed communication links become unavailable following radio silence.

Figure 2 shows the functional blocks which make up the ASTER experiment during the campaign. The ASTER experiment can be divided into a Ground Station (GS) and an On-board segment, as shown in Figure 2. The On-board segment can be further subdivided into the FFU and the Rocket Mounted Units (RMU). Prior to launch the GS can send telecommands to the RMU via the REXUS communication system, however this connection is lost after entering Radio-Silence Mode. Until ejection the telemetry is transmitted via the REXUS system, and following ejection the telemetry from the FFU is transmitted via Iridium. The GS is responsible for parsing and storing the telemetry and providing the capabilities to send telecommands.

The FFU is separated into several subsystems and consists of a 150mm cube with an additional 30mm high recovery module. These subsystems are the On-Board Datahadling (OBDH), the ACS, Electronic Power System (EPS), and Recovery and Communication system.The most important subsystem for the purposes of the ASTER experiment is the ACS, which consists of 3 reaction wheels (RW), the design of which is shown in Figure 3. The attitude of the FFU is determined by two IMUs. The RW components are 3D printed and CNC milled which ensures to be feasible for students. During free-fall, RWs will spin to stabilise the FFU and then a second mode will be activated, in which a series of pre-programmed slew manoeuvres will be executed. Additionally the recovery and communication system is vital to ensure a safe landing and recovery of the experiment. The recovery system will trigger the parachute release that slows down the FFU. The location of the FFU during descent is determined using GNSS data, which, along with the ADCS data, is then transmitted to the GS. RECCO reflectors will be mounted to the FFU to allow for a precise localisation after touchdown.

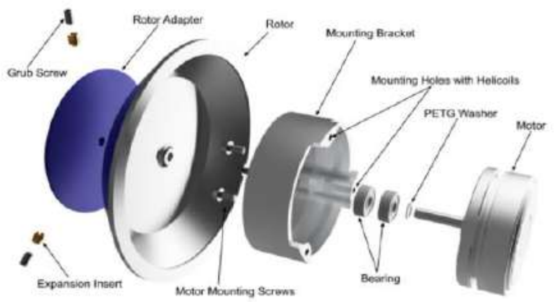

Figure 3. Reaction Wheel exploded view

The RMU houses the FFU and the ejection mechanism. It provides the electrical and communication interface between the rocket and the FFU. The RMU is responsible for ejecting the FFU from the rocket by a spring-loaded mechanism.

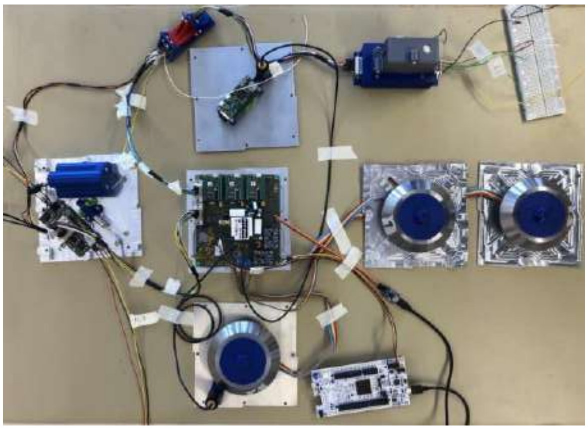

Figure 4. Flatsat configuration of the ASTER FFU during testing, Spring 2021

DOI: 10.5821/conference-9788419184405.111

3. Lessons learned

Team ASTER has progressed through the regular stages of a space project design process, but has also faced additional challenges in the past few years. The team has adapted to the different situations quite well, however there were some aspects that the team could have addressed differently and might be useful for other student projects. The main lessons learned are listed in this section, and they follow the stages in the project timeline, see Figure 5, and are listed sequentially according to the order they happened.

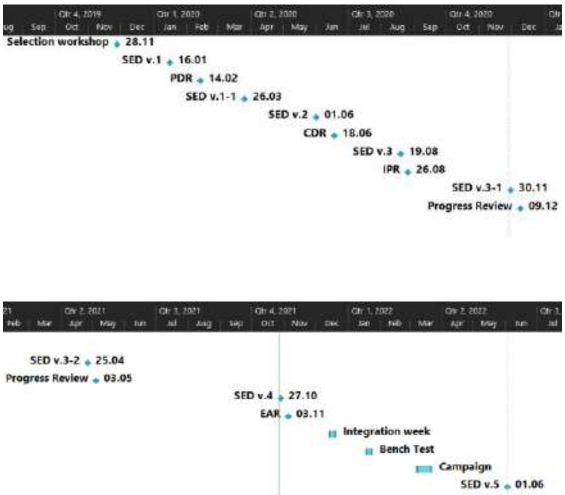

Figure 5. Project Timeline with the major design milestones indicated

3.1. Early stages

The main challenge during the early stages of the project was defining the experiment. The general idea was clear in the proposal, but some subsystems needed further details. The initial team was expanded through the recruitment of additional students. The larger manpower pool ensured that the team for each subsystem had the required resources. The only issue was how to manage and structure such a big team, which led to not having effective work packages and the roles of team members being ill defined. In retrospect it has become clear that it is more efficient in the long term to spend time at the beginning of a project to structure the team properly rather than starting to work without a clear aim or structure. The management of available work hours is difficult in a student team, as the members will have assignments and exams. In the early phases of the project it was especially difficult to balance the needs of member's studies and the needs of the project. However, the experiment concept was very promising and the motivation of everyone in the team pushed the project forward.

3.2. Preliminary Design Review

The lead up to the submission of the first version of our Student Experiment Document (SED) for Preliminary Design Review (PDR) to the REXUS panel was an intense, nerve wracking and stressful period. This is when the consequences of a lack of clearly defined roles and tasks became evident. Due to a lack of experience in this kind of project it was difficult to establish clear communication between team members which in term led to difficulties when resolving design decisions affecting multiple subsystems. However, several problems arose on the management side of the project, which negatively impacted the team.
A significant source of individual stress arose as a result of unclear guidance and instructions in the REXUS/BEXUS User-manual. This was rectified by increasing the volume of communication between REXUS personnel and ASTER following the PDR workshop week, but a big lesson learned was to get involved and communicate more before the SED-PDR report was submitted. Following PDR it was decided to modify the team structure to attempt to resolve some of the structural problems identified during the lead-up to PDR, and during the PDR itself. As such the position of Project Controller was established to help track deadlines and work within the team. It was hoped this would clarify the tasks of each team member, and lead to improved work packages.

3.3. Critical Design Review

The preparation of the Critical Design Review (CDR) put a lot of pressure on the team since the experiment design cannot be changed after the review. Most of the design actions that the team got at PDR were addressed, but there were others that were not fulfilled by CDR. For example, not being specific enough in some of the requirements, not providing enough details on risks and testing, and a lack of local outreach, such as radio or newspapers. The main driver of this last one was that the team members were focused on the technical aspects and it was difficult to find the time for other tasks, despite outreach being an important aspect of the REXUS/BEXUS programme. The solution the team adopted was to create an official outreach department and some of the team members could spend some of their time on outreach tasks, while continuing to work also on the technical side of the project.
A short time before CDR it became clear that

DOI: 10.5821/conference-9788419184405.111

the changes to the team structure, implemented following PDR, would likely not resolve problems in the team culture, so it was decided that a new project manager and system engineer would provide a clean slate.

3.4. Integration Progress Review

Integration Progress Review (IPR) took place relatively close to CDR, and followed the summer holidays. As such not much progress had been made in the design or manufacture of the experiment. However, as the procurement process took considerably longer than expected, some important lessons were learnt regarding the time required for the delivery and assembly of components.

3.5. Experiment Acceptance Review

For the EAR campaign, the main focus was to have the subsystem tests carried out together with the integrated system to demonstrate a fully working system for the panel. The tests for each subsystem were pretty much done, but the integration test of the full system had not been working out properly. This was due to the fact a quantity of people had left Kiruna, and the remaining part was not able to fulfil all the various tests. Because of this, the tests inside the tracking department (GPS/Iridium), the ACS, and FFU integration into RMU were experiencing issues which could not be solved in time. Although not passing the EAR, a second chance to display the experiment functioning for the bench test and integration week were agreed upon between the panel and team ASTER.

3.6. Bench test and integration week

During the Bench test and integration week, the experiment was not able to verify a reliable communication to and from the experiment, which in term might have been induced by the STM processor and unreliable pogo pin interface. The STM was an occurring problem which was something the team didn't manage to solve. Overall, hardware issues piled up and the decision was made to fly with deactivated payload. To allocate more time for testing of the system was critical for a success in the hardware category and a closer look into redesign should have been carried out in earlier stages, mainly on the pogo pins and STM in combination with communication modules.

3.7. Covid-19 pandemic

During the beginning of the Covid-19 pandemic in 2020, various challenges presented themselves in the team. The campaign was delayed from March 2021 to March 2022 because of the epidemic, due to the risk in travelling during this time. A significant issue was the various countries each team had people located in outside of Sweden. Early summer of 2020 was the main time for team ASTER to order components, since it was positioned after the CDR, during this time some of the components were delayed and could show up months later due to the uncertainty in delivering services. During this time, team meetings were occurring every week, which could be questioned because of the standstill in the project timeline and lack of updates concerning the whole team at times. It can be argued that it might have been better to have more subsystem/department meetings and less frequent team meetings.

4. Discussions and Conclusions

Due to the challenges faced by the project in the last phase of its development, the designed ADCS system would not be able to fly as an active payload on the REXUS rocket during the scheduled 2022 campaign. But because of the uncertain geopolitical situation, the scheduled launch campaign was postponed until March 2023. This led to an opportunity to complete the set-out goals mentioned in the introduction section, Primary and Secondary objectives.

The team is currently preparing for the next Experiment Acceptance Review (EAR) that would ensure that the experiment is ready for flight. No further modifications to the experiment are allowed after EAR and therefore the team has to ensure that the technical problems are solved before the review. The team will recruit new students at the Kiruna Space Campus to have the sufficient manpower to optimise the ACS system design and perform the necessary testing at subsystem and system level on site.

Following the launch campaign at the Esrange Space Centre in Kiruna, Sweden, the post-flight analysis, and results will be gathered by the team to ultimately validate the platform. The design and results obtained will be published on an open source basis available for future experiments and missions.

ASTER is looking forward to helping students and low budget experiments access to space.

Acknowledgements

We would like to thank our supervising professor, Prof. Thomas Khun, LTU Department of Computer Science, Electrical and Space Engineering

We would also like to thank Olle Persson, LTU Department of Computer Science, Electrical and Space Engineering, for his continued guidance and support throughout this project.

This project was carried out as part of the REXUS/BEXUS programme (https://rexusbexus.net/). The REXUS/BEXUS programme is realised under a bilateral Agency Agreement between the German Aerospace Center (DLR) and the Swedish National Space Agency (SNSA). The Swedish share of the payload has been made available to students from other European countries through the collaboration with the European Space Agency (ESA). Experts from DLR, SSC, ZARM and ESA provide technical support to the student teams throughout the project. EuroLaunch, the cooperation between the Esrange Space Center of SSC and the Mobile Rocket Base (MORABA) of DLR, is responsible for the campaign management and operations of the launch vehicles.

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On-board Image Classification Payload for a 3U CubeSat using Machine Learning for On-Orbit Cloud Detection

Mark Angelo C. Purio[1], Timothy Ivan Leong[2], Yasir M. O.Abbas[3], Hoda Awny Elmegharbel[4], Koju Hiraki[5], Mengu Cho[6]

Abstract

CubeSats are giving the opportunity for educational institutes to participate in the space industry, develop new technologies and test out new ideas in outer space. CubeSat missions are developed to perform scientific research and demonstrate new space technologies with relatively cheap cost and limited resources. This category of satellites has many limitations such as the short development time, the power consumption and the limited time and capability of data downlink. Earth Observation from a Low Earth Orbit is one of the most appealing m applications of CubeSats developed by students or non-space faring countries. Investigating new technologies to improve image quality and studying ways to increase acquisition adequacy is very promising. This paper aims to introduce a mission hardware design and machine learning-based algorithm used within an Earth Observation (EO) CubeSat. The case study of this paper is Alainsat-1 project which is a 3U CubeSat developed with the support of IEEE Geo-science and Remote Sensing Society (GRSS) at the National Space Science and Technology Center, UAE. The satellite is planned to be launched by 2022. A low-resolution Commercial off-the-shelf (COTS) camera for EO is developed as a primary mission in this CubeSat. The compatible hardware design and software algorithm proposed is responsible for classifying the images captured by the camera into different categories based on cloud intensity detected in these images before downloading them to the ground station. A microcontroller-based architecture is developed for controlling the mission board; it is responsible for accessing the memory, reading the images, and running the cloud detection algorithm. The cloud detection algorithm is based on a U-net architecture while the algorithm is developed using a Tensor-flow library. This model is trained using a dataset of images taken from the Landsat 8 satellite project. Moreover, the SPARCS cloud assessment dataset is used to evaluate the developed model on a new set of images. The overall accuracy achieved by the model is around 85% in addition to the acceptable performance of the model observed on a set of low-resolution images. The plan is to make the design modular and optimize its performance to be used on-board CubeSats fulfilling the size constraint and overall power consumption limitation of an add-on module to a camera mission.

Keywords

CubeSat, Cloud Detection, Image Classification, U-net architecture, Microcontroller

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1. Introduction

The popularity of CubeSat development due to its cheaper cost and ease of production has allowed testing new ideas in space. However, these CubeSats present limitations in terms of power, size, and downlink capacity. To compensate with these limitations, the development of optimized algorithms which uses limited bandwidth and power and are limited in size are an important part of developing these CubeSats' efficiency.

Cloud detection [1], [2] is an important step for the collection of satellite imagery. In most scientific studies in Earth Observation, cloudy images have little to no use due to its contamination of the satellite image[3]. Since this is the case, the time to download such cloud-contaminated images and their storage may be an additional work to satellite mission execution and operation. This is also true for cube satellites which has relatively limited bandwidth and short data downlink time. Due to this, the development of algorithms able to accurately determine clouds in each image is an interesting and useful topic in CubeSats with imaging payloads.

On board classification algorithm could prove to be a useful tool for these scenarios. Being able to select data useful for the satellite's application could optimize data downstream to the ground station as only useful data are downloaded. In the literature, on-board computing in CubeSats have been implemented in different applications. For instance, Thompson et al (2015) did an onboard machine learning classification of images by a CubeSat in Earth orbit [4] while Thompson et al (2015) and Hernández-Gómez et al (2019) present nine processing-intensive algorithms very commonly used for the processing of remote sensing data which can be executed on-board on this platform [5]. Machine-learning based payload for CubeSats were also done by Manning et al (2018) used various Convolutional Neural Networks (CNNs) to identify and characterize newly captured satellite images [6], and Maskey & Cho (2020) provides an innovative approach of combining a novel CubeSat image dataset and a lightweight Convolutional Neural Network architecture for automatically selecting images for downlink on a 1U CubeSat [7]. More so, cloud detection for a CubeSat were also explored and developed by Zhang et al (2018) to reduce memory cost and interference speed by utilizing image-compression strategy and depth-wise separable convolutions [8] and another work of the same author (2019) use a combination a convolutional neural network and wavelet image compression is proposed to explore the possibility of onboard cloud detection [9].

This paper presents a mission hardware design and machine learning-based algorithm used within a CubeSat called Image Classification Unit (ICU). The case study of this paper is Alainsat-1 project which is a 3U CubeSat developed with the support of IEEE Geo-science and Remote Sensing Society (GRSS) at the National Space Science and Technology Center, UAE. The satellite is planned to be launched by 2022. The compatible hardware design and software algorithm proposed is responsible for classifying the images captured by the camera into different categories based on cloud intensity detected in these images before downloading them to the ground station. A microcontroller-based architecture is developed for controlling the mission board; it is responsible for accessing the memory, reading the images, and running the cloud detection algorithm.

2. Materials and Methods

2.1. Data Preparation

2.1.1. Image Selection

To detect cloud in an image, the model is required to be fed with an image and the mask of cloud associated with the image. It also requires a large amount of data so that it can get high accuracy while not overfitting to its training dataset. Freely available images were used and taken from Landsat 8 courtesy of the US Geological Survey (USGS) from which bulk of the images would form the dataset.

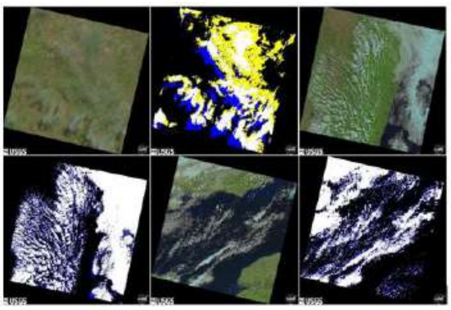

Figure 1. Example of images from Landsat 8 alongside its quality band (Images courtesy of the U.S. Geological Survey)

DOI: 10.5821/conference-9788419184405.112

The model has been trained using only the RGB band of an image as this would probably be what most cube satellite would be able to capture. With this process around 200 images were downloaded from the USGS website.

2.1.2. Image Pre-processing

Each image and its respective quality band needed to be pre-processed to use them to train the model. The following workflow was done during this stage:

1. Manual reorientation of images and resizing to 6000 x 6000 pixels.
2. Slicing the images to multiple smaller images of 500 x 500 pixels.
3. Transforming quality bands into black and white to keep cloud position information.
4. Normalizing all coefficients to 0 or 1 before including in the dataset.
5. Resizing the 500 x 500-pixel images to 256 x 256 by doing an average of color over a region of pixels.
6. Feeding the model with the resized images.

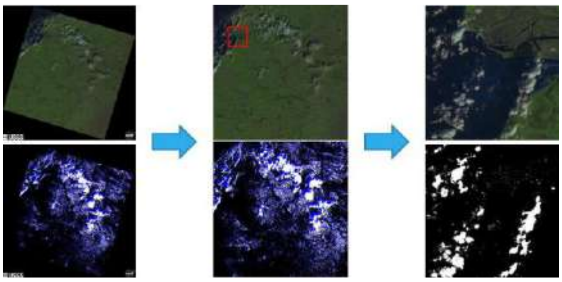

Figure 2. Processing of a Landsat 8 image to an image used in our dataset

The last two processes down samples the Landsat 8 images from 30m resolution to about 300m resolution to fit normal CubeSat images After processing a new dataset consisting of 15,263 images was generated

2.1.3. Evaluation Dataset Selection

To properly evaluate the model, the SPARCS cloud assessment dataset [10] was used as a validation dataset. The 80 scenes of the dataset contain all types of photos a cloud detection algorithm might encounter and thus is very useful to evaluate such an algorithm. An evaluation dataset is also necessary to evaluate the model on images it has not been exposed to.

Images from CubeSats such as CubeSats such as Horyu-4, BIRDS 3, Calpoly, and MySat1 were also gathered to evaluate the machine learning model on images of lower resolution. These images could not be used in the dataset as they didn't have any pre-generated cloud mask. Thus, the prediction made by the model on such images will only be empirically evaluated.

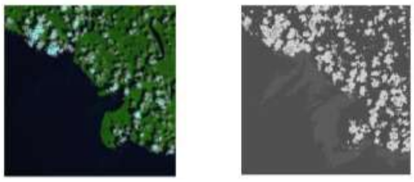

Figure 3. Example of a SPARCS images and their associated cloud mask

2.2. Algorithm Implementation

Normal CNN implementation is not enough for our purpose as it tends to extract the features out of an image while losing any spatial information about these features. To output a mask of cloud, this lost spatial information need to be regained. This is done using a U-net architecture designed by Ronneberger et. al. in 2015 [11]. It consists of a contracting path that is basically a normal CNN network and a symmetrical expanding path. The contracting path extract the features from the image, while doing so the tensors height and width get smaller and smaller and only the features are left. As seen in Figure 4, each down sampling divides the height and width of the tensor by 2 while the depth of the tensor increase, i.e., the number of the extracted features increases. To upscale the tensor back to the input tensor size, a 2x2 convolution is used (Up-convolution). Since this up-convolution half the number of features of its input tensor, a concatenate operation is done with the corresponding tensor from the contracting path.

2.3. Training and Optimization of the Model

Having built the dataset that will train our model and defined the neural networks architecture used for our model, training and optimizing said model becomes the next step. The first model trained achieved an accuracy of around 85%. To get a more accurate model, multiple parameters could be changed:

- The size of the input image and the augmentation of the images in the training dataset
- The size of the training batch and validation batch of images fed to the model each iteration before updating the weights.
- The number of Epoch

- The number of layers and the number of filters implemented in the neural network
- The dropout parameter
- The optimizer function used in the architecture
- The threshold at which a pixel is deemed to be a cloud

For this purpose, a multitude of model with varying parameters were trained and evaluated based on their accuracy and if they were overfitting or not to their training dataset. The duration of each simulation lasting around 30 minutes, the task was relatively long to accomplish and the influence of each parameter on the accuracy of the model could only be interpreted with a relatively few numbers of points for each parameter.

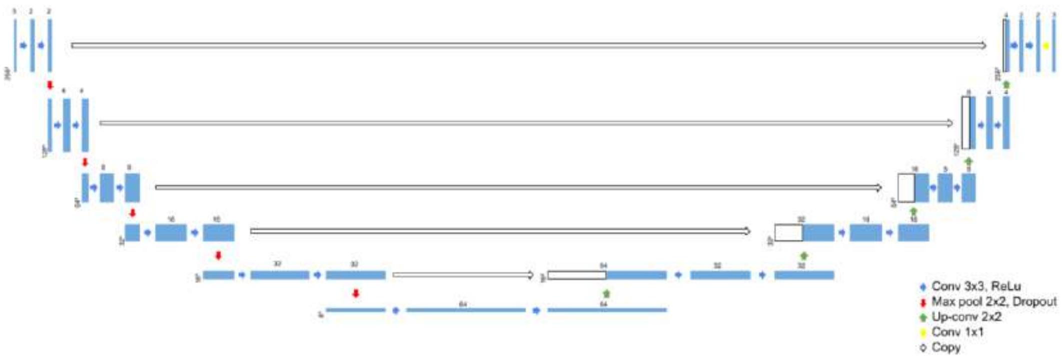

Figure 4. Architecture of a U-net Convolutional neural network, inspired from Ronneberger et al. (2015) [11]

2.4. Microcontroller Implementation

To implement the newly built model inside a microcontroller, several things were done:

1. Quantizing the model to reduce to a size suitable for the microcontroller RAM.
2. Converting the model to C++ code array so it can run in the microcontroller.
3. Write an algorithm that will (a) retrieve an image from the flash memory, (b) convert it to the input tensor format used by the model, (c) run the model to retrieve the resulting cloud mask and (d) save it in a flash memory.

2.5. Performance Evaluation

After training the dataset, the model was evaluated and by calculating its accuracy over the training dataset, the validation dataset, and the evaluation dataset. The model was evaluated based on its confusion matrix, precision, recall, false omission rate, commission rate, overall accuracy and the F1 score. The model was also evaluated on the nanosatellite images to see if it could properly work with lower resolution images.

2.6. Payload Hardware Design

Before the PCB was designed, the model was first tested inside a STM32F746G-DISCO development kit. This development kit offers similar specification as the one the final PCB design so making the model work inside this board will guarantee that it will work inside the other board.

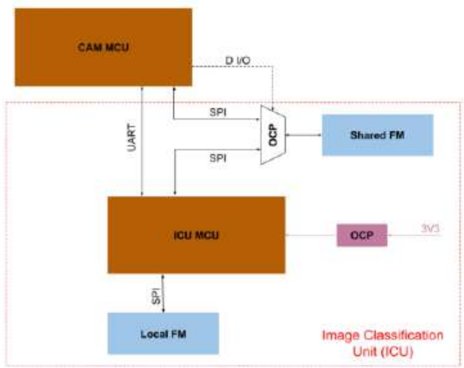

Figure 5. Basic schematic of the ICU Payload hardware

3. Results and Discussion

3.1. Selected Model

In Table 1 the parameters that were set for the best model is shown. Multiple models had higher accuracy than the one presented here, but once they went through the quantization process, their size remained too big to be usable inside the microcontroller. In the end the model size managed to be reduce to 867 Kb.

DOI: 10.5821/conference-9788419184405.112

Table 1. Model Parameters Used

Parameters	Value	Reason
Size of the image	256 x 256	Limit the memory usage while keeping high enough details
Image Augmentation	Yes	Make the model react better to various type of images
Training Batch	15	Update the weights as often as possible
Validation Batch	5	Validation dataset is smaller
Number of Epoch	15	Model reached a plateau around this amount of Epoch
Number of layers	5	Number of layers limited by the microcontroller RAM
Number of starting filters	2	Number of filters limited by the microcontroller RAM
Dropout	0.3	Best results
Loss function	Binary Cross entropy	Best loss function to use in this case
Optimizer function	Adam	Best results
Mask threshold	0.5	Best results

3.2. Performance Evaluation

The chosen model was tested using the different performance metrics and is summarized in Table 2. On the other hand, the confusion matrix for the training, validation and evaluation dataset is shown in Table 3 to provide a better visual representation of the performance metrics. Figure 6 presents sample predictions on training, validation, SPARCS, and CubeSat images.

Table 2. Accuracy Assessment of the model

Method	Training Dataset	Validation Dataset	Evaluation Dataset
Precision	0.7297	0.8246	0.6151
Recall	0.6969	0.7313	0.5373
False Omission Rate	0.1565	0.1529	0.1079
Commission Rate	0.2703	0.1754	0.3849
Overall Accuracy	0.8060	0.8396	0.8452
F1 score	0.7129	0.7751	0.5736

Table 3. Confusion Matrices for training dataset, validation dataset, and evaluation dataset.

Training Dataset		**Predicted Class**	
		Cloud	Non-Cloud
Actual Class	Cloud	0.6969	0.3031
	Non-Cloud	0.1364	0.8636
Validation Dataset		**Predicted Class**	
		Cloud	Non-Cloud
Actual Class	Cloud	0.7313	0.2687
	Non-Cloud	0.0946	0.9054
Evaluation Dataset		**Predicted Class**	
		Cloud	Non-Cloud
Actual Class	Cloud	0.5373	0.4627
	Non-Cloud	0.0808	0.9192

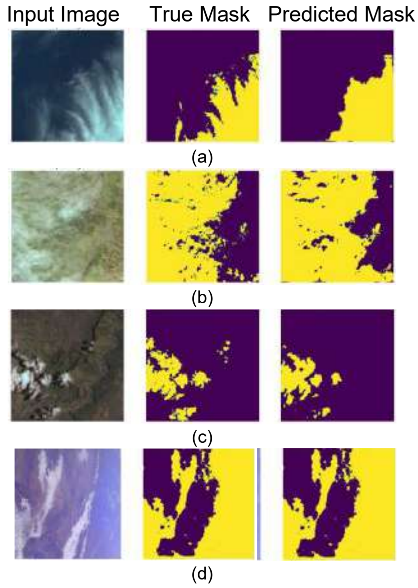

Figure 6. Example predictions for (a) training, (b) validation, (c) SPARCS and (d) CubeSat images

3.3. Payload Design

The payload was design and is currently under manufacturing. Figure 7 shows the PCB design and the 3D render of the board. Such board includes both the image classification unit payload and the camera payload designed by Telkom University.

Figure 7. PCB design and 3D render of the payload (Credit: Telkom University)

Considering the lessons learned in the BIRDS-4 satellite project, a PCB is to be fabricated to implement the software. It consists of a microcontroller, one shared Flash memory with the camera microcontroller and one local flash memory. In addition, it is integrated with the camera payload designed by Telkom University. The final purpose of this system is to have a cheap module that can be implemented on as many CubeSats as possible, so the hardware design was kept simple and replicable. All the chosen components have space heritage already. This will ensure that the new PCB design should be able to work in the harsh environment of space. Both radiation, thermal and vibration test will still be conducted on the new PCB to ensure its resistance to the space environment. One of the main challenges faced by the design is the RAM size, with the cloud detection the amount of stored data in the

DOI: 10.5821/conference-9788419184405.112

RAM and in the Flash is huge because of weights and activations of the model. The size of the Flash in the STM32F7 device is enough but we needed to add the external RAM. To provide hardware acceleration for the JPEG decoder, we are considering using STM32F767 instead of STM32F746. They have pin to pin compatibility.

4. Discussion and Conclusions

A U-net convolutional neural network was designed and trained to be implemented inside a CubeSat payload. For this purpose, satellite images from Landsat 8 were gathered and processed to generate a new dataset consisting of 15,263 images.

After a lot of models were trained with different parameters to obtain the best model possible, several models were selected and quantized to observe the influence of the size of the model's architecture on its final optimized size. The chosen microcontroller's RAM size of 2 Mb limits the selection of high accuracy models which are big in size, but additional RAM is found to be a better improvement.

The final chosen model manages to obtain good result considering the size limitations when it was significantly reduced in size via a quantization method. It has been properly loaded inside an MCU proving that the model will eventually be able to run inference. Since the model doesn't seem to be losing accuracy when exposed to high reflective area and the relative shape and area of the clouds is relatively respected by the model, the results were deemed satisfying for the purpose of this paper. Thus, even if the evaluation score is lower than what normal cloud detection algorithm can achieve, implementation inside a microcontroller will still be conducted and tested.

5. Future Work

The problem of the size versus the accuracy model will have to be one of the main themes of any future work. They will have to work both on the issues the algorithm has with running in the microcontroller and changing the architecture of the model to obtain better results while keeping the model small enough to make it run inside the microcontroller. Integrating the quantization process during the learning step of the neural network could be one method to explore to allow this compromise between size and accuracy.

To date, the payload hardware is still under manufacturing so full implementation results are to be discussed in the future.

Acknowledgements

- The Laboratory of Lean Satellite Enterprises and In-Orbit Experiments of Kyutech for supporting to carry out the project and allowing the use of its laboratory equipment and facilities.
- BIRDS-4 Satellite project and its members, as this project is where the mission idea originated.
- Funding support from IEEE Geo-science and Remote Sensing Society (GRSS) at the National Space Science and Technology Center, UAE through the Alainsat-1 project.

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University of Nottingham Student Space Activities to Enrich the Traditional Curriculum

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Abstract

Students at the University of Nottingham have been establishing several student-run extra-curricular groups to build their own space technology. These include model rockets, CanSat and CubeSat projects, involving students from bachelors up to PhD level across a variety of Departments. These projects have been supported through staff supervision, international collaboration, and access to facilities including a new space-focused laboratory space. Some students have recently benefitted greatly from modules and thesis projects being tailor made to further train them in hands-on space research and enable them to earn credits from participating in these projects.

This paper presents their initial findings and products of their work, along with their honest experiences which may be of interest to other new student groups hoping to establish similar programs at their university. Students have had to learn and put into practice a range of new skills and experiences, not normally found within taught course modules, and all of this under their own organisation. While the experiences are hugely valuable, for both professional and personal development, students need to work hard to maintain project longevity and team spirit when faced with difficulties from coursework deadlines, new skill demands and handover to new students after graduation.

Keywords

Rocket Design, CubeSat, CanSat, Hands-on Space Projects, Student Competitions

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Acronyms/Abbreviations

ESA	*European Space Agency*
UnB	*University of Brasilia*
UoN	*University of Nottingham*
UKSEDS	*UK Students for the Exploration & Development of Space*

1. Introduction

Students at the University of Nottingham are developing their own clubs, student societies, and extra-curricular projects to support their peers with career goals in the space sector and as a common interest group to explore our Universe. Subsequently, SpaceSoc (the official society) and NottsSpace (the project teams within it) have been set up to allow students from any department to come together and collaborate on space-specific activities they are interested in. While both groups have crossover, NottsSpace primarily focuses on the projects and academic side, whereas SpaceSoc focuses on bringing people together through socials and space events.

SpaceSoc has only been set up for a year but has already hosted socials as well as a viewing experience for the UK National Student Space Conference. A priority for SpaceSoc in the next academic year is to raise awareness of NottsSpace projects and help increase student involvement, particularly from other departments that may not be aware of such opportunities without regular contact with committee members.

NottsSpace un-officially formed without a name in late 2020, although is now formalising as part of SpaceSoc to enable students to earn credits for their work as part of dissertation modules. Early projects involving only a few students started including OPHELOS (a student payload project) and KIC-CAM (a prototype Cube-payload microscope), and prototype CubeSats such as TemboSat. Since then, students have been developing flight-intended CubeSats and CanSats including WormSail (in collaboration with Universidade de Brasilia) and now AstroJam for ESA's fourth Fly Your Satellite competition. Most recently students have also been involved in developing a model rocket and upgraded CanSat for entry into the Mach-22 competition later this year.

Through participation in a NottsSpace project, students can learn:

- Practical engineering skills that aren't learned or practiced through lectures-based work.
- How designs transfer into the manufacturing process as well as the challenges this presents
- How to collaborate across disciplines and expertise levels to resolve conflicting ideas
- How project management, systems engineering and testing are key to project success
- Independence & self-motivation to conduct their own research and development without direct supervision from staff members

As in the wider space sector, student space projects are an interdisciplinary undertaking, and so efforts are being made to involve students from engineering, computer-science, physics, geography, and others in NottsSpace & SpaceSoc. This reflects the reality of space missions and the philosophy of the National (UKSEDS) and International "Students for the Exploration & Development of Space" Societies that SpaceSoc is a branch of. For now, the majority of members are from Aerospace Engineering, although the committee is working hard to forge links with other Departments.

Another development of the NottsSpace programme is the opportunity for students from across different University Departments to become involved in exciting hands-on projects as part of their accredited dissertation projects. This is an incredibly useful development for any student project team, as it supports students to develop their skills and knowledge to a depth that would have been difficult without "getting hands-on" with their subject matter; or would be required unenviable extra-curricular (un-accredited) time commitments from the student. Further, this ensures that the project team has a ready supply of committed, well-trained workers with good time availability to support the mission.

2. Mach-22 Rocketry Competition: HARP

Mach-22 is a competition organised by UKLSL, UKSEDS and Discovery space UK. Teams will have the opportunity to gain hands-on experience in materials, electronics, and mechanical areas by building a model rocket and CanSat. The event ends with the launch and conference day, where the team will launch their designs and participate in various workshops that will further develop their skills.

The University of Nottingham has gathered a team of undergraduate students to design, manufacture and launch a large model rocket and a CanSat to as close to an altitude as 1km as possible. The team will gather data from the launch, such as measuring and transmitting altitude, inertia and position during flight and recovery to a ground station. Additionally, a lander module will be ejected at apogee and release a planetary probe upon landing, simulating a lander mission. The UoN's team is called HARP, which stands for High Altitude Rocketry Project.

Figure 1. HARP Logo

The rocket will be integrated with an I-class rocket motor, and the main body will be made from carbon fiber. The rocket nose will be manufactured with the aid of a 3D printer that uses Rigid 4000 Resin as a material instead of regular PLA to ensure that it can withstand the G loads during launch. This is very exciting as if it was not for this competition, students would not have the opportunity to work with these materials and manufacture processes.

The main rocket body will be divided into five sections: the motor, payload, recovery, and avionics bay. The motor bay will include a structural mount and a high-powered Cesaroni solid rocket motor to propel the craft to 370 mph in under 2 seconds.

Figure 2. Rocket Model Render

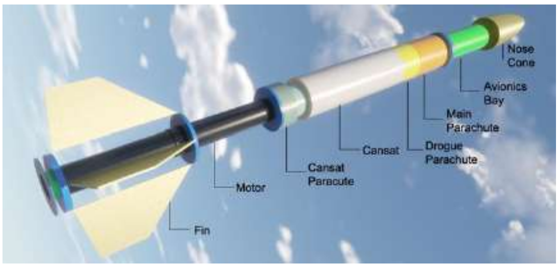

Figure 3. Internal Rocket Model Render with systems description

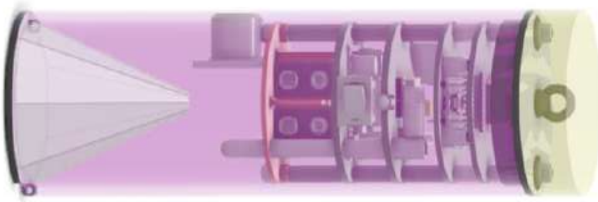

Figure 4. CanSat Model Render

The payload consists of a CanSat that will emulate a lander mission which will release a module, where it would then unfurl to release a rover-like payload. The Lander module will be equipped with solar panels to ensure it can charge independently. The CanSat is also equipped with sensors to collect critical data to complete the mission: temperature and pressure sensors are used to calculate the altitude of the CanSat. Moreover, the CanSat would have a camera on-board to take pictures and record the descent after being ejected from the rocket. To aid the recovery process of the CanSat, it would be equipped with a GPS module that uses a patch antenna to send back position data to help the recovery team collect the CanSat after the descent.

The rocket is required to have a maximum drift (due to wind) of 1km from launch, to facilitate this it was decided to use a complex dual deployment solution utilizing a drogue chute that deploys at apogee, and a main chute that deploys near the ground. This allows the vehicle to descend quickly for the majority of the decent, before slowing to a safe landing speed just before it touches down. The drogue chute is deployed with the CanSat by a black powder charge, and the main chute is deployed by a latch that releases at a predetermined time, allowing the drogue to pull out the main. The avionics system will include batteries, an on-board computer, radio, Inertial Measurement Unit (IMU), altitude sensor and GPS.

The team is confident that the launch will succeed as testing will be performed to validate the design using wind tunnel, black powder, avionics, and recovery system testing.

Extra-curricular projects like the ones presented in this paper provide essential technical and soft skills that student otherwise would not gain just by doing the course program. Diverse technical skills such as mechanical engineering, materials trade-off and selection and systems development including its programming and soft skills such as teamwork, leadership, communication, organization and time management can be showcased during job interviews. This attitude was well appreciated by different aerospace companies during the successful interview of different team members.

3. CubeSat Projects

3.1. WormSail

WormSail is a collaborative CubeSat project with the University of Brasilia to develop a 2U, multi-payload CubeSat by an international team of students spread out across the world. Combining software, hardware, know-how and experiences of spaceflight missions between the two teams, students at both institutions; built payloads, designed deployment systems, and tested subsystems that would make up WormSail in just a few short months during the 2020 pandemic [1].

WormSail features a miniaturised microscope for observing colonies of the nematode *C. elegans* during their flight in space. *C. elegans* is a model organism, about 1mm in length, that has been used for decades to study the muscular, genomic and neurophysical changes of animals (including humans) in space and on Earth. WormSail also held a student-developed deployable drag sail, that could be deployed remotely from Earth to increase the drag area of the satellite to 0.689m². This would enable faster, more controllable de-orbit times – within 608 days from a 600km altitude SSO - and help demonstrate a critical developing technology in space sustainability [1].

WormSail could not be launched on its intended rocket, so development was postponed after months of hard work and practice. However, the mission is ready to be begun again if a new launch slot appears pending further qualifications tests. The partnership formed during WormSail has encouraged further collaborative projects between UoN and UnB, including UoN's participation in Alfacrux mission and the installation of "sister ground stations" at both Universities – mutually supporting both Universities' missions as they pass over the world.

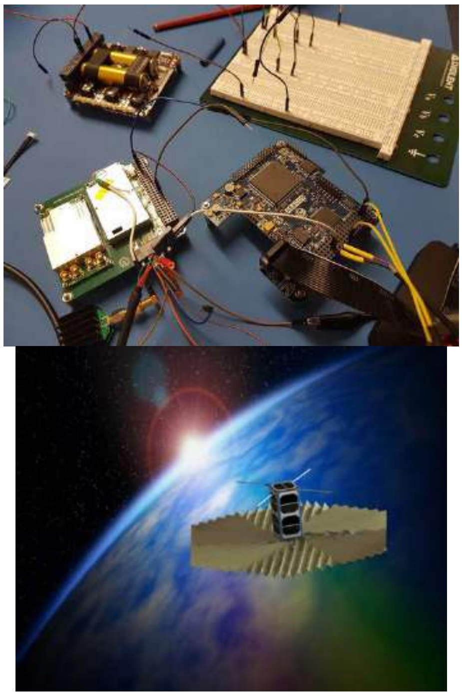

Figure 5. Photos of WormSail

3.2. AstroJam

The lessons learned from these experiences led to a renewed effort in the student CubeSat programme to develop AstroJam. A 3U CubeSat to improve upon the technology designed for WormSail, demonstrate a more formalised project organisation, and support real research from the University of Nottingham. AstroJam has student-developed science payloads supported by the UoN Astropharmacy Research Group and Nottingham Geospatial Institute (NGI). The payloads include a miniaturised fluorescence spectrometer for the in-situ analysis of cell free bioreporters producing analogue astropharmaceuticals and a CubeSat-based GNSS interference mapping payload. Additionally, an identical ADCS magnetorquer cooperatively developed with Universidade de Brasília will be used for detumbling and pointing the satellite.

AstroJam's uses the same COTS bus subsystems (OBC, EPS and radio transceiver) as WormSail, strengthened by a now more experienced student testing team. Structural components will be partly manufactured in-house at UoN, while other components will be manufactured using additive manufacturing technologies from specialised companies in Nottingham and Europe. Both payloads represent cutting-edge research from UoN that, once demonstrated, have many applications to for exploration and Earth observation science.

DOI: 10.5821/conference-9788419184405.113

AstroJam is intending to take part in the fourth Fly Your Satellite competition run by ESA.

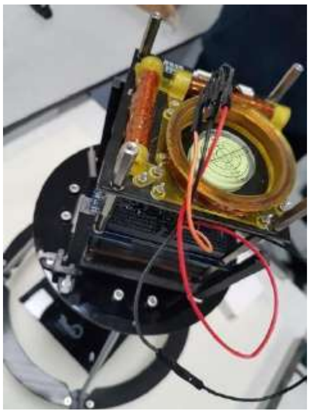

Figure 6. AstroJam Magnetorquer Testing

4. CanSat Projects

4.1. MACH-21: PEAK CanSat

Mach-21 was the first time the University of Nottingham entered a CanSat competition which was hosted by UKLSL [2] at the Machrihanish Airbase [3] and supported by Gravitilab Aerospace Services which provided the launch opportunity at the competition.

The team was called UON-ADCP (University of Nottingham – Atmosphere Data Collection Probe), which entered the Peak category. Selecting a simplified mission was suitable to reduce the risk and complexity of developing a soda-sized satellite.

The payloads of UON-ADCP consisted of COTS sensors, primarily an atmosphere sensor to compare the atmospheric data between Nottingham and Scotland. It also had an altimeter to measure temperature and pressure. For recovery, the CanSat had a GPS module to help locate its position after the descent.

The team finished second place within the PEAK category and reached third place overall.

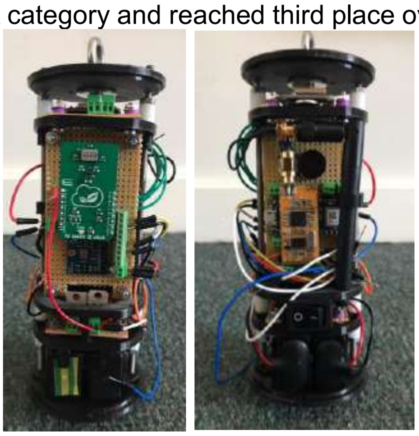

Figure 7. PEAK CanSat Engineering Model

4.2. MACH-22: Advance CanSat

HARP's advance CanSat, combined entry for Mach-22 builds on the lessons learned from the PEAK category CanSat developed for MACH-21. The new CanSat has additional operational requirements compared to MACH-21. The fixed volume constraint was removed and a minimum requirement of 1kg has been added to classify the CanSat as "Advance".

The CanSat would feature COTS sensors on-board for temperature and pressure measurements, and a GPS sensor to record the position of the CanSat. Secondary payload of the CanSat would be equipped with a camera to capture the descent and landing phases of the mission. and a lander module, which is designed would be deployed during descent decent and release a mini-vehicle to simulate a rover ready to explore a new planet.

The Advance CanSat is 78mm in diameter and 240mm tall. It has two main mechanisms - a release hatch to release the lander module and another release mechanism to open the lander module and allow the rover to exit.

The design of the lander module is influenced by the Rover Egress Lander [4] mission, where it would deploy a mini-vehicle that would roll out of the lander module emulating the start of the surface operation in a new environment. The lander module would unfurl and release the rover by using a thermos-cutter which would be activated by a timer on the microcontroller.

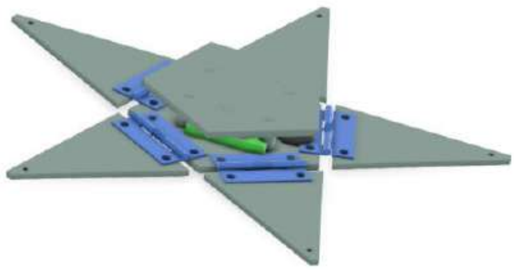

Figure 8. Lander Module

Electronic hardware would use a Printed Circuit Board (PCB) to ensure the CanSat stack would survive the launch environment. The structure would be designed to survive a 10G impact and up to 233Hz vibrations and undergo testing to ensure structural parts and electrical components would survive throughout the whole flight profile, from launch to the landing and descent phases.

Programming the microcontroller would also use a version control platform (i.e., GitHub) which would keep track and store the version history of the programming. The CanSat and rocket's avionics team will collaborate since the same COTS components were selected to simplify the procurement of the design.

HARP team is working in collaboration with the SNARC (South Notts Armature Radio Club) on developing the ground segment with the students at The University of Nottingham. It would involve the design architecture of a robust portable ground station for both the Rocket and CanSat downlink telemetry.

Currently, HARP's CanSat is being developed and has received maximum marks for its PDR (Preliminary Design Review) stage. The team is now working towards the CDR stage and preparing for manufacturing structural elements using an additive manufacturing process in the University of Nottingham Rapid Prototyping Centre.

5. Conclusions

These projects have revealed a huge appetite for hands-on student space missions within UoN and across many departments. This is a message that echoes those from group such as the National UKSEDS Society, which has run similar competitions to those described here for years in an effort to further engage, motivate and train space students in the UK. These are run similar to ESA competitions with a judging and support panel of industry experts, but also feature novel mission types including rover building and rocket launching. One analogous network of similar programmes can also be found in the international "Formula Student" competitions, which tasks teams to develop miniature race cars and test them. These have existed for many years and succeeded in gaining a solid reputation within the larger industry – including sponsorships deals - as well as widespread involvement from students and Universities across the world. The authors, students who are involved in projects described in this paper, agree with the general trend of space sector organisations running similar programmes and that they have been of crucial benefit for out student, and later career, journeys.

One result found throughout communication between the various NottsSpace project groups is that the importance of choice, independence and self-teaching are key to the motivation of students to participate. Having the multitude of hands-on projects available not only increases the diversity of skill sets learned (and shared) by students, but also enables students to choose which roles and teams they want to be part of and how much time they can dedicate to these extra-curricular activities. This last point is particularly important as training highly skilled, confident graduates relies on them not being over-worked and burned-out during pivotal years of learning.

Acknowledgements

The authors wish to thank the Faculty of Engineering and associated Departments for their financial contribution and staff time in supporting these students' projects, in particular the UoN M3 and Aerospace Engineering courses. We hope you will continue to support future generations of students launch their careers through these schemes. Additionally, thanks to the extended student team members past, present and future who have been involved in these projects and assistance in producing this manuscript.

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Earth observation education for Zero Hunger: A Massive Open Online Course towards achieving SDG #2 using EO

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Abstract

Persisting hunger and malnourishment continue to be a problem of global concern, which recent climate change, as well as environmental and socio-economic crises and their impacts along the food chain further exacerbate. Earth observation (EO) holds the capacity to deliver large temporal and spatial coverage information that allow for better decision-making in food production and distribution. Furthermore, the rapidly increasing amount of freely available data and tools potentially enable an expanding user community to bring this information into practice. However, more people need access to EO education to realize this potential. EO Connect (funded by the German Ministry of Education and Research) addresses this demand by developing a Massive Open Online Course (MOOC) towards the UN Sustainable Development Goal (SDG) 2: Zero Hunger. Since a conventional course can barely reflect the comprehensiveness of SDG #2 regarding both content and the people involved in achieving the goal, the Zero Hunger MOOC leverages modern learning approaches in a non-linear, adaptive learning environment to cater to a large audience and diverse target groups, and to their different scopes and levels of desired learning outcomes. The use of micro-content, drip-feeding and feedback-guided course development shall ensure maximum effectiveness. To accomplish this ambitious endeavour, the Zero Hunger MOOC is developed with a community of stakeholders from the realms of EO, education, information technology, and food security. It builds on contents from this community which are adapted, streamlined and assembled to course modules, as well as on the expertise from the over 20 contributing universities, space agencies, national institutions and international organizations. While the Zero Hunger MOOC contributes to bridging the gap between the available EO technology and its application to increase food security, it likewise promotes stronger stakeholder connection in EO education.

Keywords

SDG #2, Zero Hunger, MOOC, networking, community building

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Acronyms/Abbreviations

EO	*Earth Observation*
FAO	*Food and Agriculture Organization of the United Nations*
MOOC	*Massive Open Online Course*
SDG	*Sustainable Development Goal*

1. Introduction

In 2015, the United Nations defined 17 goals towards sustainable development to be reached by 2030. Sustainable Development Goal (SDG) #2 is dedicated to "End[ing] hunger, achiev[ing] food security and improved nutrition and promot[ing] sustainable agriculture" [1]. The world has made progress in reducing global hunger over the past decades and there is evidence that our food supply systems can adapt to the challenges of meeting future food demands. Yet, over 800 million people still suffer from hunger and 2 billion are malnourished [2]. And after some decades of steady decline in hunger, the uptick since the middle of the last decade uncovers the unvarnished vulnerability of food systems to climate and societal shocks [ibid.].

Earth observation (EO) has the potential to support food security by providing large temporal and spatial coverage information that allow for better planning and decision-making in food production and distribution. But while we are witnessing a dramatic increase in the volume of freely available EO data and in the number of open EO tools, insufficient diffusion of EO technology from the space to the user communities impedes its adoption to its full potential [3]. EO education helps to put EO technology into practice [3] and thus contributes to the adoption of EO technology in support of food security [4]. Due to its flexibility, reach and didactic possibilities, digital learning has proven to be a valuable instrument to promote learning for sustainable development [5] and even more in times of restricted access to formal education since the COVID-19 pandemic [6].

Stakeholders from academia, space agencies, institutions and organizations increasingly make their training materials available online at no cost. They thus acknowledge the need for open EO learning materials while sharing their instructional design and content with the EO educator community, promoting the synergies that strong communities yield. Through the contest "CONNECT Education-Research-Innovation", the German Federal Ministry of Education and Research is funding five projects that work towards strengthening international cooperation in research and extending existing networks around innovative nucleus projects. EO Connect is one of the winning CONNECT-FIVE projects. It addresses the rapidly growing demand for low-barrier access to EO knowledge and applied skills for food security by developing a Massive Open Online Course (MOOC) towards SDG #2, hereafter referred to as the Zero Hunger MOOC. It uses the advantages of knowledge and learning material exchange across EO educator networks, likewise strengthening and widening the networks. Its objectives are:

- to develop a MOOC on the role of EO for the Zero Hunger Goal,
- to strengthen the EO educator community around this joint effort.

2. Dissemination of EO-based approaches towards SDG #2

2.1. EO education for food security

The capacity of EO-based approaches to support reporting towards the SDGs and to inform decision-making and planning for increased food security is widely recognized as it provides consistent, timely and disaggregated data at comparatively low cost [7]. The Food and Agriculture Organization of the United Nations (FAO) defines food security as a state where "all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" [8]. This definition reflects the multi-dimensionality of food security. A plethora of EO-based approaches around food security exists and can mostly contribute information at the supply side of food systems. Food production plays a crucial role for food security outcomes. Therefore, the Zero Hunger MOOC shall cover the food production system categories agriculture, livestock, forestry and fishery.

MOOCs enable large-scale teaching beyond traditional teacher-learner environments, where massive refers to the reach and basically unlimited learner participation and open to the accessibility of the resources [9]. These characteristics make MOOCs particularly relevant in the context of a global goal such as Zero Hunger. EO-based approaches that can contribute to food security are numerous and so is the number of fields where learners can make use of them. To account for this heterogeneity, the Zero Hunger MOOC shall furthermore leverage modern learning approaches like non-linear learning, and use micro-content and drip-

DOI: 10.5821/conference-9788419184405.114

feeding, which are particularly effective for reaching applied learning goals in a practical setting [10]. Thus, the MOOC shall cater to the diverse needs of the large target audience, and offer the possibility to select different learning paths according to their scopes and levels of desired learning depth.

2.2. Target group definition

To design a course, defining its audience is key. However, if every person involved in the global food system is a potential beneficiary of the Zero Hunger MOOC, the target audience become highly heterogeneous with respect to their background, knowledge and motivation. Based on fictitious personas, we identified three distinct target groups:

- Group 1: Persons who are technology proficient, sufficiently equipped and seek to use EO data for their work
- Group 2: Persons seeking EO-derived information for personal or business decisions (e.g., optimization of fertilizer application), but who are unlikely to start processing EO data because of technical constraints or because of low cost-efficiency
- Group 3: Persons in key positions in the public or private sector, wanting to get familiar with the capabilities of EO-based approaches for decision-making

The target groups serve to facilitate communication and idea exchange. They are useful in defining learning paths, desired learning outcomes, foreseeing challenges, and validating finished modules. Group 1 is likely to draw the most direct benefit from the Zero Hunger MOOC and therefore served as the focus target audience.

3. Stakeholder community building around the Zero Hunger MOOC

3.1. Activating stakeholders and organizing collaborative work

At the start of the conceptualization phase of the Zero Hunger MOOC, a call to action was launched to make potential collaborators aware of the opportunity to join forces towards the Zero Hunger MOOC. The call was shared in existing networks including people with whom previous or current formalized project work was conducted, research collaborators, institutions with previous or ongoing in-kind activities, formalized networks, key persons at institutions, former colleagues and students. Therefore, most respondents were from the closer existing networks, but also included stakeholders without previous collaboration. This initial call already resulted in the registration of around 20 interested stakeholders.

During the following meetings, we pitched the MOOC draft concept and created space for experience and idea exchange among the potential collaborators from academia, public and private sector. Afterwards, we created a database of our own learning materials and the ones stakeholders wanted to contribute. Work was further organized through a collaborative whiteboard with the following categories: Content and learning goals, available materials, personas and respective challenges, stakeholder areas of expertise, and learner feedback options. This board enables continuous collaboration and provides transparency to the stakeholders.

3.2. Defining a common language

To ensure efficient collaboration, we had to define a common language. In terms of how to speak about the role of each collaborator, we defined the following main tiers of collaboration, which exist in combination and may change over time:

- Tier 1: Stakeholders who contribute learning materials and give feedback on the modules they contribute to
- Tier 2: Stakeholders who engage in knowledge exchange on the course's instructional design or act as experts or resource persons on specific EO or food security-related topics
- Tier 3: Stakeholders who endorse the course and provide their own networks to promote the MOOC

Tier-1 collaborators provide a wide range of different materials, from literature to videos, quizzes and tutorials. A simplified typology based on the actual contributions is presented in Table 1. Sources are usually text-form materials stakeholders recommend for specific EO and food security topics. They provide context and content for MOOC modules rather than didactic elements. Type-I and Type-II learning materials include content and didactic elements with or without the intention of use outside of the teaching environment. The most complex type of contribution is a full course, which is self-contained and comprehensive for a specific topic. The material type has direct implications on how content is used to create MOOC modules.

Type-I and Type-II materials are often easy to embed in the module context, although the quality differs. In contrast, sources require didactic preparation. Full courses that can span hours of learning have to be dissected to extract individual elements. All materials need to be arranged and streamlined to fit the module's learning goal, as well as adapted to a common Zero Hunger MOOC layout. Available content is shortened or expanded by additional content to fill gaps. It is critical to share how the materials are adjusted, complemented, referred to with the stakeholders, and how they acknowledged.

Table 1. Simplified learning material typology

Material type	Description
Source	Mostly text-form materials as suggested or curated by the stakeholder; e.g., research articles, reports, policy briefs
Learning material - Type I	Digital learning materials created without the explicit intention of reusing them outside the original teaching environment; e.g., university course tutorials, vocational training materials
Learning material - Type II	Digital learning materials created with the primary or secondary aim of making them available outside the original teaching environment; e.g., webinars, workshop recordings
Full course	E-learning courses or other high-end self-contained materials, often hosted on specific platforms or downloadable as standalone products; e.g., MOOCs

4. Development of the Zero Hunger MOOC content

4.1. Mapping available resources

To define the MOOC outline, we followed a two-pronged approach. On one side, we defined our expectations on what should provide based on literature research and on the personas. On the other side, we mapped the provided and potential further open learning resources. Then, we overlaid them to refine the MOOC outline.

Mapping and describing the resources on the collaborative whiteboard crystallized into clusters around food production systems, hazards, basics of remote sensing, and climate as a potential impact on each production system. Since many materials belonged to multiple categories, we assigned tags to them. Tag categories are, for example, background and tutorial, the food production systems, optical and radar imagery, tools, specific sensors etc. This approach also allowed simulating possible learning paths through the mapped materials.

4.2. Shaping course modules

The course has a modular structure which allows learners to choose the entry point and thematic focus. It is designed as a sequence of shorter modules which offers different learning paths and uses the advantages of micro-learning. The more modules are released, the more can learning paths differ and the more can learners be supported with adaptive learning, e.g., through a recommender system. The modules are defined based on the mapped learning resources at the intersection of the food production systems and the target audience, paying special attention to transferring knowledge and technical skills around the SDG #2 targets and indicators. How much content should be released around which food production practice is evaluated from the available resources, but also from their representation in a selection of relevant publications and conferences.

Interaction of stakeholders and the core team on and learner feedback shall guide course development and thus help optimize the content and the didactic form in which it is provided. The stakeholders who provide content for a module as well as stakeholders that act as experts in the respective field are consulted before it is released (Tier-1 and Tier-2 collaboration). In contrast, learner feedback is enabled post-release. Each module has a feedback section and possible other, more targeted learner feedback is envisaged to be gathered, the reaction to which is enabled by the flexibility of sequential module release. In combination with a user survey upon registration, this also serves as a monitor of whether the target audience is reached. In particular in the beginning, Tier-3 stakeholders will contribute to reaching potential learners by disseminating the course through their networks.

5. Discussion

5.1. Collaborative course development

Figure 1 represents the Zero Hunger MOOC approach to course development. It accounts for the diverse factors that hamper, and the variety of EO-based approaches that support food security. It acknowledges the value of networks and the existence of available high-quality third-party learning materials with their potential to create new course materials based on them. Enhancing community building in EO and making learning resources extensively available, usable and reusable have become widely recognized goals in the EO landscape. All collaborating stakeholders were motivated and positive about their contributions towards the MOOC. Yet, more non-conventional and often non-formalized collaboration entails challenges concerning interaction and technicalities.

When partners collaborate officially and formally, they discuss and define their roles before formalizing the collaboration. They also develop implicit knowledge on the partner's expectations and way of working throughout the process. In contrast, the explicit and implicit knowledge that regulates the collaboration does not exist per se in looser cooperation. This increases the risk of misunderstandings around the tasks, can lead to a loss of interest, reduced effort and eventually even to dropping out of the collaboration. In the case of the Zero Hunger MOOC, misunderstandings mostly revolved around the role and thus types of engagement and around which learning resources to share and how. Therefore, it proved to be a prerequisite to successful communication to develop a common terminology around these aspects.

On the technical side, some materials and logos needed clearance from other administrative levels or from responsible persons other than the Zero Hunger MOOC point of contact within an institution. In some instances, individual elements in full courses fell under the licensing of additional third parties, which complicated the access to the respective resources. Particularly when additional administrative levels or third parties not previously and directly involved are addressed, using the developed vocabulary simplified the communication. This finding is in line with other efforts to define common standards of communication on existing learning resources in order to facilitate exchange within the EO community.

5.2. The Zero Hunger MOOC

MOOCs cater to a large audience and are therefore well adapted to work towards a global goal. However, preparing a course around a complex topic and for heterogeneous learner groups with different backgrounds constitutes a big challenge. MOOC development can hence particularly benefit from approaches that differ from conventional linear course layouts. Smaller-sized content and freedom in choosing the learner journey according to the topics of interest and learning objective allows to customize the learning experience. Smaller adjustments to module design can then be made based on learner feedback to already released modules. To which extent the feedback can be integrated has yet to be tested.

Other challenges are related to working with available open online resources from our own previously released courses and from other stakeholders. Looking at and mapping out available resources showed that some categories were under-represented (e.g., EO and livestock, agroforestry). It was interesting to note that some resources were open, but still had access barriers to learners (e.g., outdated Flash course infrastructure or only temporary access to courses). To us, some had barriers like complicated procedures to get clearance for reuse or generally complex acknowledgement and permission regulations for different parts of existing courses. Moreover, although a large number of good learning materials was available, the effort of curating, reducing, expanding, assembling and streamlining them should not be underestimated.

6. Conclusions

Online learning yields unparalleled opportunities to disseminate EO knowledge and approaches around food security to users who can put it into practice. EO educators increasingly work towards providing learning resources to a large audience at no cost and towards establishing viable networks that render this dissemination more effective and efficient. The Zero Hunger MOOC as a common goal has shown to be a good occasion to signal willingness for collaboration on common topics within the course and beyond it. This can lead to solidifying existing relationships and can broaden the network for future formal and non-formalized collaborations, thus contributing to the community-building goal in EO education.

The Zero Hunger MOOC pilots a concept that values high quality third-party materials and the potential that non-linear learning and modern learning concepts offer. This is particularly beneficial in the case of a field as diverse as food security and heterogeneous user community. This work lays out a promising concept. In the next phase, parallel module development and module release with the incorporation of learner feedback will bring further insights and show how the concept translates into practice.

Acknowledgements

We thank all stakeholders from various institutions, organizations, universities, and partners from the private sector who are contributing to the Zero Hunger MOOC with their training materials, expertise, insightful feedback, networks, and their ideas.

We also gratefully acknowledge the support and funding for the EO Connect project from the German Ministry of Education and Research through the German Aerospace Center (FKZ: 01DU20002B).

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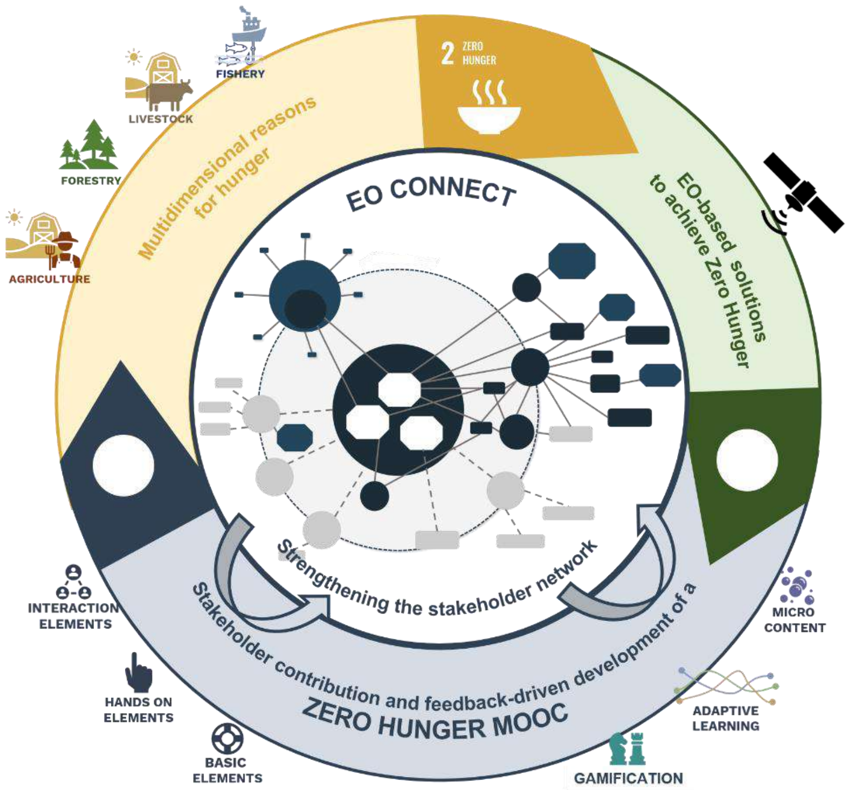

Figure 1. Graphical representation of the Zero Hunger MOOC development concept accounting for different reasons for hunger, EO-based approaches, and the exchange of knowledge and learning materials across networks while leveraging the potentials of modern learning approaches such as the use of micro-content and gamification. The course will be hosted on the EO College platform (eo-college.org).

Lessons learnt during the REXUS program on how to manage a student project

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Abstract

The paper discusses the lessons learnt during the SPEAR mission that takes part in the 12th cycle of the Rocket EXperiment for University Students (REXUS) sounding rocket programme. The mission originated after Delft Aerospace Rocket Engineering (DARE) designed a supersonic-capable drogue parachute and was unable to test it supersonically on the existing platforms available to the team. Hence, an experiment was proposed containing an ejectable test vehicle to deploy the parachute in supersonic conditions.
Throughout the 12th cycle of the REXUS program, the team has faced a number of challenges. Although during the project cycle the focus lied on resolving technical problems, in retrospect the logistical, social, and managerial challenges were just as relevant. Despite the fact that there is ample literature and knowledge available on methods to run commercial projects, it can be difficult to connect these practices to the workings of a student team. Therefore, this paper aims to collect and present the experience of the team on how to navigate challenges specifically related to student projects and their limited resources. Amongst which: 'employment' management (entry, performance and exit of team members), how to conduct internal and/or external technical reviews, assembly, integration and testing (AIT) efforts, planning and task management. As the team has gained these insights through trial and error, the mistakes made will be shared together with how this impacted the progress of the mission.

Keywords

Project management, mission planning, student project, REXUS.

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1. Introduction

The REXUS/BEXUS program allows students to perform experiments on top of a sounding rocket or balloon. [1]. The rocket flies, depending on the payload mass, to about 80km altitude. The platform is very suitable for small microgravity and flight test missions. As the payload opportunity is sponsored by the program organisers it is offered for free to universities and students. The Supersonic Parachute Experiment Aboard REXUS (SPEAR) was designed to fill the gap between simulations or sub scale testing and actual flight conditions of parachute recovery systems. The recovery team of Delft Aerospace Rocket Engineering (DARE) had access to a large database of literature and a subsonic wind tunnel, but no means to test the drogue parachute of Stratos III at representative flight conditions. SPEAR is a drop vehicle attached on top of the REXUS payload module and inside the nose cone. This allows it to be launched to the upper layers of the atmosphere, where it will be ejected and follow its own descent trajectory. SPEAR will deploy a stabilising drag cone to ensure a stable re-entry after which the drogue is ejected at supersonic velocities. After the experimental phase two main parachutes deploy, allowing the vehicle to land safely. Additionally, a telemetry system is included to transmit sensor data and video back.[2]

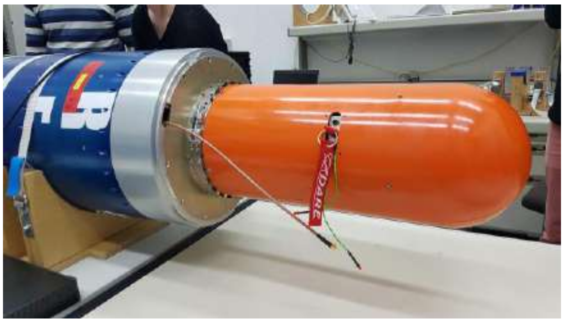

Figure 1. the SPEAR vehicle mounted on REXUS28

Within the SPEAR project, many challenges were faced and lessons learnt. Team members gained experience on the technical and managerial aspects of a project. Given that this experience consists primarily of tacit knowledge, it is not easily displayed or handed over through (technical) project documentation. This paper aims at describing this knowledge to aid future student teams and projects.

2. Lessons learnt

2.1. *Design*

External interfaces and requirements

With an external launch provider such as REXUS, there is a large external interface that sets requirements on your project. In this case the separation system design was primarily driven by vibration loads, where the REXUS programme maintained a high qualification level. However, other interfaces with the rocket, such as electronics and available volume are important as well. In the early phase of SPEAR, a larger diameter of the vehicle was foreseen by the team, which was later reduced when they were made aware of the REXUS nose cone ejection system dimensions. It is important to get a grip on these requirements early on and communicate frequently with the external parties. Not only because these requirements will drive your design, but due to the limited contact moments with external parties which makes changing interfaces difficult.

Design trade-offs

Within SPEAR, two trade-offs had a major impact on the full vehicle design. These were the separation system connecting SPEAR to REXUS and the vehicle stabilisation. During these trade-offs it was crucial that quantifiable data was gathered for all concepts, and to think through the selection criteria. The best design may only score averagely across all criteria and is a compromised solution. Quantifiable data, such as thorough and justifiable mass/volume/cost estimates, reduces the influence of subjective judgements, such as emotions.

Within SPEAR, seven concepts for a separations system were compared. Originally, the clamp band system was rejected at an early stage due to complex parts and significant production time. However, in the end this became the chosen system due to the cost of another system being underestimated and a requirement from the REXUS program being removed. This demonstrates that the trade-off results can also change throughout the project.

Rapid prototyping

Early on in the project, during the preliminary design phase, the team started making prototypes using fast and cost-effective manufacturing methods, of which especially 3D printing proved to be very useful. By making these early prototypes, the team got a better sense of scale of the vehicle and was able to identify mismatches between interfaces. Additionally, having a physical prototype of the vehicle helped to make the necessary design changes to improve the assembly procedure. It also enabled the team to show a physical version of the test vehicle to the launch provider (REXUS organizers) at a much earlier state than if representative flight hardware had to be produced.

Management of CAD

Within SPEAR, CATIA V5 was the software of choice for the mechanical design of the vehicle s, due to availability and previous experience. This version of the software does not allow for multiple people to

DOI: 10.5821/conference-9788419184405.115

work on the same file at the same time, therefore GitHub was used to share the files and allow for version control. Thus, work on the CAD model had to be properly coordinated and required rigorously following procedures. During work sessions this restricted the CAD work to one person.

Using familiar systems

Using a design that a team is already familiar with can be a great advantage to save on time and resources. The SPEAR team has based multiple systems on the experience from previous projects within DARE, which made it possible to meet the strict deadlines. For example, the clamp band separation system was very similar to that of the Stratos III rocket, which the majority of the SPEAR team was part of. The heritage reduced the development and testing time significantly.

Design reviews

Throughout the SPEAR project, multiple design reviews were held, both internally within DARE and with external parties, such as REXUS. Although design reviews with REXUS were mandatory, the team still opted to have additional design reviews within DARE. The usefulness of having multiple design review processes cannot be overstated. During the internal design reviews, more people were present with a background that matches the scope of the project, and that are familiar with the typical capabilities of DARE. On the other hand, the design reviews with REXUS proved to be valuable for the expertise on the vehicle layout, constraints, and programme. Additionally, the team experienced the different preliminary design review formats that were used by DARE and the REXUS organisation and tried to learn from this difference and implement the best aspects from both. [3] After organising a design review and receiving feedback, it is important to process this feedback in a useful manner. It is advised to keep track of the feedback given and make these points actionable through a review sheet; which contains clear action points including an ID, responsible members and status. This also enables a team to update the reviewers with how their feedback was processed.

Progressively more detailed design

When designing a system, especially one that is as complex as SPEAR, it is important to design from the top down. Starting to work out small design details while the larger subsystem hasn't been set in stone yet does not work well and can lead to additional work required or to be redone. Within SPEAR it happened that the electronics housing was completely designed down to the last bolts while the interface hadn't been determined yet. When the connectors changed from LEMO to a DSUB and the attachment point of the housing moved, all of the detailed design had to be redone leading to unnecessary time spent on it.

Within SPEAR the vehicle shape was largely determined by the available area in the REXUS nose cone and the flight stability of the vehicle. This in term lead to significant limitations for the internal configuration. It is important to gain insights into the driving requirements as early as possible such that they can be discussed and set early.

Importance of a small task with high repetition

Within SPEAR a few tasks, which are relatively low effort, had to be repeated countless times. Some examples: making many cables/connections between circuit boards or between the circuit boards and the peripherals, manually shortening bolts, assembling the M4 bolts on the pyrotechnic deployment device. Even if these actions take a small amount of time, the sheer number of repetitions makes it add up. In hindsight it would have been worthwhile to look into a different solution or design to decrease these tasks.

2.2. Production

Manufacturing

During student projects it is common not to have an experienced manufacturing engineer available. Some universities offer manufacturing courses or students rely on external parties. It is a skill that requires practice. It is recommended that students start early on in the project with manufacturing courses and keep their skills up to date. This helps later in the project when machining is critical. This not only saves time but also cost due to manufacturing errors.

Design changes throughout production and integration

Even if your design looks good on paper, in practise there will be some issues that require redesign. When building the SPEAR prototype vehicle for the first time, it became very clear that the small scale of the vehicle made it difficult to access certain components with tools. It was required to relocate some components to facilitate and speed up the assembly process. These issues can be prevented by setting requirements on minimum clearance for access, by test-fitting tools in 3D CAD models, and by writing thorough assembly procedures prior to manufacturing. Especially wire clamps in the main parachute deployment system were located in tight corners, which made them particularly hard to assemble and tighten. Another example is the main parachute canister lids that required multiple design iterations, such as proper tolerancing of the 3D printed parts, to guarantee for a successful parachute deployment.

General production tips – lathing & milling
Prior experience of metal machining allowed the team to identify design limitations that originate from the manufacturing capabilities, but nevertheless learnt some lessons along the way. The support guides for the separation system had a section of 3.0 mm diameter and 24 mm length, which proved difficult to produce due to the part bending away from the cutting edge. It is also advised to redesign parts to be made on the simplest machines possible. One of the SPEAR parts could only be produced with a CNC, and when neither the machine, nor an operator could be found, production, and thus assembly and testing was delayed.

General production tips – parachutes
The SPEAR team already had experience manufacturing parachutes from previous projects, however several lessons were learnt and recommendations can be proposed for other teams. Initially the SPEAR stabiliser was designed to be a ballute with a diameter less than 10 cm. Small parachutes are not only tedious to manufacture, but they also suffer from two issues: high stiffness and large relative manufacturing inaccuracies. Wind tunnel testing proved that the ballute would not be a feasible stabiliser for SPEAR, hence a solid drag cone was chosen.
When sewing parachutes that have a frequent and significant change in layer thickness or number, which regularly is the case for ribbon parachutes, it is challenging to set a correct thread tension. It is recommended to set the correct thread tension for the highest load-bearing parts (connection points) and accept a lower performance in other sections.

General production tips – composite parts
There are many different forms of composite production, varying in complexity and cost. Prepregs are far easier to work with and will use a lower amount of epoxy or resin, but they are expensive. Wet layup works well too, with a bit of practice, for approximately 25% of the cost. Mass predictions of composite parts are prone to the use of epoxy, which can be excessive with students or beginners. Wet layup will be more sensitive to this, however within the SPEAR project similar incorrect estimations were made for prepregs. The outer shell of the vehicle, budgeted at 300 grams mass, ended up weighing over 800 grams. It is recommended to include a wide margin on your mass budget for composite parts.
Next to this, specific equipment can be required during the production of composite parts, especially when curing in an oven and/or using vacuum infusion. There are no easy alternatives if any major infrastructure or tools are missing, so this needs to be considered during the design phase. For beginners, consider that your first 2-4 products will not be up to specs and/or usable. Finally, one has to carefully read and follow the labels of the used products, keeping parameters such as drying time in mind.
Include a draft angle on all parts where possible to aid the release. Within SPEAR the drogue parachute deployment tube did not allow for a draft angle as a sabot needed to guide the parachute over a long stroke. After the mould was used 2-3 times, it could only be removed by submerging the mould and product in a liquid nitrogen bath.

2.3. Testing

Frequent testing and assembly
The testing phase of a system is equally important as the design phase. Commonly, students have the tendency to rely heavily on calculations and simulations or assume that these match reality completely. However, during the SPEAR project, the importance of testing systems was clearly demonstrated. For example, the simulations of the drogue pyrotechnic ejection system matched poorly with the test data due to the complex nature of the phenomena. Similarly, the selection of a spring that was suitable for the ejection of the main parachutes proved to be a very iterative process, where frequent testing was necessary. Testing repeatedly also allows for multiple design iterations to optimise the functionality of the system. [4]
When testing it is important to be well prepared. Dry runs should be executed prior to an important test day, to check presence and correct fit of all parts and test data acquisition systems. Finally, a back-up day is advised as there are always unforeseen circumstances that can lead to postponing a test.

2.4. Management

Member turnover and reliance on individuals
Due to the cycle of the REXUS project and that of university there will be a change in team members throughout the project. This means there is a high turnover rate, peaking at the end of the academic year. It is crucial to allow continuity within the team such that the project can remain on schedule. When recruiting and introducing members into the team after the start of the cycle it is important to get them up to speed on the overall project quickly. New members can work together with experienced members to improve (tacit) knowledge transfer. It is

DOI: 10.5821/conference-9788419184405.115

also advised to start by giving them discrete, smaller tasks they can perform in order to get a hands-on approach early on while getting to know the system.
Each team member has their own skill set in which they excel. It is often tempting to have members do what they do best, especially when the project is on a tight schedule. However, it is not advisable to rely on a single individual to execute a task that can only be done by that person. Sharing skills and having knowledge-redundancy within the team is an absolute must to prevent skill- or knowledge gaps in case this critical member leaves the team or is not available. Documentation can help, however the assembly and testing phase comprises mostly of tacit knowledge which is difficult to write down.

Team bonding
Within the SPEAR team there was a strong feeling of team bonding throughout the project. The social atmosphere was excellent and the team also enjoyed off-time together. This meant that everyone got along with each other on a personal level as well. In every team and project, there will be stressful periods, especially before deadlines, tests or the launch. Friction can increase and it is very beneficial to have a good personal relationship with your teammates outside of the work you do on the project.

Team meetings and communication
Throughout the project, weekly team meetings were held to update all members on the mission progress and divide new tasks. These team meetings were purposefully scheduled during lunch time to force a maximum duration of one hour, which promoted a fast paced and efficient meeting. Separate work sessions were scheduled to perform (design) work for varying systems. However, the work sessions for mechanical and electrical systems were during different days of the week. It is recommended to schedule these at the same time to promote collocation of the team and regular informal updates and discussions on the design. The team has a flat organizational structure, with limited decentralized decision making [4]. The team leader and chief engineer reviewed all major decisions in the project, after these were discussed with the team.

Use of management tools
Within the REXUS project, it is required to include certain project management tools in the team documentation, such as a work breakdown structure (WBS), an organigram, task management, and a (long-term) planning overview. These are all incredibly useful tools to manage a team. However, they are tools that need to be actively used by all of the team. The WBS and organigram were made to comply with documentation criteria and were never revised or used afterwards, whilst this might have moved some attention to the ground station which stagnated throughout the project. Task management and planning were executed in Asana and Instagantt, two online tools for project planning. Although useful, it is time-consuming to enter and maintain all relevant tasks and long-term planning. It is deemed unfeasible for the team leader or any other single person to do this alone; it is necessary for the team members to be actively involved in updating their systems. The use of these tools by the team members in SPEAR was very limited; some actively updated their status but many did not regularly check or use the tools.
In a few sprints before deadlines there were many loose tasks that needed to be organised, and for this a large excel sheet was created. In general, excel sheets were used regularly to keep track of things in SPEAR: production progress, design changes, open action points. These to-do sheets were structured well and gave a complete overview: ID, system, changes/actions required, comments, who added the action point, who is responsible, status (design updated / produced / assembled / tested / completed). These sheets worked very well for the team. The largest downside is that there were many sheets for different phases of the project, however they were all collected in one place.

Internal versus external deadlines
The SPEAR project had clear and externally imposed deadlines by the REXUS project and for scheduled test campaigns. The team worked vigorously to make these milestones and complete the required work. However, it was seen that internal deadlines, with little to no repercussion when failed, were rarely met. The short-term planning also did not always include all required tasks to cumulate to the milestone point. Therefore, in a short timeframe it was much more difficult to reach a (steady) high level of progress. The effort continuously increased to a higher level before an external deadline. Even though this cyclic behaviour was noticed, it seemed unattainable to change it and spread the work load more evenly. This was also reinforced due to the necessity of rest and/or more study time after a busy period on the SPEAR project.

Adapting your planning
Within each project, unexpected road blocks will be encountered. These can increase the required time or costs of a project and requires flexibility in the team. During the SPEAR project numerous items did not occur as scheduled; a vibration test slot was available two weeks before the scheduled date, additional test campaigns were needed for the pyrotechnic mortar, the design and production of the electronics system took more time. These issues were generally solved, but they required additional time commitment from the team members on short notice. When members combine the project with a study program, this

flexibility is not evident. The majority of the SPEAR team members has at some point in time prioritised the project over their studies to keep the project on track, which is undesirable. It is unclear whether there are practical solutions for these problems, but it indicates advantages of a full-time student team. Lastly the SPEAR launch campaign was moved over eight times due to the COVID pandemic and other reasons, which required exceptional flexibility and time commitment from team members.

Prioritise

In a complex project it is important to prioritise features and functions using the slogan "First make it work, then make it better". During SPEAR it was seen that too much time was sometimes spent on a nice-to-have function, when primary functions were not yet working. It is up to the team leader, planner, and chief engineer to keep track of progress and prioritise resource allocation.

Documentation

Documentation in the REXUS/BEXUS project is done through the Student Experiment Description (SED). This is a quite large document describing the entire experiment. However, this SED is not an easy-to-read document to get people acquainted with the project. It is strongly recommended to keep writing short, almost paper like, documents at the end of a work package that people can pick up and read to get started with a new phase of the project. Besides these sections being easier to read, they also serve a different purpose. Where the SED is mainly used to detail your experiment to the organisers, these documents would be used to inform the team. Where the organisers are more interested in the final design, safety and external interfaces, the team is more interested in the design logic and choices and the internal interfaces.

Use of work packages

The use of work packages with clearly defined goals can be a pleasant and clear method of working for students within a bigger team, especially for less experienced or new members. Within the SPEAR project, work packages were created that specify amongst others an objective, due date and constraints. The use of small work packages can make individual team members work more independently, although it takes considerable initial effort for the team lead or system engineer to create the document.

Workspace resources

Having a workspace or office that is freely accessible to the team proved immensely useful. The Dreamhall had many tools and machinery to produce all mechanical lab, but the other office space was perhaps more important. It was where the electronics were soldered, parachutes produced and team meetings were held. It was also a place for the team to hang out, had informal meetings and in general improve the team spirit. Collocation is important for teams to enable face-to-face communication [5]. Doing a project of this magnitude without such a dedicated shared space is challenging and will require more planning of the available workspaces and reduce social cohesion.

Hand over to next team

Towards the end of the SPEAR project, a new team within DARE started on a mission called SPEAR II. Because the SPEAR team was still active on the project, there was a low threshold for the new team to reach out for questions. This, in combination with the extensive documentation of the SPEAR system and available CAD files, made the knowledge transfer process successful. Although the final design and testing of the SPEAR vehicle were well documented within the SED, the design process itself, including iterations and trade-offs, was not as elaborate. It is recommended to also include these sections in order to prevent reinventing the wheel or repeating mistakes. Additionally, if possible, performing system tests or integration together with the new team are highly effective ways to hand over a project and transfer knowledge.

3. Conclusion

There are many lessons learnt from the SPEAR project, which go much further than the technical and mission goals. These lessons are valuable to the engineers in this project and their future careers. With documentation such as this paper it is hoped that these lessons can also be used by other students to improve their projects. Furthermore, these lessons learnt show the importance of student projects to the industry in its totality.

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DOI: 10.5821/conference-9788419184405.115

Flight Hardware and Software Operations Performance Review for BAMMsat-on-BEXUS – a BioCubeSat Prototype Flown on BEXUS30

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Abstract

BAMMsat-on-BEXUS is a student-led project in which a CubeSat-compatible payload was designed, manufactured, and flown on the BEXUS30 stratospheric balloon. The prototype payload – BAMMsat (*Biology, Astrobiology, Medicine, and Materials Science on satellite*) – is a modular CubeSat-compatible miniaturised laboratory termed a bioCubeSat. The core flight objective was to perform technology demonstration of the bioCubeSat technology, demonstrating capability to perform experiments in space, and to understand system performance and identify future requirements. The mission aimed to validate pre-flight, flight, and post-flight operations, with a focus on biological and autonomous operations and the novel payload hardware. *C. elegans* samples were flown in the payload. The mission was partially successful, as the BAMMsat systems and autonomous software operated successfully despite challenging conditions and a large volume of payload performance data was collected; however there were issues maintaining the viability of the samples during flight and microfluidic system issues that impeded sample containment and imaging operations. Post-flight analysis has been performed, the root causes of the issues identified, and upgraded novel payload hardware is currently being developed and tested.

Keywords

BioCubeSat, Laboratory, Operations, Stratospheric balloon

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DOI: 10.5821/conference-9788419184405.116

Acronyms/Abbreviations

ADC	*Analogue-to-digital converter*
BAMMsat	*Biology, Astrobiology, Medicine, and Materials Science on satellite*
BEXUS	*Balloon Experiments for University Students*
BoB	*BAMMsat-on-BEXUS*
C&DH	*Command & Data Handling*
MCSD	*Multi-Chamber Sample Disc*
PCB	*Printed Circuit Board*
RTD	*Resistance Temperature Detector*
SPI	*Serial Peripheral Interface*
TRL	*Technology Readiness Level*

1. Introduction

BAMMsat-on-BEXUS (BoB) was a student-led project in which a CubeSat-compatible payload was designed, manufactured, and flown on the BEXUS30 stratospheric balloon. The prototype payload – BAMMsat (Biology, Astrobiology, Medicine, and Materials Science on satellite) – is a modular CubeSat-compatible miniaturised laboratory termed a bioCubeSat. This is the 2nd iteration of BAMMsat, and was flown with the goal to develop and better understand the payload hardware and systems, software and autonomous operations, and biological operations. The primary objective of BoB was to demonstrate a capability to support biological experiments in space. Increasing the Technology Readiness Level (TRL) of the BAMMsat platform via this initial flight will support future work on orbital versions of the platform with the goal to eventually enable better and cheaper research in space environments.

2. BioCubeSat Heritage

The bioCubeSat concept is established and has limited space heritage; six bioCubeSats have been successfully demonstrated in Low Earth Orbit by NASA, and one by a private company, SpacePharma. The previously flown bioCubeSats are GeneSat [1], PharmaSat [2], O/OREOS [3], SporeSat [4], Dido-2 [5], EcAMSat [6], and Dido-3 [7]. BAMMsat leverages experience gained from these to contribute to the advancement of the field.

3. System Architecture

The design ethos of BoB was scoped to meet the tight deadlines of a one-year (extended to two-years due to exceptional circumstances) student project, while still providing a robust system appropriate for the extreme environments in stratospheric flight, close enough to eventual spaceflight models such that valuable performance data could be gained during the BEXUS30 flight. An extensive verification and testing campaign was required to qualify the systems for the stratospheric demonstration flight.

BoB is effectively split into two distinct systems: the 2U pressurised payload which contains BAMMsat's core systems and technologies, and a 1U avionics bus that provides power management, Command & Data Handling (C&DH), and an interface to the BEXUS balloon gondola. An exploded CAD model of the system is shown in Figure 4.

3.1. 2U Payload

The 2U payload contains BAMMsat's core systems and novel technologies, including:

- The Multi-Chamber Sample Disc (MCSD), where the biological samples are housed.
- A Geneva Drive rotary mechanism which enables direct access to each discrete sample chamber for microfluidic and imaging operations via rotation of the MCSD.
- An optical camera and LED to take observations of each sample chamber.
- A microfluidics system enabling various fluids – such as growth fluid and preservative – to be pumped in and out of each sample chamber.
- An active thermal control system, enabling life support for the biological samples.
- A suite of additional sensors monitoring environmental conditions, the microfluidics system, and enabling additional autonomous hardware operations.

The MCSD, shown in Figure 1, contains 32 discrete sample chambers. It comprises multiple layers of different materials with laser-cut pathways enabling microfluidic transfer operations, and an aluminium load spreader to ensure even torquing of the system when installed.

For the BEXUS30 flight, several different strains of *C. elegans* were loaded into the sample chambers, allowing insight to be gleaned on the performance of the environmental control systems by monitoring the behaviour and motility of the different strains, which have different growth phases, characteristics, and responses to varying temperatures.

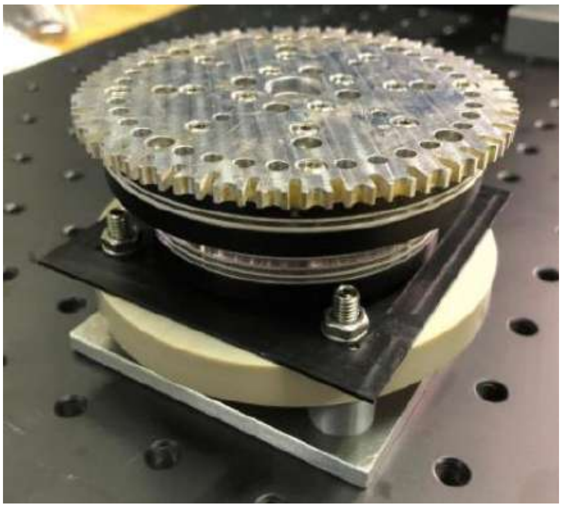

Figure 1. Multi-Chamber Sample Disc

The MCSD facilitates late loading of biological samples, although at the time of flight the rest of the BoB system did not properly support this as complex re-assembly of the surrounding systems was required.

A Geneva Drive rotary mechanism – autonomously controlled using an incremental rotary encoder and photo-microsensor – enables full rotation of the MCSD in both directions, allowing each sample chamber to be accessed by the microfluidics system or imaged in turn.

The optical camera was an off-the-shelf Raspberry Pi v2 camera, which can be modified by installation of additional optics for better resolution and focus on the sample chambers.

The microfluidics system – external to the pathways inside the MCSD – comprised a series of fluidic reservoirs connected to a manifold, in which solenoid valves were installed to control fluid flow. A micropump, flow rate sensor, and liquid bubble photosensor were used to control and monitor microfluidic operations.

Also contained in the pressurised 2U payload are several bespoke PCBs and wire harnesses interfaced with the 1U bus via a hermetic feedthrough.

3.2. 1U bus

The 1U bus houses the C&DH and Electrical Power System (EPS), and provides the interface between the payload and BEXUS balloon gondola. Two external photodiode sensors were included to monitor sunlight exposure during flight. Due to interfacing and volume requirements, the 1U bus was produced solely for the BEXUS flight, and will be completely re-designed for an orbital system.

3.3. Computer architecture

BoB used two flight computers: a Raspberry Pi 0 for communications and general control, and an auxiliary ATSAMD51-based microcontroller provided additional Serial Peripheral Interface (SPI) buses for use with the analogue-to-digital converters (ADCs) providing thermal sensing, and served as a redundant watchdog in case of issues with the primary computer. The Raspberry Pi simplified the imaging system design,

Python was used for the majority of the flight code; its simplicity and flexibility were well-suited to a fast-paced student project and enabled rapid prototyping of the advanced autonomous operations. However, an extensive testing campaign was required to qualify the software for flight, as it is generally easier to miss issues in Python than in strictly typed and compiled languages such as C++, which was used for the auxiliary flight computer software.

3.4. Software operations

Flight software was designed to be fully autonomous where possible, with minimal operator intervention required. This included not only general housekeeping and environmental control systems – such as thermal control – but also the entire experiment sequence which comprised MCSD rotation, imaging, microfluidics operations, and autonomous error-correcting operations where anomalous system states are identified. Manual override was available at all times during the flight, so long as there was an active communications link.

Prototyping autonomous operations was important to increase the TRL of the general system, as in order to reduce the operating costs of future orbital missions, the system must

DOI: 10.5821/conference-9788419184405.116

be able to operate fully autonomously between ground passes and – if hosted on the International Space Station or a future commercial station – astronaut time requirements must be minimised.

The general system architecture and autonomous operations requirements has been discussed further in previous work [8] [9].

4. Flight

The evening prior to flight, the *C. elegans* samples were loaded and fed growth media using the microfluidics system. During pre-flight feeding operations, an unplanned power cycle was forced to halt MCSD rotation, as an unusual noise – investigated earlier in the day - was heard. As the rotary encoder is incremental only, a power cycle mid-rotation could cause loss in information of the current aligned chamber, or lead to misalignment prior to flight. However, the autonomous error-correcting code resolved the issue and re-aligned the MCSD on power-up.

The noise was the result of small leaks in the MCSD and subsequent corrosion of the primary securing bolt by the growth fluid, which has high salt content. It was determined that the system was still suitable for flight, as the rotary mechanism has sufficient torque to rotate the MCSD despite bolt corrosion.

At the start of flight countdown, all systems appeared nominal. However, as countdown progressed and external temperatures decreased, anomalous readings were noted in some of the Resistance Temperature Detectors (RTDs) used for thermal control. It is likely that the issue was not with the RTDs themselves, but with either the ADCs or 2U PCBs (which would affect the SPI buses) being impacted either by thermal contraction or increasing humidity within the pressure vessel due to MCSD leaks. This remained an issue throughout most of the flight, though fortunately most critical sensors were unaffected, so thermal regulation of the samples was possible. Autonomous thermal control was occasionally overridden by operator command to compensate for the anomalous temperature readings, especially during the harsh ascent phase.

During flight, there were several periods of communications blackout. This was not a problem, as BoB was already on its own internal countdown and the entire experiment sequence proceeded autonomously. The flight phase was several hours longer than expected, so after communications was restored, it was possible to perform several additional semi-autonomous experiment sequences. A large volume of data was collected which has helped to understand system performance.

5. Results and Discussion

6.61 GB of imaging data – comprising 125 photos and 95 videos of the sample chambers – was collected, as well as housekeeping data from all sensors for the entire flight duration, although the RTD data was partially compromised by the anomalous readings.

Sensor data showed the pressure vessel and electrical subsystems performed nominally. The thin-film heaters also maintained adequate thermal control, however this had to be manually supervised due to the previously-mentioned RTD issues. Although MCSD temperatures appeared to stay within range, qualitative inspection of the *C. elegans* indicates that the rate of heating may have been too high to maintain good health. However, due to the lack of thermal sensors inside the sample chambers, it is not possible to say with certainty whether there was a thermal issue. This must be investigated further for future BAMMsat generations. Figure 3 presents the temperature of the sample disc top surface recorded during flight.

Humidity data and unusually poor fluidic pump performance indicated that the MCSD was leaking significantly, likely due to a mixture of bolt corrosion, and a design issue: the MCSD comprised too many layers, creating many possible areas for leaking. This was confirmed post-flight, as growth fluid residue was found on the inner insulation of the pressure vessel.

A combination of leaking, a lack of semi-permeable membranes on the sample chambers, and possible pre-flight sample integration issues meant only a few of the *C. elegans* samples could be imaged during flight. An example of an imaged chamber is shown in Figure 2. Some others had likely leaked, and some were only found in post-flight inspection, having relocated down the fluidic channels out of sight. Semi-permeable membranes would have prevented this issue, and will be included on future flights. It was noted, however, that progeny was produced, likely during the flight itself, and there were several viable – though unhealthy – samples still alive during post-flight inspection.

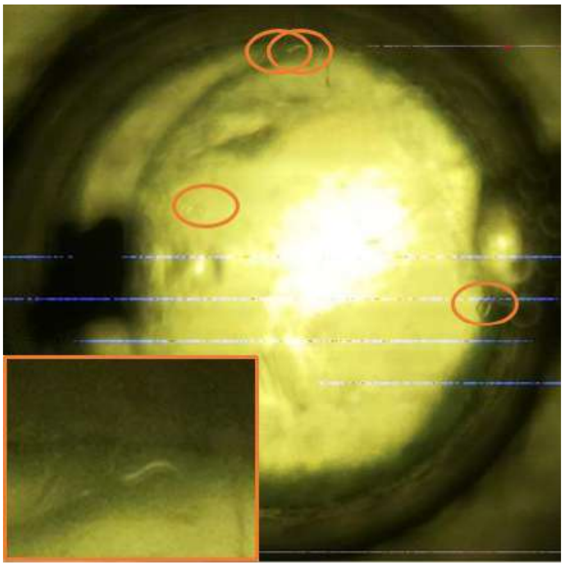

Figure 2. Sample chamber during flight showing four *C. elegans* samples

While there were several issues during flight, the large volume of engineering and imaging data gained has helped to understand payload hardware performance, and improved versions are currently being manufactured and tested for a 4th generation of BAMMsat. Supporting systems operated nominally despite challenging conditions, and the software and autonomous operations systems performed excellently, and will be updated to work on new hardware and spaceflight-suitable computing hardware.

6. Conclusions

BoB was flown on the BEXUS30 stratospheric balloon to demonstrate and collect performance data on payload hardware, supporting pre-spaceflight systems, software, and biological and autonomous experiment operations. While design issues were noted during flight, the experience and data gained has already informed the design of upgraded payload hardware. We consider the design of several BAMMsat systems to have advanced from TRL4 to TRL5-6.

The MCSD and microfluidics system – the most novel technologies, and those which presented most issues during flight – are currently being upgraded and are now produced using additive manufacturing to significantly reduce the complexity, layer count, and potential for leaks. Cranfield University and a spin-out company – Frontier Space Technologies – are collaborating to produce the next generations of BAMMsat with the goal for an orbital demonstration in the near future.

Acknowledgements

Many thanks to all members of the REXUS/BEXUS programme, without whom this would not be possible. The REXUS/BEXUS programme is realised under a bilateral Agency Agreement between the German Aerospace Center (DLR) and the Swedish National Space Agency (SNSA). The Swedish share of the payload has been made available to students from other European countries through a collaboration with the European Space Agency (ESA). EuroLaunch, a cooperation between the Swedish Space Corporation (SSC) and the Mobile Rocket Base (MORABA) of DLR, is responsible for the campaign management and operations of the launch vehicles. Experts from DLR, SSC, ZARM and ESA provide technical support to the student teams throughout the project. REXUS and BEXUS are launched from SSC, Esrange Space Center in northern Sweden.

Additionally, we thank Cranfield University, the University of Exeter, and our sponsors Hamamatsu Photonics, Bartels Mikrotechnik, FAULHABER, Sensirion, 3D Hubs, and ES Precision for their support.

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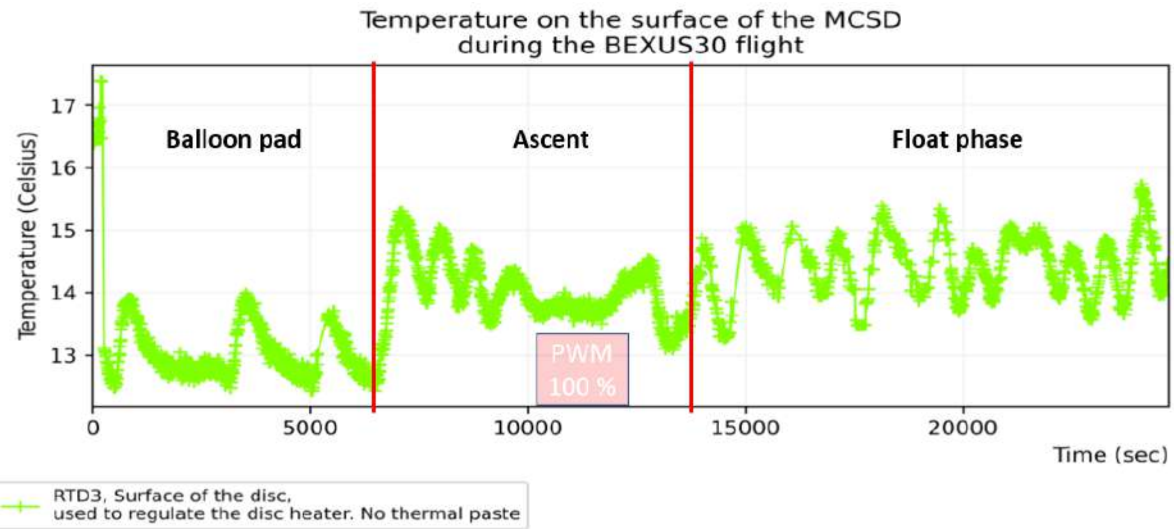

Figure 3. Temperature on the surface of the MCSD during the BEXUS30 flight

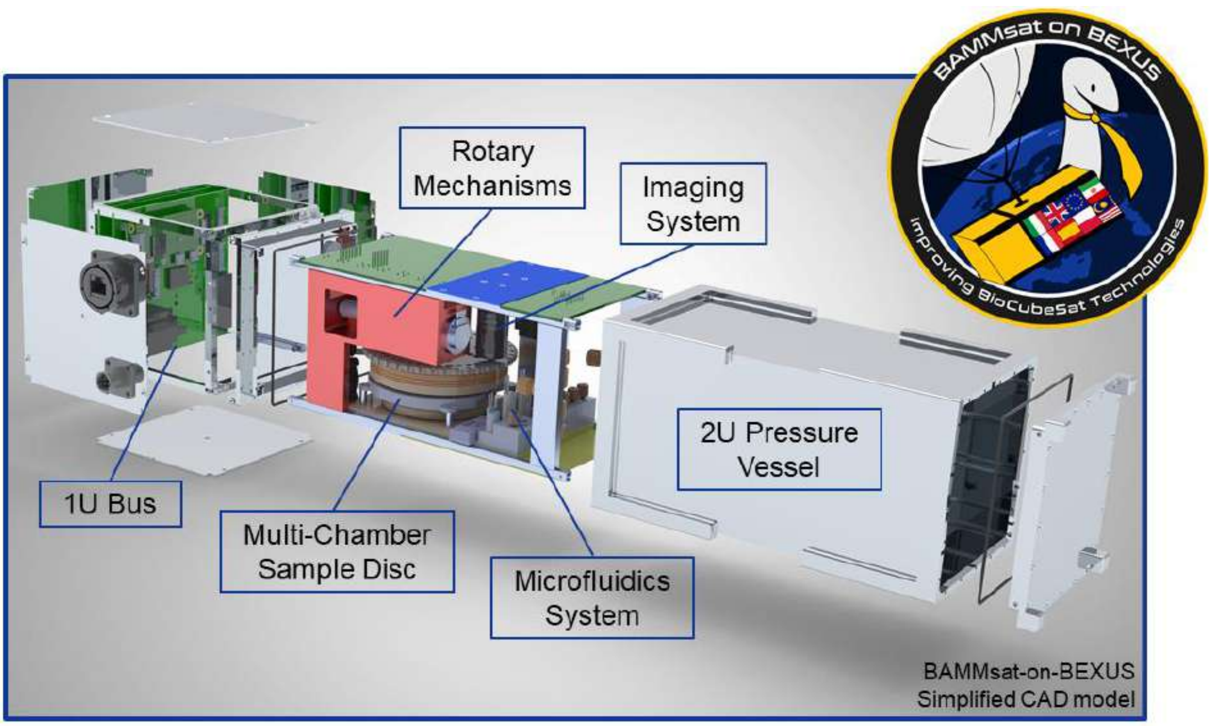

Figure 4. Simplified CAD view of BAMMsat-on-BEXUS

DOI: 10.5821/conference-9788419184405.116

Development and Flight Results of TalTech University CubeSat Mission

Muhammad Shadab Khan[1], Rauno Gordon[2], Martin Simon[3], Kristjan Tonismae[4], Dzmitry Kananovich[5], Veljo Sinivee[6], Marko Karm[7], Kaarel Repän[8]

Abstract

Student Satellite program at TalTech, Tallinn University of Technology, Tallinn, Estonia was initiated in 2014 with an aim to impart space technology knowledge to the Estonian students as well as assist towards development of new Space Technologies in Estonia. Two 1-Unit CubeSat named Koit and Hämarik that translates respectively as Dawn and Twilight in Estonian are part of the TalTech Satellite Program. The main scientific mission of the CubeSats was to demonstrate Earth observation and Optical Communication technology. Satellites had two types of cameras, an RGB Camera and an NIR Camera to carry out Earth Observation over Estonia. Testing High Speed Optical communication technology from LEO (Low Earth Orbit) was the second major scientific goal and for this purpose the CubeSats had LED (Light Emitting Diode). Koit CubeSat was successfully launched to space on-board Soyuz rocket on July 5, 2019 and Hämarik CubeSat was launched to Space on September 3, 2020 on-board Arianespace Vega Rocket. Koit CubeSat did not contact the Ground station for more than a year since its launch and it was assumed to be lost but on November 21, 2020 it made the first contact with the Ground Station. Hämarik CubeSat was first contacted on November 15, 2020. The team has been successful in updating software of Hämarik and further work is being done on the software with broader functions. Optical communication has not been tested yet because ground station for optical communication has not been developed yet but a good achievement in the path to optical communication was to see the satellites with small hobby telescope and one of the satellite team member was successful to detect the Hämarik CubeSat on 17 August 2021 which was at a distance of about 792 Kilometres. Satellite team is in contact with the Hämarik and has been successful to download a few thumbnails and is working to establish a quick data connection with it and determine its exact position so that the cameras can be focused towards the Earth in order to get the whole images captured by the CubeSat.

Keywords
CubeSat, TalTech, Estonia

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Abbreviations

ESA ***European Space Agency***
EPS ***Electrical Power System***
ADCS ***Attitude Determination and Control System***
LED ***Light Emitting Diode***
SSMS ***Small Satellite Mission Service***
LEO ***Low Earth Orbit***
COTS ***Commercial off the shelf***
POD ***Poly-Picosatellite Orbital Deployer***
NIR ***Near Infra-Red***
OBC ***On-Board Computer System***
FPGA ***Field programmable Gate Array***
UHF ***Ultra High Frequency***

1. Introduction

CubeSats are a class of Nano-Satellites that are small in size and low in cost. The standard CubeSat size uses a "one unit" or "1U" measuring 10x10x10 cm^3 and is extendable to larger sizes; 1.5, 2, 3, 6, and sometime more larger version in 12U format [1]. There is growing demand of CubeSat Technology globally for various applications considering its low cost of development. While CubeSat technology provides a cheap and low cost access to Space, it is also helpful to provide training to University students to help them get first-hand experience in Spacecraft Engineering in different aspects like Design, Manufacturing, Testing and Project Management to help them prepare to contribute to the Space Technology activities in their respective countries. Space Technology activity in Estonia was initiated with the successful launch of the First Estonian Satellite "ESTCUBE-1" in 2013 that was designed and built by the students of University of Tartu [2]. The success of the mission inspired other Estonian Universities to start Student Satellite Missions and in this regard the Satellite Program started at TalTech University of Technology, Tallinn, Estonia in 2014 to not only provide hand on training to the students of the University in Spacecraft Engineering but also to propel Estonia to higher Orbits in the field of Space Technology. The Satellite program at TalTech University is supported and funded through Estonian Government and the European Commission to encourage scientific research in Estonia. DATEL and several other Estonian companies are also sponsoring the Satellite program. In the framework of the Student Satellite Program, 1-Unit CubeSat mission was chosen to be built by the University students from different backgrounds with the support of the Professors, University Laboratories and other partner laboratories in Estonia. The Satellite Program [3] is operated at the Mektory Space Centre of the University and is led by Dr. Rauno Gordon and there were about 70 students working on different aspects of the CubeSats including some interns from other countries.

European Union
European Regional
Development Fund

Investing
in your future

Figure 1. European Union Development Fund

2. Satellites

1-Unit CubeSat according to the CubeSat Design Standard was chosen to be developed as part of the Satellite program and Mission concept and top level requirements including feasibility study and preliminary design was completed in 2015 and. During 2016-2017 construction of the CubeSat subsystems and Frequency permits and legal documentation were obtained. The CubeSats were named as Koit and Hämarik that translates respectively as Dawn and Twilight in Estonian. Koit was the first CubeSat (Fig.3) to be developed and readied for launch and its flight Model was ready in early 2019. Hämarik was the second CubeSat (Fig.2) to be developed and its flight model was ready by January 2020.

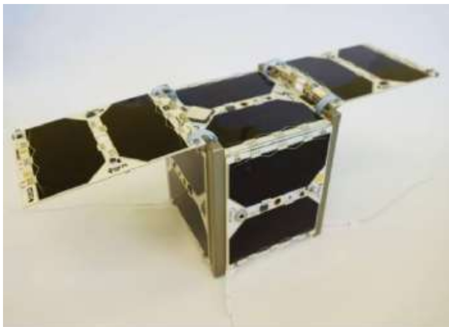

Figure 2. Hämarik CubeSat Flight Model

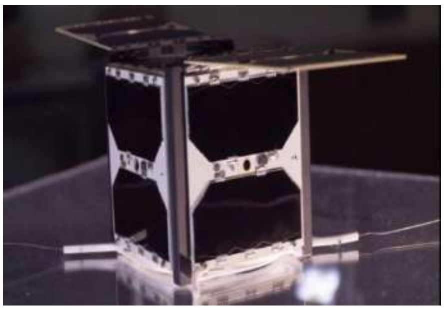

Figure 3. Koit CubeSat Engineering Model

DOI: 10.5821/conference-9788419184405.117

3. Scientific Mission

The primary scientific mission of Koit and Hämarik CubeSat is Earth observation and demonstration of Earth observation technology. The satellites include two cameras (RGB and Infrared), image processing and communication with ground station. For cameras RGB sensor for visual light image and NIR (Near Infra-Red) sensor for near-infrared image was used to help in assessing vegetation growth, climate, geology and sea conditions. Image processing on the satellite makes sure that only those images that provide valuable information are downloaded. The main objective was to provide Satellite Imagery about the water and vegetation in Estonia and for this purpose the camera angle orientation was such that it points to the Estonian geography as shown in the Fig.4.

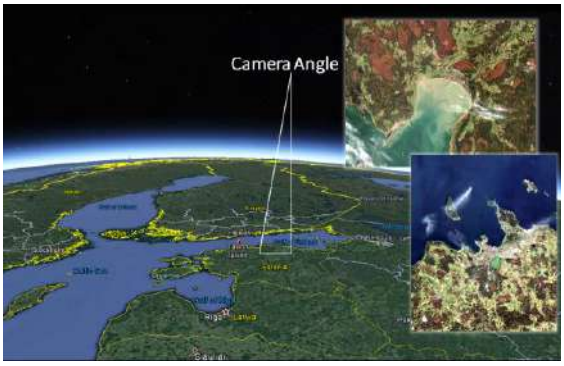

Figure 4. Camera Orientation over Estonia

In addition to Earth observation technology there are scientific experiments: computational fault tolerance and optical communication. The experiment for fault tolerance of computers is carried out on a reprogrammable FPGA integrated circuit. Different computer hardware configurations can be implemented in this chip. For optical communication experiment LEDs and laser-diodes were integrated in the satellite to transmit signals. The blinking satellite was to be observed by a tracking telescope with optical sensors that can see the satellite and decode the data. Satellite is able to turn the LEDs and lasers towards ground and transmit test signals. Telescope tracks the motion of the satellite and it is possible to see slow blinking. This way it is possible to send data to ground from the satellite.

4. CubeSat Subsystems

System and Subsystems components on both the CubeSats Koit and Hämarik were same. The location of the subsystems in the Satellite can be seen in the Fig 5.

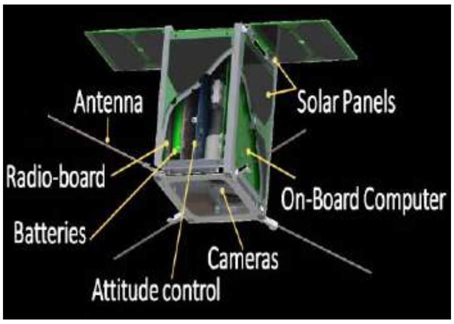

Figure 5. CubeSat Subsystems

Most of the CubeSat subsystems were COTS but some of the subsystems including EPS was developed in-house at TalTech University.

- On-Board Camera
- Attitude Determination and Control System (ADCS)
- Electrical Power System (EPS)
- Communication Subsystem
- On-Board Computer System (OBC)

5. Satellite Testing

The two CubeSats were taken to University of Tartu Space Facility in Tartu, Estonia for the Vibration Test, Shock Test (Fig.6) and Thermal Vacuum Testing (Fig.7) and all these tests were performed at this facility throughout the development of the two CubeSats.

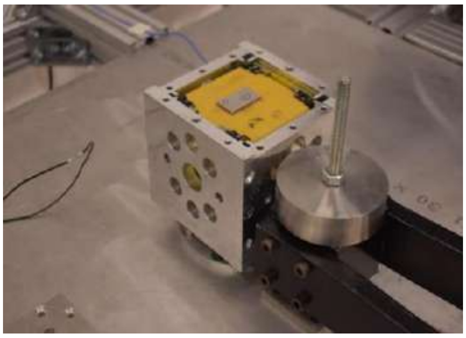

Figure 6. Shock Test on the Koit CubeSat

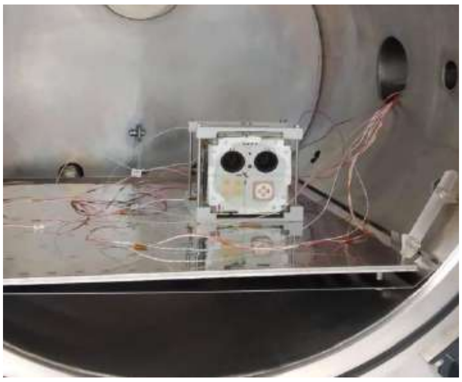

Figure 7. Thermal Vacuum Test of Hämarik CubeSat

DOI: 10.5821/conference-9788419184405.117

Some of the tests like Magnetism Test on the CubeSat components were done at the NICP Laboratory of the TalTech University to analyse the magnetic behaviour of the CubeSat components like Battery Connectors, Battery Cover, Screws, Deployment Switch and Resistor [4]. The tests results showed most of the components showed paramagnetic behaviour so it was concluded that it will not have any effect on the CubeSat in the orbit.

6. Ground Station

The ground Station for the Satellites has two different types of Antennas. A UHF Antenna and a 5m parabolic dish S-Band antenna. Initially only a UHF Antenna was ready and later the 5m parabolic dish S-Band was developed atop the Mektory Space Centre Facility as shown in the Fig.8. List of equipment at the ground station includes software-defined transceiver and two steerable antenna systems operating in 432 MHz and 10 GHz amateur radio frequency bands. Ground station computer controls satellite tracking by antennas and remote operation of transceiver.

Figure 8. Parabolic Dish S-Band Antenna

Communication with the ground station works on two modes: two-way communication on 435.450 MHz radio band and one-way data download on 10.460 GHz (Koit) and 10.465 GHz(Hämarik).During two way communication, satellite shares its data and information about the status of subsystems, whereas ground station shares the information about next mission – what kind of pictures to take and which test to start. During one-way communication it is possible to download the pictures taken by the satellite. Since the data transmission is not fast enough to download all the pictures taken, image processing system in the satellite has to decide which ones are more valuable and worth to be kept. Satellite's communication protocol is AX 25.

7. Launch

Koit (TTÜ101) was integrated to the POD by Exolaunch GmbH in Germany (Fig.9) which was transported to Vostochny Cosmodrome in Russia where it was integrated with the Soyuz Rocket.

Figure 9. Koit (TTÜ101) integration in POD in Germany

It was launched (Fig.10) from Vostochny Cosmodrome in Russia on 5 July 2019 onboard Soyuz 2.1b mission [5].

Figure 10. Soyuz-2.1b Launch

Hämarik CubeSat was integrated into the Arianespace Vega Rocket by SAB Aerospace (Fig.11).

Figure 11. Hämarik (TTÜ100) integration in POD in Netherlands

DOI: 10.5821/conference-9788419184405.117

The CubeSat was initially to be launched in the beginning of 2020 but due to the pandemic the launch was delayed and it was successfully launched (Fig.12) onboard the Arianespace VEGA SSMS (Small Satellite Mission Service) VV16 on 2 September 2020 from Europe's Spaceport in Kourou, French Guiana [6].

Figure 12. Vega VV16 Launch

8. Flight Results

The first contact with Koit (TTU101) CubeSat was made on 21st November 2020 after more than a year since its launch in 2019. It was the only satellite from the Soyuz launch that was above the horizon at the time, the correct assignment was found in the aforementioned catalog (NORAD 44401, provisionally named Object R). The satellites for this launch are highlighted in white as shown in Fig.13. A three-meter-diameter satellite dish and a 2 kW transmitter power of the Tõravere Observatory were used to send commands .Yagi Antennas in Tõravere and on the roof of the University of Tartu received messages from the satellite.

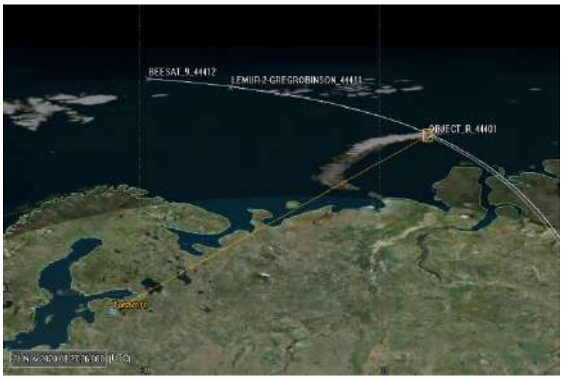

Figure.13 The first contact with Koit (TTU101)

Hämarik (TTÜ100) was launched in September 2020 it successfully separated from the launch vehicle and by the beginning of October; almost all the objects of this launch had been defined, with one exception, which was Hämarik (TTÜ100). Because of this, it was obvious it could be Hämarik (TTÜ100) (NORAD 46312, temporarily named Object AS). The position of Hämarik (TTÜ100) calculated from the start vectors is indicated in turquoise (Fig.14). The correct position is marked in red. All other satellites from this launch are marked in white.

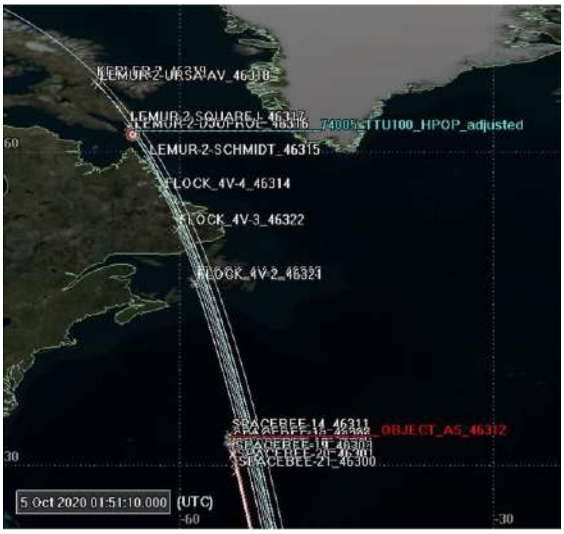

Figure.14 Position Vector of Hämarik (TTÜ100)

Optical communication testing was one of the scientific missions of the CubeSats and for this purpose the CubeSats had LEDs. A small telescope on Earth could be used to observe their fly-by and also see the flashing. On the late evening of August 17 in 2021 at about 22:55 (Estonian Time), Dzmitry Kananovich, a senior researcher at TalTech University was able to capture the first image (Fig.15) of the Hämarik (TTÜ100) CubeSat in fly-by mode [7]. The distance from the satellite was about 792 km at the time image was taken and it had a brightness of ~ 10 magnitudes.

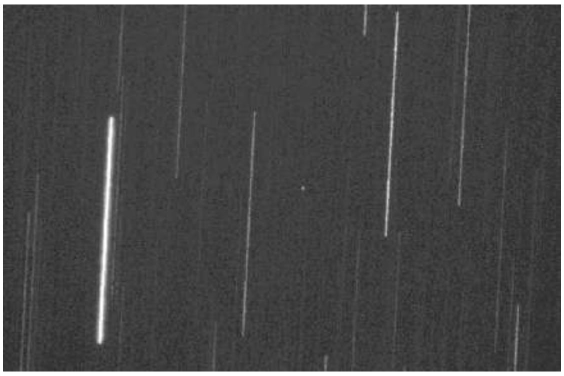

Figure.15 The little dot in the center is the Hämarik (TTÜ100) CubeSat

For this purpose a specific little tracker that could be fitted with camera systems weighing up to a few kilos was used. A consumer camera lens was chosen as the telescope. It turned out that with this technique, an object flying by in the sky can be observed over 10 minutes so smoothly that even a subject with very low brightness can be viewed if the shutter speed of each frame is set to 2 seconds on the camera. There has not been any concrete communication with the Koit CubeSat that allows keeping regular contact with the CubeSat but Hämarik Cubesat is functional and the Satellite team at TalTech University continues to be in contact with the Hämarik satellite and its software has also been updated, though software with wider functions is still being developed. The main goal is to get the feature of taking pictures of the Earth to function. TalTech Satellite Team is working in coordination with DATEL, an Estonian IT Company with experience in space technology to achieve quick data connection, so that pictures of space taken by Hämarik could be sent back to Earth. Until today a few thumbnail images have been downloaded from the CubeSat and the next mission of the team is to determine the exact location of the satellite and focus the satellite's cameras towards the Earth so that the data received from the position control system's sensors can be displayed and complete images taken by the CubeSat can be downloaded. There is an optical sensor on each side of the satellite that acts like a small camera.

9. Conclusion

CubeSat development activity at TalTech University, Estonia has taken a good start with the successful development and launch of the two 1-Unit CubeSats and the preliminary results from these CubeSat missions has paid way to further continue the Satellite development activities at the University. The future goals for the Mektory Space Centre Satellite team includes analysing the results from the CubeSat missions that includes issues with long delay in contact with Koit CubeSat to prepare for the future Nano-Satellite activities to contribute towards Estonian Space technology activities. The Satellite team is currently planning to design and develop a PocketQube Mission as part of continuation of the Satellite development activities at TalTech University.

Acknowledgement

TalTech University Satellite Team would like to convey thanks to European Space Agency (ESA), University of Tartu, Estonian Research Council, Research in Estonia and Estonian Embassy in India for their support towards the Satellite Program at TalTech University, Tallinn, Estonia. The Satellite Team would also like to convey thanks to its supporters DATEL, Telegrupp AS, EANS, MEDIQ, STONERIDGE, and CGI towards the Satellite program.

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Development of a Low-Cost Ground Segment Capable of Receiving Data from Nanosatellites: a Partnership between Brazil and Portugal

Júlio Santos[1], João Braga[2], Henrique Alves[3], Jeremy Silva[3], Daniel Resende[3], André Teixeira[4], Marcos Kakitani[2]

Abstract

Two universities joined forces to develop a shared ground segment (Ground Stations and Mission Operation Centers) for satellite signals reception, capable of working together autonomously in a network to receive telemetry data and decode information. The main objective of this cooperation and network is to, firstly, give both universities an infrastructure capable of receiving signals in VHF and UHF. Secondly, and most importantly, it aims to create an exchange of experiences between students from these universities while also contributing to the regional development of each country in nanosatellite data reception technology. The ground segment itself provides mutual data collection on a private server, using two ground stations located in different hemispheres to expand global coverage and minimize revisit time, which also contributes to supplying the nanosatellite telemetries database, which is being built in Portugal. The server architecture allows both universities to schedule future passes of their chosen satellites, recording them in a log file that can be used in future studies, enabling research groups to gain experience in signal processing analysis. The modular system is developed entirely using Commercial Of-The-Shelf (COTS) components and 3D printed parts, including Antennas, Amplifiers, Filters and also SDRs (Software Defined Radio), leaving the door open to new integrations that can expand frequency coverage, or system performance improvements. The design supports a wide variety of missions, operating on amateur radio frequency in VHF (2 m band of 144-146 MHz) and UHF (70 cm band of 430-440 MHz), enabling remote access and remote control of the antennas and their recorded data.

All the ground segment architecture, hardware, and software, as well as its operational procedures, are discussed in this paper and can be found in detail on our public repository in GitLab. As of March 21st, it has completed several observations for verification. The results are being processed on a low-cost computer (Raspberry Pi4) connected to an SDR which in turn connects to the antennas. The assembly of this interface intends to give a friendly user experience and, if desirable, an easy expansion of this system. The project developed can be easily replicated in other locations around the world, mainly because of its low price and ease of use.

Keywords

Antennas, COTS, Ground-Station, Low Cost, Nanosatellites

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Acronyms/Abbreviations

BPF *Band-Pass Filter*

COTS Commercial Off-The-Shelf

GUI Graphical User Interface

LNA Low-Noise Amplifier

MODCOD Modulation and Coding

NAS Network Attached Storage

OS Operating System

RHCP Right Hand Circular Polarization

SatNOGS Satellite Network of Open Ground Stations

SDR Software-Defined Radio

VNC Virtual Network Computing

1. Introduction

CubeSats have been widely used due to the growing wave of nanosatellites, mainly due to the recent democratization of the use of space, made possible by the so-called New Space. More and more nations, organizations, and universities are developing, assembling, integrating, testing, and launching their small satellites into space, whether for scientific experimentation or for carrying out complex missions. With the number of launches of nanosatellites increasing from 10 in 2007 to more than one hundred in 2017, and the possibility of application for educational purposes and not only, the development of ground stations have become more important than ever.

Aiming to expand the student's knowledge and the amount of telemetry data from nanosatellites, the Alma segment, Figure 1, is a partnership between the University of Beira Interior in Portugal and the Federal University of São João del-Rey in Brazil, that consists in the creation of a shared ground-station network that allows students from both universities to make use of an antenna that is placed far from them, on another continent, providing telemetry data from various satellite missions. This partnership is intended to offer students the possibility to develop the ground segment from the beginning, receiving signals from nanosatellites, challenging them to build and decode signals, introducing them to basic concepts of satellite tracking, as well as knowledge of satellite operations and orbital mechanics. Being developed by students, the cost of this ground segment is an important variable. Therefore, a low-cost approach was applied, achieving an overall cost of €1134.

Figure 1. The Alma cooperation patch mission.

Thus, in Section 2, some literature is presented where it is possible to glimpse the development of other ground segments for educational applications in some research institutions; Section 3 presents all the hardware, specifications, and operating frequencies of the ground stations proposed in this work, one in Brazil and one in Portugal; In Section 4, the software for antenna operation and control is described, as well as the overall system architecture. Finally, Section 5 contains some results and lessons learned from this cooperation between Portugal and Brazil for the development of the ground segment, and Section 6 presents the next steps and future upgrades.

This project aims to, hopefully, motivate students and researchers to be involved in future projects whilst gaining hands-on experience in space operations and ground segment architecture, enhancing the visibility of space initiatives at both universities.

2. Current low-cost ground segments

Most of the actual low-cost ground segments use Commercial off-the-shelf (COTS) components such as antennas, low-noise amplifiers (LNA), filters, software-defined radios (SDR), diplexers, and computers. In addition, most of them are based in the Satellite Network of Open Ground Stations (SatNOGS), which is an open-source global network of satellite ground stations all over the world. This network enables people to use other ground stations, expanding user available coverage. Additionally, this facilitates the access of space-based data far more often than they can with a static one.

Some examples of the development of low-cost ground stations can be found, for educational purposes at the University of Alabama [1]. Most recently, in [2], a ground station was designed to be modular and to use commercial off-the-shelf (COTS) products such as SDR to reduce the total cost as well as the construction time.

Building your own ground stations network is expensive and can bring financial and regulatory issues since different countries have different regulations on accessing the available frequency spectrum. Thanks to the Satellite Network of Open Ground Stations (SatNOGS), it is possible to spend little money on a ground station when compared with professional ones and join a network of nearly 300 active ground stations. However, despite knowing the value of this powerful network, with this paper, the idea was to do something different than simply joining an already defined ground stations network. Our main goal was to develop our own network, allowing students to gain experience on the development behind an already established ground segment and making them feel and go through the difficulties that appear on this journey. So, from the partnership between Portugal and Brazil, Alma Segment was born.

3. Ground segment hardware

The hardware associated with the ground segment varies depending on whether the ground station is directional or omnidirectional.

In Portugal, with regards to communication, a directional ground station was built, made of two high-gain Crossed-Yagi antennas - one in UHF (70cm band), and the other in VHF (2m band). Despite not joining the SatNOGS available network, its rotator v3.0.1 was built to move the antennas, being the price the deciding factor in comparison to other commercial options, as Yaesu Rotator. Both dipoles on the two antennas are driven by one signal, with different phases, making it possible to achieve circular polarization. To increase the signal reception in VHF, a low-noise amplifier (LNA), as well as a Bandstop filter were introduced, the last being capable of attenuating broadcast FM frequencies (typically >40dB, 80-115 MHz), while ensuring VHF Airband. On the UHF side, just a low-noise amplifier (LNA) was added.

Figure 2. Directional ground station in Portugal

Additionally, an enclosure box was fixed to the two frames of the rotor, with a hole to pass all the cables from the switches of the end-stops and the stepper motors. Inside the enclosure box, was organized all the hardware needed for the rotor operation (Arduino, CNC controller with A4988 drivers and its power supply unit), the hardware needed for remote access operation (Raspberry Pi4 and its respective power supply unit), and last but not least two RTL-SDRs connected to the microprocessor.

Also, to understand what the constraints of the place are where the ground station in Portugal is located, altitude and azimuth were measured.

Table 1. Ground Station Location Constraints

Azimuth	Minimum Elevation
0º-90º	10º
90º-230º	8º
230º-360º	22º

The full 360º panoramic view can be seen in Appendix A.

In Brazil, the ground station employs a designed and 3D built Turnstile Antenna. It has Right Hand Circular Polarization (RHCP) and was projected to receive signals at frequencies ranging from 434 MHz to 439 MHz. This type of antenna is basically made of two dipoles with a 90º phase difference between the dipoles, Figure 3.

The first step was to set the center frequency at 435.500 MHz. Then, to find the wavelength (λ), Eq.1 was used:

$$\lambda = c / f \qquad (1)$$

where c is the speed of light and f is the desired operating center frequency. Next, to find the dipole total length, Eq.2 was used, where X is the dipole length.

$$X = (\lambda/2) * 95\% \qquad (2)$$

After that, to get the size of the reflectors, Eq. 3 was employed

$$Y = (\lambda/2) \qquad (3)$$

Finally, the distance between the dipoles (Z) and the reflector, needs to be calculated, and for that Eq.4 was used:

$$Z = (\lambda/4) \qquad (4)$$

The parameters obtained for the design using the previous equations were: $\lambda = 0.68$ m, $X = 0.32$ m, $Y = 0.34$ m, $Z = 0.17$m.

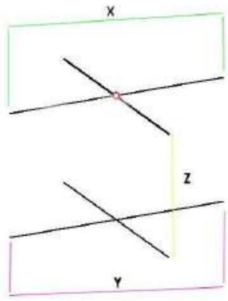

Figure 3. Turnstile 3D Design: Calculated dimensions in m.

To verify and validate the Turnstile design, and to ensure more precision in the calculation of the length of the dipoles a free software called MMANA-GAL was used to simulate and optimize the antenna. In Figure 4 the radiation diagram obtained from the simulation is illustrated:

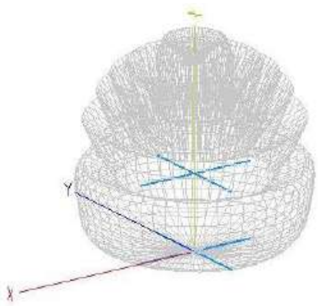

Figure 4. Turnstile Radiation Pattern

The main idea of this ground station in Brazil is to be as cheap as possible, but with the possibility to receive the same satellite signals that Portugal's ground station receives.

Besides the Turnstile Antenna, to build this ground station, two more components were employed, one Low Noise Amplifier (LNA) to amplify the signals received by the antenna and one Band-Pass Filter (BPF) to reject signals outside the 434 MHz to 439 MHz range. The combination of this equipment is fundamental to increase the quality of the received signals.

Figure 5. Turnstile Antenna Design

For a full list of all the hardware used in the project and to get more information about the development process, simulations and software deployments, we managed to list everything on our public GitLab Repository [3].

4. Software and Architecture

The architecture of the ground segment is defined as in Figure **6** and uses two ground stations capable of receiving signals on their own.

In the case of the ground station in Portugal, a Raspberry Pi4 and an Arduino Uno were used as the main processing unit. The Raspberry Pi controls the Arduino which, in turn, controls the rotor. Since the decision was to use a Raspberry Pi, an OS was to be chosen. A very good option would be PiSDR image, which is a very popular Linux distribution and known amongst amateur radio enthusiasts, because of its pre-installed software like Gpredict, GNURadio and gqrx, however it was not used because of its performance, when remotely accessed the operation, it was really slow.

Ultimately, there is no Operating System (OS) that is perfect for every user, and it mostly boils down to personal preference and/or necessity. For instance, in this project, Raspbian Buster 32-bit was used because one of the software requirements was the need for 32-bit architecture, as explained in the paragraph below.

DOI: 10.5821/conference-9788419184405.118

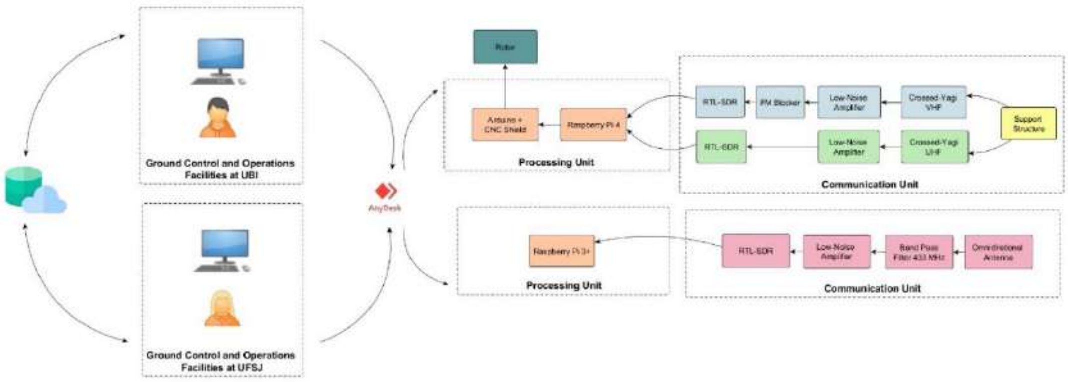

Figure 6. Ground Segment Overall Architecture

To allow for remote access, different tools were tested such as: Anydesk, Virtual Network Computing (VNC) and Team Viewer. Despite all the tests, none compares in terms of performance to Anydesk, and because of that, it was chosen. However, this performance came at a cost: Anydesk was not ready for 64-bit architectures (as of March 19th). This was the main reason for the need of a 32-bit OS.

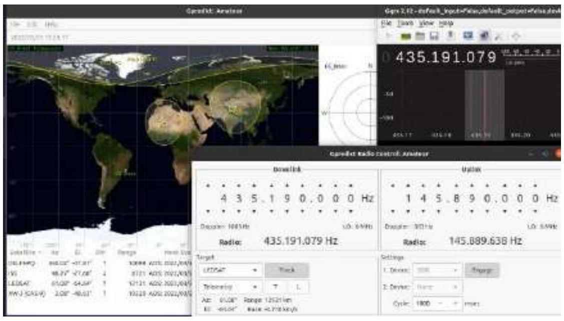

Figure 7- Remote access to the ground station using Anydesk

To control the rotor, a radio control library called Hamlib was used. This library contains software that handles the stepper motors by receiving serial data containing certain objective angles and, so, calculating the respective steps needed to achieve such angles. The serial data is sent from the Raspberry Pi to the Arduino by GPredict, which outputs the respective angles that both the elevation and azimuth stepper motors should be at (corrected for both ground station altitude and location). With Anydesk installed on both Raspberry Pi's, it is possible to have a Graphical User Interface (GUI) of the computer environment that contains all the software needed for remote operation.

For instance, it also allows to see the selected satellite's future passes and check the current pass to see if the satellite is in line of sight with the ground station, and then engage the antennas to follow the nanosatellite while correcting the Doppler effect. Also, a Network Attached Storage (NAS) server, hosted in Portugal, is being used to save all the records obtained from nanosatellites.

5. Results

In Portugal, several receptions were done, including satellites like LEDSAT, WX-3 (CAS-9). For CAS-9, the data was demodulated using Soundmodem, and decoded via a python script that was elaborated for that purpose.

2022-03-07
Packet number 1
0000: C0 00 86 A2 40 40 40 40 60 86 82 A6 72 40 40 61
0010: 03 F0 01 00 01 00 01 00 7E 16 03 07 01 15 37 16
0020: 03 06 02 19 2E 1E 2A 00 00 00 00 0F 00 00 00 00 4D
0030: EE 00 0B 3A 01 7E 05 06 03 58 03 1D 03 1C 00 25
0040: 00 85 00 C1 01 09 02 1E 01 14 00 00 00 00 22 17
0050: 1C 13 14 00 00 1E 00 00 00 00 00 00 00 00 00 00
0060: 00 00 55 59 FE 7F FC FF 05 00 00 00 00 00 00 00
0070: 18 C9 56 B3 03 19 0B 07 01 03 00 03 00 00 00 00
0080: 00 04 40 63 63 7F 7F 7F 01 3E 89 01 18 01 56 0B
0090: C0

Figure 8- Demodulated frame of the CAS-9

The decoding process was validated, since correct values for the time of the receptions were obtained, as well as telemetry nominal values of the subsystem's performance.

In Brazil (as of March 19^{th}) 5 observations were done with an average number of packets of 15 per observation. Satellites tracked include the recently launched Alfacrux. For that satellite the data was demodulated, but not decoded, because at the time there was not an ICD, explaining the telemetry frames.

1: [1KUNS-PF] [10:31:14R]
[priority:2 src:1 src_port:29 dest:15 dest_port:14 len:110 FEC_err:0 RS_err:0]
00 9D F3 82 10 11 AE 00 0E 08 01 FF FF 00 58 1F 03 19 5D 88 03 E8 2A D2 04 3C
2F 85 00 04 00 00 00 DC 6A EB E8 A2 00 00 00 00 00 00 E3 02 4F 02 4E 01 64
00 01 00 01 64 00 01 00 01 64 00 01 00 01 64 00 01 00 00 00 00 01 00 00 00 00
00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 3A 98 01 9E 4A
00 00 00 10 86 8B
00:34

Figure 9- Alfracrux frame

5.1. Lessons Learned

Throughout this project, several valuable lessons were learned.

Bring your tools - during the building and assembly process of the rotor in Portugal, there was always, a day's delay due to the lack of necessary tools and material that was forgotten. Materials such as: electrical wire insulating tape, soldering machine and solder, ethernet cables, extra screws and nuts always proved to be important when needed.

Be prepared for bad weather - Ground stations are located most of the time in high locations and, most importantly, out in the open. Normally there would be no issue but, when there's an exposed electrical circuit, it is always a bad idea not to cover it up. So, bring your umbrellas.

A strong foundation is key - A project is only as strong as its weakest link and more often than not, it is the foundation. In this kind of project, shortcuts often lead to such situations which, in turn, brings out delays, disappointment and frustration.

Work smart, plan in advance - Plan your work and avoid unnecessary overtime. Even if things go sideways, remember to stop, and think. As simple as that.

Be prepared for spacecraft operations- Training is an important step for operating and tracking satellites, take precautions and stay one step ahead right before the acquisition of signal.

6. Conclusions

This paper shared the first cooperative ground segment between the University of Beira Interior (UBI) and the Federal University of São João del-Rei (UFSJ). The ground station in Brazil is expected to receive and decode fewer packets because it uses an omnidirectional antenna which, in consequence, results in less gain and less performance for receiving for example CubeSats whose transmission power is normally 1W.

Future steps of this partnership will be the update of the ground segment, which is now only capable of receiving signals, to include the possibility of transmission and consequently send telecommands to the same nanosatellites. This can be done by upgrading the Software Defined Radio (SDR) to one that has Rx/Tx capabilities, options in the market include half-duplex, and full-duplex versions for more expensive alternatives however, maintaining the idea of keeping it as low-cost as possible, it is intended to be used a new low-cost SDR with the capacity of transmission whose name is CaribouLite. Additionally, the idea is to develop an API to host the interface to the rotor and a dashboard to facilitate user experience by allowing them to check and request ground station usage for satellite tracking and data collection. Now that the ground segment is available and running, it will be possible to work on signal processing methods with real records from nanosatellites, learning Modulation and Coding (MODCOD) schemes and in the end, obtaining valid frames from nanosatellites. In Portugal, to view the antenna moving towards the satellite, ensuring the correct movement in the operations of the station, a camera will be added.

Acknowledgements

Thanks to Spaceway for the material bought for the project and to the professor Sandra Mogo from the Department of Physics of the UBI for making the roof available and allowing the installation of the ground station in Portugal, also to Prof. Anna Guerman. To Mr Roland M. Zurmely (PY4ZBZ) for helping with the Turnstile simulation. This work was supported in Brazil by the Foundation for Space Science, Applications and Technology (FUNCATE) and also by CAPES and CNPq.

Appendix A

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Nanospace and Open-source Tools for CubeSat Preliminary Design: Review and Pedagogical Use-case

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Abstract

This paper aims to facilitate getting acquainted with CubeSat preliminary design by presenting a review of open-source tools commonly used during project first steps, and a concrete example. The light but realistic preliminary design framework is based on a real 3U CubeSat use-case, the CREME project, relying on Nanospace and a package of selected Open-Source tools. This example should allow students and non-related field experts to fully grasp the concepts needed to achieve the basics of a typical preliminary design.

Keywords

Preliminary design, CubeSats, Softwares

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1. Introduction

The preliminary design phase is one of the ini- tial steps in a CubeSat project (Phase 0/A in ESA nomenclature). Preliminary design is an iterative and a multidisciplinary process. It involves many disci- plines such as orbital mechanics, telecommunication, electronics, mechanical engineering, control theory, and thermal engineering. Therefore interdisciplinary exchange of information is essential to attain a pre- liminary design. System engineers normally lead the process for the different disciplines to work together, but without the aid of tools to enable this, it becomes a very time consuming task. While many ways of how to proceed with spacecraft preliminary designs have been proposed, such as Concurrent Design Engineering [1], few really propose an Open-Source set of tools and a method to attain a preliminary design. This has been identified as a gap in students' training during the Nanostar project. Nanostar has led to the development of a consistent set of tools for achieving a CubeSat preliminary design. Nanospace started to be developed in the context of the Nanostar project. Nanospace is an open-source software dedicated to facilitate the preliminary design of CubeSats for re- mote teamwork.In an academic context, open-source approaches have many reasons to be applied in CubeSat projects [1].

A full package of Open-Source software is proposed as an operational Nanospace Constellation, along with the iterative process methodology to manage them in order to achieve a simple but realistic prelim- inary design of a 3U CubeSat. Note that the process is iterative and modular, meaning that users can sim- ply deploy their own tools (maybe replacing the ones proposed) in the process to get a deeper analysis of expertise.

Generally, a team proposing a preliminary Cube- Sat design for a specific space mission should obtain:

- □ a mass budget
- □ a power budget
- □ a link budget
- □ a data budget
- □ a dissipation budget
- □ a radiation budget
- □ sometimes a propellant budget
- □ a mechanical architecture
- □ a thermal architecture
- □ an ADCS sizing
- □ an activity profile
- □ a launcher restriction choice
- □ a check for compliance with space laws
- □ a check for payloads constraints

In the following sections, first, a brieft overview of existing open-source software that allows part of a CubeSat preliminary design and related work on concurrent design engineering tools is presented. Afterwards, a use-case scenario is explained, based on a lighten preliminary design of CREME project 3U CubeSat.

2. State of the art

2.1. Existing software

Preliminary design software is a very dynamic ecosystem. This section does not aim to be exhaustive ally used during preliminary design phase. This ar- ticle does not aim to cover proprietary solutions. However, most the software mentioned here is con- sidered as "academic-friendly" for sake of pragmatism. Many open-source software, methodologies and recommendations can be easily found online. This includes the Libre Space Foundation initiative, full open-source CubeSat projects such as the UPSAT initiative, FloripaSat-I [2], and educational projects [3]. In addition the "open-source Satellite" initiative provides a first list of teams and software of the open- Below we describe different software that can be used for CubeSat preliminary design. We have clas- sified them based on their purpose: mission analysis, link budget, data budget, mechanical architecture, energy and power system (EPS), attitude determi- nation and control System (ADCS), end-of-life disposal, dissipation budget, and radiation budget. A list of the different data inputs and outputs usually taken into account during the process is also included. Inputs and outputs are illustrative and can vary de- pending each project. They may be obtained through design iterations, and may be dependent to internal processes. For example, a list of visibility windows of the ground station can be provided by the mission analysis to the module computing the data budget. Another possible option would be to provide Keple- rian parameters and ground stations location to the module computing the data budget.

2.2. Mission Analysis

Mission analysis usually consists of orbit definition, surface coverage, visibility windows, eclipse calculation.

Inputs	**Outputs**
▲ Orbital parameters	▼ Mission time availability
▲ List of ground stations	▼ Visibility windows
▲ Satellites interlinks	▼ Received solar flux
▲ 3D structural model	▼ Eclipses
▲ Ephemeris*	▼ Activity profile
▲ Attitude profile*	

* Existing CCSDS standart format are already widely in use.

Current open-source solutions:
A wide variety of software are available to complete a mission analysis. We can mention C++ based GMAT, Scilab based Celestlab, Java based Orekit, Python based Poliastro, itself partially based on Astropy [4], Julia based SatelliteToolbox. Each space agency usually provides and uses their own software (e.g. CNES with Patrius, PSIMU, Genius). Similarly, different academic institutions provide and use their own software (e.g DOCKS, or JSatorb [5]).

Non open-source options:
We can also mention the VTS tool from CNES, supported by Spacebel, with many features such as Celestia window visualization.

Activity Profile:
A spacecraft may have different operating modes. Usually, at least a safe mode and an nominal mode are defined. Spacecraft modes impact other subsystems by affecting their power consumption and thermal dissipation for example. During safe mode, all non-essential systems shutdown. An activity profile defines a typical mission profile, i.e. the successive modes through which the satellite will pass. Different activity profile might be considered including expected scenario, alternative orbit scenario and downgraded scenario. It is recommended to define at least one activity profile for space missions. Activity profiles can be handled with a basic CSV (Comma-Separated Values) file. For more advanced features, we can mention academics contributions such as the jupyter framework proposed by UC3M (Universidad Carlos III de Madrid).

2.1.2 Link Budget

Estimation of the margin for uplink and downlink budget between the spacecraft and ground stations (or another spacecraft) should be computed. These margins usually allow to size the useful data flow that can be exploited during the visibility windows of the ground stations.

Inputs	**Outputs**
▲ Orbital parameters	▼ Raw and useful data flow (uplink, downlink)
▲ Mission requirement (e.g: Bit Error Rate)	▼ Link budget margins (uplink, downlink)
▲ Material description**	

** Theoretically, it could be Electronic Data Sheets (EDS). Usually the standard material description is entered into the system manually.

Current open-source solutions:
Basic spreadsheets are usually sufficient for pre-sizing the link budget. For more advanced features, a wide range of online resources are available. We can mention the Amsat-UK spread sheet and some Python libraries: linkpredict or Dosa.

2.1.3 Data Budget

The storage capacity of on-board data should be sized according to data produced, the extent of the different telecommunications data streams, and the time between visibility windows to ground stations. During the time the spacecraft is not in visibility with ground stations, on-board storage capacity should be sufficient to accommodate gathered data until the next visibility window, including for instance housekeeping data.

Inputs	**Outputs**
▲ Visibility windows	▼ Available data flow (up-link/down-link)
▲ Activity profile	▼ Required on-board storage
▲ List of ground stations	
▲ Satellites inter-links	

Basic spreadsheets are usually sufficient for pre-sizing the data budget.

DOI: 10.5821/conference-9788419184405.119

2.1.4 Mechanical architecture

A 3D structural model (often a simplified version) is necessary. In this model it is defined the mechanical structure of each sub-component, and the composition of the different sub-components (or mass of the different sub-components depending of the software).

Inputs	Outputs
▲ Components listing and specification	▼ 3D structural model

Current open-source solutions:
Some generic software are designed to build the mechanical structure: OpenSCAD or Blender. See following models for OpenSCAD and Blender.

The Libre Cubes Space foundation repositories and the OreSat [6] project also provide their source code and CAD available (here for the OreSat project).

Alternative non open-source options:

IDM-CIC is not open source software. However academics usually have access to a free license. IDM-CIC is designed to build a preliminary mechanical architecture, and compute mass and power budgets. It allows to take into consideration the different spacecraft modes when estimating the power consumption. IDM-CIC incorporates Sketchup which is not open-source either.

2.1.5 Energy and Power System

Concerning the Energy and Power System (EPS), preliminary design includes checking the ability of the platform to provide enough power for the mission. In CubeSats, the source of the power usually comes from energy collected with solar panels. Batteries allow to store energy and to provide it during eclipses, phases of peak demand (e.g. telecommunication bursts), or when solar panels have not yet been deployed.

Inputs	Outputs
▲ Activity profile	▼ Required batteries
▲ Eclipses	▼ Required solar cells
▲ Attitude profile*	▼ Power consumption profile
▲ Material description**	

Basic spreadsheets are usually sufficient for the pre-sizing of the EPS. For a more advanced features, the reader can refer to Libre Cube Space foundation repositories or academic projects such as nanopower.

2.1.6 ADCS

Concerning the Attitude Determination and Control System (ADCS), during the preliminary design, a basic sizing study is usually enough. According to sensors accuracy and actuators capacities, pointing and stabilization requirements must be checked. In addition, the preliminary ADCS simulations may usually provide an AEM file (Attitude Ephemeris Message) related to the platform.

Inputs	Outputs
▲ Material Description**	▼ Check actuators and sensors mission compliance
▲ Activity Profile	▼ Attitude Profile*
▲ Ephemeris*	

Basic spreadsheets are usually sufficient for the pre-sizing of the ADCS. For a more advanced features, the reader can refer to the UPSAT repositories or academics contributions.

2.1.7 End-of-life disposal

Legal or regulatory aspects should not be neglected during preliminary design. ESA highlights that "it is recommended that satellites and orbital stages be commanded to reenter Earth's atmosphere within 25 years of mission completion, if their deployment orbit altitude is below 2000 km (in the LEO region)." This 25 year period is also supported by the Inter-Agency Space Debris Coordination Committee as stated in their IADC Space Debris Mitigation Guidelines [7]. In order to respect this recommendation, orbit should be propagated with sufficient accuracy over a long period of time.

Inputs	Outputs
▲ Orbital parameters	▼ Check compliance with Space Law
▲ 3D structural model	
▲ Launch date	

Current open-source solutions:
Most mission analysis tools described previously (see 2.1.1) can be adjusted to propagate orbits with sufficient accuracy on a long term period. For example, GMAT already include some propagators such as RungeKutta89 or PrinceDormand78 that can be adjusted to propagate orbits on a long time period by setting large temporal step size.
Alternative non open-source options:
The Java freeware Stela (Semi-analytic Tool for End of Life Analysis) [8] allows to propagate LEO (and also GTO or GEO) orbits on a long term period. This allows to estimate time of re-entry.

2.1.8 Dissipation budget

Building a simplified thermal architecture allows to estimate temperature reached on each relevant node of the spacecraft. A thermal architecture allows to check if each equipment is operating within its correct temperature range.

Inputs	Outputs
▲ Solar Flux Received	▼ Nodes temperature
▲ Activity profile	▼ Check compliance with hardware specification
▲ Attitude profile files	
▲ 3D structural model	

Current open-source solutions:
open-source software dedicated to thermal analysis are uncommon. Proprietary software remain heavily used to simulate the thermal behavior, even in academic CubeSats. Nevertheless, it is possible to proceed to a basic analytical study [9]. In addition, Simusat is an academic open-source software which allows basic thermal node simulations. It is also interesting to point out that thermal models can be found, for example SwissCube [10], along the feedback of thermal flight data.

2.1.9 Radiation Budget

Considering radiation during the design stage may increase mission success. Some initiatives are already proposing open-source radiation tested platforms such as the PyCubed project [11]. A short description of the radiation environment is provided in [12].

Inputs	Outputs
▲ Solar Flux Received	▼ Received radiation flux per equipment
▲ Attitude profile files	▼ Check compliance with hardware specification
▲ 3D structural model	

Current open-source solutions:
Open-source software dedicated to radiation analysis are uncommon. Proprietary software remains heavily used, even on academic CubeSats. Nevertheless, an order of magnitude of the radiation expected to be received on the equipment can be roughly estimated

with conventional models [13].

Alternative non open-source options:
Space environment and radiation effects can be modeled using OMERE. Online tools such as ESA's SPENVIS [14] or NASA's Oltaris [15] are also available.

2.2 Methodology

Concurrent Design Engineering (CDE) applied to space mission preliminary design [16] is a methodology applied to facilitate the process of subsystem design parameters converging into preliminary models, and architectures. A review and comparison table between these tools has been proposed by Knoll and Golkar [17], also accessible online. Concurrent engineering does not replace standard project management tools. Such functionalities need to be covered by other tools. In the following, we assume that we have deployed:

- Nanospace [18] framework which supports a CDE methodology;
- standard project versioning (e.g a Git deposit);
- common team chat service (e.g RocketChat);
- video conference service (e.g Jitsi);
- project scheduler (e.g ProjectLibre);
- dedicated framework for task management, bugs and issues tracking, often coupled with previous tools (e.g GitLab).

3 Use-case scenario and tools

One of the prospects for the CREME mission is to offer space industry companies a low-cost, low-profile and small mass radiation monitor that is very versatile; so that it can be easily integrated on commercial satellites.

For CREME's preliminary design a python script was developed and used. Python's scripts used for this preliminary design are available here[1] under AGPL v3 licence. For pedagogical purposes, simple mission analysis scripts are provided, as well as

[1] https://gitlab.isae-supaero.fr/creme-project/creme-scripts

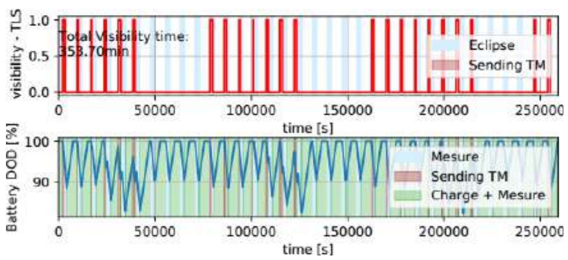

Figure 1. Simulation example: battery remaining power (3 day at 2000km with a SSO midday/midnight orbit - 4 solar arrays of 6 W).

an example of an input file is provided in .yml format (orbital parameters, power consumption of the platform, etc.) and an example of outputs, including:

- intermediary results such as remaining power graph and data budget graph
- a full report (in Markdown format) as a light but realistic preliminary design synthesis.

Orbitography calculus - Orbit propagation, eclipses determination and contact with ground station events - are managed with a automatically generated GMAT script. Link budget analysis is done with Dosa [2] (also in Python). Python scripting is used for the miscellaneous computations. The script is self sufficient for a first step mission analysis preliminary design. Nanospace [18] benefits from a python API that can be directly used in the script to share data between experts.

In this preliminary design example, neither ADCS, nor radiation or thermal considerations are included. These elements are of course fundamental during a real CubeSat mission preliminary design and each of these elements can be easily added since the approach is modular.

Traditionally, to ensure mission success, the worst case scenario is considered. This allows to consider margins, even if refinement of models may be required when the problem ends up being too constrained.

[2] https://sourceforge.isae.fr/projects/dosa_link_budget_analysis

For the example, the following are the requirements derived from the Payload Principal Investigator needs and desires:

- Orbit: LEO Orbit
- Payload altitude: highest possible
- Telecommunication: Bit error Rate $< 10^{-5}$
- Payload required power: 1W

4 Conclusion

With this paper, we emphasize that different open-source tools, as well as methodologies, are available and can be used for achieving a complete and relevant CubeSat preliminary design. A pedagogical use-case, based on CREME CubeSat project, as well as corresponding open-source scripts are available on a gitlab repository, for a light illustration of a preliminary design.

Future works include graphical interface version of these scripts, full integration of relevant and different open-source tools with Nanospace framework (i.e a minimal thermal architecture of a CubeSat is required, but few open-source tools are really providing help to design it).

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Designing Greenhouse Subsystems for a Lunar Mission: The LOOPS - M Project

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Abstract

The 2020s is a very important decade in the space sector, where international cooperation is moving towards the exploration of the Moon and will lead to stable lunar settlements, which will require new, innovative, and efficient technologies. In this context, the project LOOPS–M (Lunar Operative Outpost for the Production and Storage of Microgreens) was created by students from Sapienza University of Rome with the objective of designing some of the main features of a lunar greenhouse. The project was developed for the IGLUNA 2021 campaign, an interdisciplinary platform coordinated by Space Innovation as part of the ESA Lab@ initiative. The LOOPS-M mission was successfully concluded during the Virtual Field Campaign that took place in July 2021. This project is a follow-up of the V-GELM Project, which took part in IGLUNA 2020 with the realization in Virtual Reality of a Lunar Greenhouse: a simulation of the main operations connected to the cultivation module, the HORT[3], which was already developed by ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development) during the AMADEE-18 mission inside the HORTSPACE project. This paper will briefly describe the main features designed and developed for the lunar greenhouse and their simulation in a VR environment: an autonomous cultivation system able to handle the main cultivation tasks of the previous cultivation system, a bioconversion system that can recycle into new resources the cultivation waste with the use of insects as a biodegradation system, and a shield able of withstanding hypervelocity impacts and the harsh lunar environment. A wide overview of the main challenges faced, and lessons learned by the team to obtain these results, will be given. The first challenge was the initial inexperience that characterized all the team members, being for most the first experience with an activity structured as a space mission, starting with little to no know-how regarding the software and hardware needed for the project, and how to structure documentation and tasks, which was acquired throughout the year. An added difficulty was the nature of LOOPS-M, which included very different objectives that required different fields of expertise, ranging from various engineering sectors to biology and entomology. During the year, the team managed to learn how to handle all these hurdles and the organizational standpoint, working as a group, even if remotely due to the Covid-19 pandemic. Through careful planning, hard work and the help of supervisors, the activity was carried out through reviews, up to the prototyping phase and the test campaign with a successful outcome in each aspect of the project. By the end of the year everyone involved had acquired new knowledge, both practical and theoretical, and learned how to reach out and present their work to sponsors and to the scientific community.

Keywords

Education, LOOPS-M, IGLUNA

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Acronyms/Abbreviations

ENEA	*Italian National Agency for New Technologies, Energy and Sustainable Economic Development*
LOOPS-M	*Lunar Operative Outpost for the Production and Storage of Microgreens*
SPENVIS	*Space Environment Information System*
SWS	*Stuffed Whipple Shield*
TRL	*Technology Readiness Level*
V-GELM	*Virtual Greenhouse Lunar Experimental Module*

1. Introduction

The Moon is at present considered as the gateway for further voyages in the solar system. As such, national agencies are cooperating to design and conduct missions regarding the exploration of the satellite, in preparation for future more distant space travels. These missions require innovations with the highest TRL (Technology Readiness Level) available, to ensure safety during the achievement of their objectives.

To cultivate such technologies and to assist the younger generations contribute to the lunar colonization, the IGLUNA platform was created by Space Innovation as part of the ESA_Lab@ initiative launched by ESA. During each IGLUNA Campaign, teams from allover the world worked on a project regarding the main aspects of lunar settlements, ranging from structures to power generation. These projects were structured as real technological development project, undergoing reviews typical of space missions such as PDR (Preliminary Design Review), CDR (Critical Design Review) and RR (Readiness Review) under the judgement of experts. In this context, the LOOPS-M Project took place, participating in the IGLUNA 2021 Campaign [1].

The project had a wide heritage from the earlier projects V-GELM (Virtual Greenhouse Lunar Experimental Module) and HORTSPACE that took part in respectively the IGLUNA 2020 Campaign, and the AMADEE-18 mission [2][3]. HORTSPACE featured the first version of the cultivation module used in the later campaigns, the HORT^3, a vertical hydroponic cultivation element fit for the production of microgreens, which as per mission objective, was tested and validated in the Oman Desert. V-GELM studied the design for a lunar greenhouse employing the HORT^3, later realized in a virtual environment creating a digital twin of the designs. The LOOPS-M project was therefore aimed to enhance the designs of both the module created for HORTSPACE and the lunar greenhouse design created with V-GELM. It was divided in four main objectives: creating a new fully automated vertical cultivation system (the HORT^3 MKII), designing a shield for the lunar greenhouse from both micrometeorites and the lunar environment, adding a new layer of sustainability with a new bioconversion system, and lastly to represent these innovations in virtual reality. All these systems were successful in reaching their prototyping phases. The vertical cultivation system was based on the heritage from the HORT^3, but was completely revised and built anew to be compatible with a robotic arm capable of conducting all the operations from sowing to collection of microgreens autonomously.

Figure 1 Autonomous Cultivation System [1]

The shield was based on the Stuffed Whipple Shield (SWS) and was designed to withstand the harsh environmental conditions on the moon surface such as the temperature and the radiations, while also protecting the greenhouse from potential micrometeorites [4].

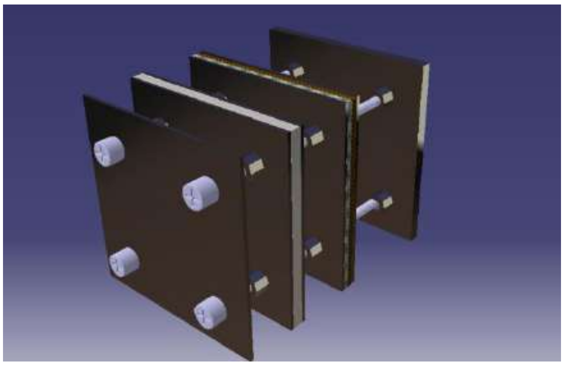

Figure 2 Stuffed Whipple Shield CAD [1]

The bioconversion system was designed to use insects for the biodegradation process of excess microgreens and their resource recycling, turning waste into potential protein and fertilizer.

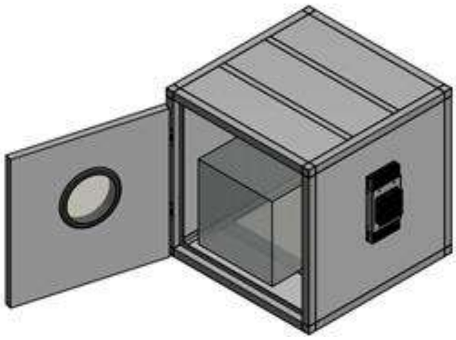

Figure 3 Bioconversion System Design [1]

The virtual reality simulation was created to represent these new systems in a virtual environment to allow further and more optimized monitoring, diagnostics, and prognostics to modify the assets to enhance their capabilities and ensure their performance, but also to show through a more successful mean the potential of the project.

Figure 4 Virtual Reality Outside Overview [1]

To reach all these achievements, the activities were led by a team of twenty students coming mainly from Sapienza university of Rome, under the guidance of supervisors of both the university and ENEA.
During the development of the four systems the teams had to face various hurdles, that will be discussed in this paper. These obstacles once overcome became an important part of the expertise gained by the students, which would have otherwise not been achieved during normal course studies. The activities will be categorized as: Management, Knowhow and Outreach.

2. Management

Management is a crucial aspect of every space mission. A very clear team structure is fundamental, but there are also many other instances in which the management capabilities are fundamental. In this paper, the focus will be laid on team management, documentation, and sponsorships.

2.1. Team Management

In this paragraph the general organization of the LOOPS-M team will be addressed, starting from its overall structure to the tasks division via a top-down approach.
To deal with all the project's aspects the team members had a Project Manager to refer to and were divided into four sub teams, each developing a precise lunar greenhouse subsystem. This division led to the birth of units regarding Automation, Bioconversion, Micrometeorite Shield and Virtual Reality. Each of the four resulting sub teams had a Team Leader who was responsible for the internal sub team organization to comply with the schedule, to interact with the LOOPS-M Project Manager and all the supervisors both from La Sapienza university of Rome and from our project partner ENEA. Another sub team composed of members coming from each other separate unit was assigned with the task of managing LOOPS-M social media, which were used to spread information regarding the objectives and outcomes of the project. Each sub team had to face deadlines not coming only from the IGLUNA 2021 mission, but also from supervisors and sponsors, as the latter needed the team's directives to manufacture the components they were committed to supply.
To meet the deadlines, all the tasks were equally divided among each sub team's members, taking into consideration the personal university commitments. To guarantee this flexibility the most trying tasks (e.g., the technical ones) were assigned preferably to at least two team members.
Most team members did not have or had limited experience; therefore, it was difficult to schedule activities predicting their exact time duration. In fact, the team accumulated delays also depending also on other major causes such the Covid-19 pandemic; however, all these possible delays were estimated during the risk analysis, one of the major skills obtained by the students during the activities, and thanks to time buffers the delays still brought to a successful prototyping phase within the time restraints of the IGLUNA Campaign.
With the aim of making the team organization function optimally updates to project manager and the supervisors were scheduled through weekly meetings with the whole LOOPS-M

team, along with updates via weekly documents. Individually each team member learned how to manage its time between the project, university, and personal life.

2.2. Documentation

The project was structured as a space mission, which in turn required an accurate documentation depicting everything that regarded the project. This guided the team through the management and careful planning of activities. The team members learned how to successfully write a documentation using technical phrasing, work in a group on each technical feature and how to express them clearly, but especially had to work on new aspects never encountered in their academic courses. These aspects were the mission planning in form of work breakdown structures, the risk analysis that required foresightedness, and timelines which required concrete knowledge of the theoretical aspects of the project.
All the documentation was managed by each sub team for their own subsystem, revised by the project manager, and then revised by the supervisors, only then to be delivered to the expert panel for the official reviews. This organization required planning around deadlines, but also personal life commitments such as exams.

2.3. Sponsorship

The last management goal was to plan activities also according to the sponsors' needs and to learn how to handle the supplies. The team had to find on their own sponsors and supplier to make their project feasible, which required reaching out to many companies, only a handful of which actually supported the project, also because of difficulties brought up by the Covid-19 pandemic. This made the team face many trade-offs to bring the subsystems into existence, managing the needs in terms of hardware and software based on the possibilities given by the sponsors, modifying the project as the possibilities changed. Moreover, they also learned how to negotiate with suppliers, and manage deliveries and contracts.

3. Knowhow

Since the beginning of the project the team has been engaged with different tasks and challenges, related to software implementations and hardware integration. Such assignments are key to every engineering project and can use technologies that vary widely depending on the subsystem that is currently under study. Therefore, all the sub teams had to learn how to utilize various software languages and how to properly handle the hardware for the prototyping. The team during the integration and design phases had the possibility to have technical discussions with ENEA experts that had expertise with either tools or specific systems.

3.1. Software

The use of various types of software required the team to acquire knowledge regarding a wide variety of programs and their applications.
In the earliest phase of the project the team had to design theoretically the prototypes to satisfy the project purposes in terms of required performances. According to the preliminary studies, the prototypes have been designed using different typologies of software for developing CADs and 3D modeling, such as SolidEdge and Blender for more refined and complex models, or Catia for models to be later used in mechanical simulations. These software for creating CADs have been chosen because of their integrability with other numerical simulation software.
Each sub team needed specific software to simulate very distinct problems, mainly ranging from testing of hypervelocity impacts, radiative or thermal analysis to autonomous activities and system control.
For the first two cases, which regarded the micrometeorite shield, Ansys and SPENVIS (Space Environment Information System) were employed.
Ansys is an engineering simulation software, that has been utilized to analyze the shield thermal conductivity and its behavior under projectile impacts, in terms of deformation, stress and threshold thickness. The SPENVIS is an ESA operational software, and it has been used to simulate the radiative lunar environment.
To investigate the conditions and to conduct activities autonomously, Grolab and the Farmbot Web App were employed.
GroLab was needed to control all sensors to measure the environmental parameters and more such as humidity of the soil, ambient temperature, water level stored in the tank and power supply. The FarmBot Web App is a software used to customize the growing process of the microgreens, seeding, watering and pruning, and was utilized to handle to vertical operating robotic arm.
The team learned also to program using languages, as MatLab, C++ and Python, that

DOI: 10.5821/conference-9788419184405.120

were fundamental for many applications throughout the project. MatLab was needed to integrate additional computations with the Ansys simulation results. A code written in C++ operated through an Arduino allowed to implement a system to control fundamental components of the vertical cultivation unit. Lastly, the team has developed a web socket in Python to establish a connection between the GroLab sensors and the FarmBot Web App controlling the actuators.
Lastly, the Virtual Reality simulation was powered by the Unreal Engine, which required a great amount of optimization of models and activities, for it to be run successfully using an Oculus Quest device.

3.2. Hardware

The LOOPS-M team designed and developed three main physical protypes: the HORT^3 MKII (fig.1) which is an autonomous system for the cultivation of microgreens and a SWS (fig. 2) for the protection from micrometeorites, and a Rearing Module used as bioconversion system. The prototype realization was a challenging task for the team since all team members had little experience regarding hardware integration. The main issue during the prototype realization was to ensure that all the operations were carried out safely and without any risk. One of the first struggles encountered during the assembly process was the utilization of tools never used before by any team member. Concerning the HORT^3 MKII, the team had to design and realize electrical and hydraulic connections which required a deep understanding of the behaviour of complex integrated systems such as the robotic arm and the irrigation system and the interface with a control system. The main challenges that the team faced in the SWS integration was the choice of materials appropriate with the requirements and then the approach with materials such as Kevlar, Nextel and Aerogel which required specific processing before utilization. The shield assembly required a specific procedure that the team members acquired after several protype realization to avoid mechanical interference. Analogously, the most challenging aspect of the Bioconversion unit was understanding the right parameters for the biological processes to occur and therefore the integration in the system.
All the prototypes had to go through extensive test campaigns to ensure that they would be able to function properly in their respective working space. The tests were conducted in both Sapienza and ENEA facilities, and required a new type of expertise to completely validate the prototypes. The prototypes were therefore tested for their components, as for the Automation and Bioconversion units, and regarding the operational conditions, such as the thermal test, and especially the radiative test conducted and the Calliope Co-60 Gamma Irradiation facility at Enea Casaccia Research Centre.

4. Outreach

The goals of promoting the LOOPS-M Project and its achievements were various. The first objective was to show the public the importance of scientific research conducted and the impact that the technology progress has to everyday life. Then there was the goal of creating a sense of community, to create attachment to the project and make people intrigued about lunar exploration and human colonization. Lastly, there was the necessity to have both financial and technical support to make feasible the project and it was decided to involve time and energies in showing to companies and experts in the field the potential of LOOPS-M ideas and designs. To reach these goals, the team worked mainly in three different communication areas: social media, sponsorship communication and technical and disclosure presentations.

4.1. Social Media

Thanks to social media we had the opportunity to share the project and the team's passion for research and technology with a wide public (both technical and general). Three main social media profiles were used: Instagram, Facebook, mainly to reach the general public of different ages, and LinkedIn, to reach companies and experts. A proper editorial plan for each platform was devised, with weekly appointments and updates on each project sections. The contents were prepared specifically to reach platform specific users and with different formats, languages, and communication styles. Other pages and entities were contacted to explain the project and create social collaboration with two main aims: to variegate the content proposed and to show LOOPS-M to a wider public.

4.2. Sponsorship

During the development of the project the team had to interact with sponsors and supporters in different ways at the beginning, during and at the end of the project. For example, once deals had been reached, often companies asked the team to write about the project and its goals on their website. During the development of the project, the team would update them on progress made and collaborate with the sponsor on different aspects of the project. The possibility to be helped by companies that had more knowhow than the team increased the quality of the project and the individual skills of each member. At the end of the project, the team sent reports on the results obtained and the visibility received by the sponsor. This experience taught the team how to look for and collaborate in an adequate way with a sponsor supporting the project.

4.3. Presentation and scientific disclosure

Presenting to an audience, whether it be technically expert or simply curious, leads to face multiple challenges, especially for unexperienced students as the team was composed of.

To understand how to communicate effectively with the target listener, the team had to learn how to approach differently an expert panel and the general public. The presenters adapted the vocabulary and the presentation itself according to the target. The public got easily involved by avoiding too technical terms and numerical values, while these were required for official scientific presentations and project design reviews.

Disclosure and comprehension were facilitated by the introduction of photos, videos, animations, and CAD models aiming also to etch the project on the audience mind. Moreover, as a further learning, each member, in turn, was encouraged to be a speaker. This was not only helpful to overcome introversion, but also to show the project dimension and team members variety.

5. Results

During the IGLUNA 2021 Campaign, the team members of the LOOPS-M Project managed to successfully prototype four different subsystems of a lunar greenhouse, while learning on the field various important lessons regarding management, knowhow and outreach. The project was carried out fruitfully throughout its many milestones as a true space mission, organized internally and judged externally by a panel of experts. The feedback by experts, industrial partners and sponsors was positive and led to a complete success for the LOOPS-M project, that has been thereafter disseminated.

6. Conclusions

The team learned personally about management, knowhow and outreach in their field, but also had an increased personal growth thanks to the many revisions and assistance of supervisors that followed their steps throughout the project. All the activities conducted, and the important lessons learned would have not been possible during an academic course of studies, which remarks the importance of such extracurricular activities.

Acknowledgements

Thanks to the support of many companies, industrial partners and institutes, LOOPS-M was successfully concluded in July 2021. Therefore, we must thank our partner MarsPlanet and all our sponsors: OpenGrow, Idroponica.it, Refresh.ag, Manifattura Maiano, ItalianSprout, K-Adriatica, Crescience, Teknowool, Aviometal, ITG, and Evo Conversion Systems, who helped us realize this big student project with their kindness.

This was all made possible by those who provided this opportunity and supported us during the activities, ESA_Lab@ and the IGLUNA initiative and team.

Special thanks go to the Calliope Co-60 gamma irradiation facility team, who allowed us to perform tests regarding the radiative lunar environment.

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Teaching computational thinking to space science students

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Abstract

Computational thinking is a key skill for space science graduates, who must apply advanced problem-solving skills to model complex systems, analyse big data sets, and develop control software for mission-critical space systems. We describe our work using Design Thinking to understand the challenges that students face in learning these skills. In the MSc Space Science & Technology at University College Dublin, we have used insights from this process to develop new teaching strategies, including improved assessment rubrics, supported by workshops promoting collaborative programming techniques. We argue that postgraduate-level space science courses play a valuable role in developing more advanced computational skills in early-career space scientists.

Keywords

Space Education; Postgraduate Education; Computational Thinking

Acronyms/Abbreviations

UCD *University College, Dublin*

SS&T *Space Science & Technology*

1. Introduction

Computational thinking has been identified as a key skill for 21st century graduates. It refers to the ways we think when we design computer programs to solve problems [1] [2]. This should be distinguished from "coding" or "computing" [3], which means implementing a solution in a specific programming language.

While computational thinking is an increasingly influential idea in education [3] [4], it has always played a key role in solving problems in space science. Modern space scientists will use it for Earth observation, data analysis, and flight system control, with space software a major area of growth in the space industry [10]. However, little has been written on how space science education helps early-career space scientists to develop these skills.

1.1. Computation & the MSc Space Science & Technology at UCD

The MSc in Space Science & Technology (SS&T) at University College Dublin (UCD) is a taught program designed to prepare science and engineering graduates for careers in the global space sector.

A typical cohort consists of 12–16 students, most of whom are recent graduates from Irish universities. Typically, 20–30% of the class are female. Approximately one third of the class are international students and about 10% join after a period working in industry. Most students have degrees in physics or astrophysics (about 60%) or engineering (about 30%, usually aerospace or electrical engineering).

The 12-month course consists of a total of 90 ECTS credits. It includes classroom-based modules covering the space environment, applications of space science, and professional development, as well as optional modules on Earth-observation, climate physics, advanced astronomy and astrophysics, and data science. Three 10-credit laboratory or project-based modules cover space detectors, CubeSats, applied systems engineering and space mission design. A final 30-credit 12-week internship with a space agency, company, or research group leads to a minor thesis and presentation.

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Programming plays important and varied roles in many of these modules. Students write short programs to do calculations on homework assignments, and develop longer, complex programs to control complex space systems. They write data processing pipelines to calibrate and characterise gamma-ray detectors in the Space Detector Lab. They design and simulate space telescopes. In the Satellite Subsystems Laboratory, they write software to interface to our CubeSat simulator, EduCube [5], and to control their own "TupperSats" – Raspberry Pi-based experimental payloads that they fly on high-altitude balloons [6].

While computational ability is an essential skill in the SS&T course, it is often not an explicitly assessed learning outcome. For example, the learning outcomes of the TupperSat project focus on understanding the space mission life cycle and systems-engineering processes. Since space project teams need software expertise as much they need mathematical or written skills, students need appropriate support to develop these computational skills.

We encourage our students to use Python to solve these problems, and students need to use advanced programming techniques, including handling large data sets, concurrency, object orientation, and exception handling. To solve problems of this scope and complexity, students must also learn to think clearly and creatively about what they are doing: they must learn computational thinking, as well as how to code.

From talking to our alumni and employers, we know that our students value the computational skills that they develop during the course as they move into industry. But we also know that they find the learning curve steep, with expectations set far higher than they are used to as undergraduates. We see this as instructors: often, students' progress early in the course is slowed to learn these core skills.

This sets the aim of this work: to better understand our students' needs and challenges developing the level of programming and computational skill needed to succeed on the course and in the space sector. We can do this with a user-focused, design thinking framework.

2. Methods — Design Thinking

Design Thinking is a creative problem-solving approach used in industry and education to improve user experiences. It is often framed as a sequence of stages or mindsets: "empathise, define the problem, ideate, prototype, test" [7], or "inspiration, ideation, implementation" [8]. These all capture a general principle: you must understand your user before you can understand their problems, and you must understand the problem before you can solve it.

Using this idea, we divided our work into three steps: understanding our students, defining the problem, and implementing solutions.

3. Step I — Understanding Our Students

The first step in our design process is to empathise with our students, to understand their needs, views and experiences on the MSc SS&T. To do this, we surveyed students who completed the course between 2018 and 2021.

The anonymised questionnaire consisted of 33 questions divided into sections covering students' prior experience, the course itself, and their reflections looking back from their current career position. Some questions were posed as (numerical or verbal) rating scales, (eg., asking students to rate their confidence in a skill), but most used more open-ended written responses, to elicit students' experiences or perceptions.

The 4 cohorts contacted included 56 students, and we received responses from 29 students. We reviewed the responses with respect to several key questions:

1. what do incoming students know?
2. what do students do after the course?
3. what do students find helpful?
4. what do students find challenging?
5. what do students expect on the course?

We used students' quantitative responses (as shown, for example, in Figures 1–3), supported by select quotations from their written responses. We focused on identifying common themes and challenges from across the written responses by affinity mapping [9].

3.1. What do incoming students know?

All respondents reported some prior programming experience, across a range of languages, but few students claim to have been confident programmers before joining the course (Fig. 1). One respondent specifically noted that they had been "over-confident" in their abilities, while another "didn't realise that [they] knew as little as [they] did".

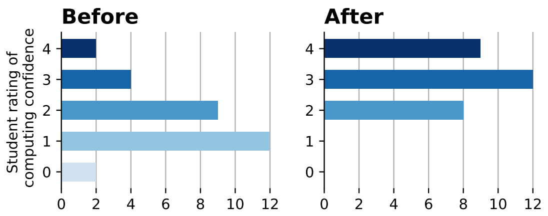

Figure 1. Space-science students self-assessed programming confidence before and after the MSc SS&T (scale 0 - 4)

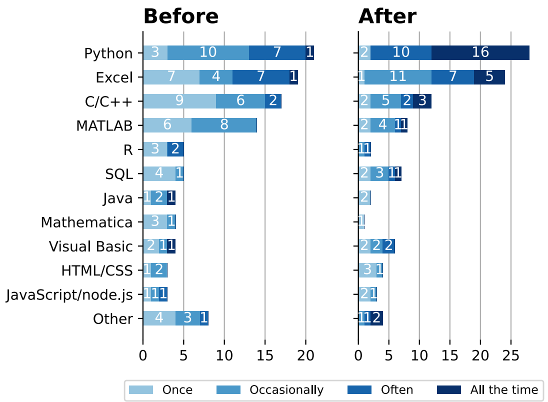

Figure 2. Programming languages used by our incoming students, and graduates.

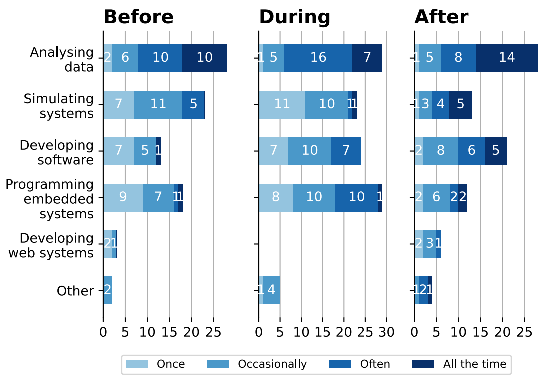

Figure 3. What do space-science students use computing for?

Nearly three quarters of students had used Python (Fig. 2), mostly for processing, analysis, and visualisation of laboratory data, or as part of an undergraduate research project. Almost two thirds had used C or C++ (often with Arduino microcontrollers), but students were less familiar with these languages. A small number had used technical or statistical software (eg., R, SAS).

Although most students (16 out of 29) had taken dedicated programming modules, this is not reflected in their written responses, which emphasise learning by writing code in labs. Formal programming classes appear disconnected from the rest of their learning; two respondents noted that after taking a course in C++ or Java, they "never used it again".

In general, most students' experience comes from data analysis or visualisation in labs. Figure 3 shows that this is the only programming application that students report as an often or always present part of their undergraduate experience. Most students have some experience with embedded programming, but usually only associated with a single project.

We supplemented this picture with a brief review of publicly available information on programming in physics and engineering at a selection of universities in Ireland and the UK. The general qualitative picture is that physics students' prior knowledge is narrow and deep, while engineering students' prior knowledge is broader and shallower. Students from a physics background typically have experience using Python for data analysis in undergraduate laboratories throughout their degree, with occasional courses in C/C++. Students from engineering courses tend to have used a wider range of languages (often including MATLAB, Excel or C), for a wider range of purposes (including modelling and numerical methods), but often only in the early years of their course.

3.2. *What do students do after the course?*

All respondents said that their confidence in their abilities increased after the course (Fig. 1). Figure 3 shows that computation is a routine part of their work. Three quarters of graduates use computers for data analysis often or all the time. Significant minorities of graduates use simulation or software development often or all the time, with a noticeable increase compared to undergraduate experiences (Fig. 3).

The course's emphasis on Python appears justified, as clearly the most popular language. It is used almost universally by respondents, with one noting that it was "considered a default requirement" when applying for jobs.

When asked to identify gaps in their learning, graduates want more experience with advanced technical skills. This includes a wider selection of languages (especially C++, although SQL, R and Ada were mentioned), advanced paradigms (especially object-orientation, which the course introduces briefly), and machine learning (which 5 students identified as a significant part of their career). Graduates

DOI: 10.5821/conference-9788419184405.121

reported that the course gave them a "much more realistic expectation of what to expect to do in the workplace", but they want to develop skills including a better understanding of the software development cycle, and of what professional, production code should look like.

3.3. What do students find helpful?

About half of responses identify the software development for their balloon experiment as the most useful part of the course, highlighting its scope and complexity ("the most complex coding project I had engaged with"), the need for robustness ("[creating] code that…would work every time"), the new technical skills learnt (particularly object-oriented programming and concurrency), and "the importance of clarity in code for collaborative programming".

Students mentioned "structuring code" most often as the most valuable skill that they developed during the course. They mention that this helps with "better layout", with writing "good code that… can be read easily", and with "trying to break…problems into smaller chunks". They identify its role in enabling collaboration, noting that "being able to explain code to others… is much easier when code is structured neatly". and that "compartmentalisation…simplifies comprehension for larger projects".

Generally, these comments about collaboration and structure suggest that graduates see a gap between the simple problems they meet as undergraduates and the more complex problems they face in industry or research, and that they need help to cross this gap.

3.4. What do students find challenging?

The responses show that students find the amount of new material and the steep learning curve challenging. A quarter of respondents identified "adapting to a relatively new language", knowing what level of ability was expected, or finding appropriate resources as a source of difficulty at the start of the course. A similar number of students identified difficulty learning more advanced skills (eg., model fitting, objects, and embedded systems).

Students also identified challenges in the step up to more complex and open problems, in which you "really had to think for yourself" to come up with solutions, and where the program structure needs to be considered as part of this.

3.5. What do students expect on the course?

Students generally appear to be surprised by the level and nature of the programming that they encounter on the course. 15 respondents mention that there was more than they expected, while only 1 said there was less (specifically, less low-level programming). Five respondents commented that they "ultimately really appreciated" the amount of programming on the course, suggesting that although they find the process (unexpectedly) difficult, they can see the benefit on reflection.

Four respondents said that the type of programming that they were asked to do was unexpected. They "expected to spend most… time on data analysis", but that the course "moved away from analysis". The "software development was a lot harder than [they] expected", but they feel that they can apply skills to "more real-world tasks now". This again suggests that undergraduate courses cover a narrower range of applications and skills than graduates use in the space sector.

4. Step II — Defining the Problem

In the next step in the design thinking process, we identify the problem to be solved. By reviewing the student responses, we have built a clearer picture of a typical space-science student's experience, wants and needs. Through our affinity mapping exercise, we then identified a set of emergent themes, each framed as a problem experienced by students:

1. what is good code? Students are unclear what makes code "good", and how to implement good practice.
2. managing expectations – students are surprised by the level and nature of programming required by the course.
3. learning the basics – students find it difficult to learn the Python language at the same time as course material.
4. finding support – students want help to find additional learning resources.
5. managing larger problems – students struggle to manage the amount of data generated in the Space Detector Lab, and to adapt to the larger project scope in the Satellite Subsystems lab.
6. learning advanced skills – students find it difficult to learn the more advanced programming techniques that they use on the course.

Addressing these problem statements will form the basis of our course development work.

5. Step III — Implementing Solutions

The last three stages in the design process — ideation, prototyping, and testing — cover finding and implementing solutions to the problem(s) that we have defined. Using these problem statements and drawing inspiration from the students' questionnaire responses, we have trialled several interventions within the course in the current 2021-22 academic year.

5.1. Improved Assessment Rubrics

We have introduced a new assessment rubric for code submissions, to address students' uncertainty about what makes good code.

The assessment rubric is based around 3 criteria: functionality, structure, and style. Each criterion assesses a distinct aspect of thinking about code. Functionality assesses how well the code does what it needs to do. The structure rubric assesses the organisation of code, with credit for code that is logical, flexible, and reusable, that uses compartmentalisation and abstraction appropriately, and that separates what is being done from how it is done. Style assesses how professionally the code is written, including readability, effective documentation, consistent styling, and writing idiomatic code.

By giving equal credit to these three areas, we encourage students to think about both what their code does and how it is put together.

5.2. "Writing Programs in Python" Workshop

We ran a 3-hour introductory workshop to support this rubric, illustrating our expectations using a series of paired-development exercises.

The workshop consists of 3 activities. First, students are placed in pairs to peer-review another student's solution to a short pre-class coding exercise. The instructor then leads a class discussion on helpful and unhelpful practices in programming. They introduce the assessment rubric, with a live demonstration to illustrate how to transform bad code to good. Finally, the class divides into pairs for a pair-programming exercise based on the popular "FizzBuzz" problem [11]. In this activity, pairs of students act alternately as programmer and reviewer in short (6 minute) programming sprints, with the reviewer guided to look at the structure and style of students' solutions.

Using collaborative exercises helps students learn to write code that communicates their intentions. Students see what makes good code by watching someone else write code, learning from the strengths and weaknesses of their practice, using the rubric as a guide. Introducing pair programming and code review also helps students to learn the professional skills needed to work as part of a software team, a skill which our graduates valued in their own careers.

6. Discussion

6.1. Who are our students?

We can use our empathetic research in Section 3 to build up a profile of a "typical" member of the Space Science & Technology cohort.

Our typical student has previously used Python (or possibly MATLAB) for data analysis but has very little formal computing education. They like that the course teaches them code structure and collaboration, and they like learning advanced topics (including object-oriented programming and machine learning). They find that they struggle with the learning curve at the start of the course, and they are unclear about what is expected of them as a programmer.

Of course, this profile comes with the obvious caveat that it does not attempt to capture the academic and social diversity that our students bring to the course, and we must be mindful that any solution based on it cannot be a one-size-fits-all answer. Nevertheless, it suggests that postgraduate space science courses should not be afraid to emphasise advanced computational skills, but cannot assume students will have more than basic familiarity with coding.

6.2. What special programming skills do space science students need?

There is a gap between the programming skills our students learn on undergraduate courses, and the skills they need in industry. We can see this in the number of responses identifying "structure" as the most important skill they learn from our course. This tells us that students' previous experiences may have given them the basic literacy needed to complete small data analysis tasks, but have not prepared them to think about and solve the larger and more varied software development and data analysis problems they meet in the space sector.

Postgraduate space-science courses have an important role here. As well as teaching students space-sector specific knowledge and skills, they introduce students to the more complex computational problems that they may encounter as graduates working in software teams. Indeed, when students talk about learning to structure code, they often mean learning how to think about code – that is, computational thinking.

6.3. How well did it work? What next?

The design thinking process encourages reflection and iteration, and there are lessons to be learnt from this exercise for future years.

The rubric was used throughout the first semester lab modules to guide students and give feedback. This has enabled more focused discussions with students as they developed their code, and simplified giving feedback.

From our (qualitative) observation of this year's cohort so far, students have taken onboard our emphasis on professionalism in their code development, suggesting that the emphasis on style and structure has worked. For example, we have seen more instances of students discussing their code together or using whiteboards and flow diagrams to plan out and structure their code before they write it.

Although students have a clearer understanding of the level that they will be expected to achieve, we have not yet addressed the challenges faced by those students learning to code with little or no prior experience. We expect students to prepare for the course by familiarising themselves with the fundamentals of the Python language, but find that this is done inconsistently. This is a harder problem to solve: the obvious solutions involve finding additional resources (by providing a pre-course training camp on Python), or compromising other parts of the course (by reducing space-science specific learning outcomes). We are looking at technology-enabled solutions to help incoming students reach a clearer common baseline.

Lastly, we have focused here on the needs and experiences of students and recent graduates. However, other stakeholders will need to contribute to developing best practice. Most notably, we will need industry input to identify the most useful technical and professional computational skills for new space-scientists.

7. Conclusions

Our work on teaching programming on the MSc Space Science & Technology at UCD provides a case study in using design thinking processes in education. This has helped us to identify some challenges our students face developing computational thinking skills as they move from higher education into industry, especially in understanding the higher standards, greater complexity, and wider variety of programming problems that they encounter as early-career space scientists. We have briefly described possible ways to use clearer expectations to smooth this transition, but this is an evolving area where best-practice has yet to emerge.

Acknowledgements

We thank UCD School of Physics for supporting this work, and the MSc SS&T students for their insights, engagement and enthusiasm.

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The effect of spaceflight on the otolith-mediated ocular counter-roll

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Abstract

The otoliths of the vestibular system are seen as the primary gravitational sensors and are responsible for a compensatory eye torsion called the ocular counter-roll (OCR). The OCR ensures gaze stabilization and is sensitive to a lateral head roll with respect to gravity and the Gravito-Inertial Acceleration (GIA) vector during e.g., centrifugation. This otolith-mediated reflex will make sure you will still be able to maintain gaze stabilization and postural stability when making sharp turns during locomotion. To measure the effect of prolonged spaceflight on the otoliths, we measured the OCR induced by off-axis centrifugation in a group of 27 cosmonauts before and after their 6-month space mission to the International Space Station (ISS). We observed a significant decrease in OCR early post-flight, with first-time flyers being more strongly affected compared to frequent or experienced flyers. Our results strongly suggest that experienced space crew have acquired the ability to adapt faster after G-transitions and should therefore be sent for more challenging space missions, e.g., Moon or Mars, because they are noticeably less affected by microgravity regarding their vestibular system.

Keywords

otolith deconditioning, ocular counter-roll, spaceflight, centrifugation, learning effect

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Acronyms/Abbreviations

BDC	Baseline data collection
CCW	Counterclockwise
CW	Clockwise
GIA	Gravito-Inertial Acceleration
ISS	International Space Station
OCR	Ocular counter-roll
R+*x*	x days after return
SCC	Semicircular canals
VVIS	Visual and Vestibular Investigation System

1. Introduction

1. *Human vestibular organ: a multisensory system*

Humans highly depend on the vestibular system, located bilaterally in the inner ear, for the coordination of movements and to ensure balance and gaze stabilization [1]. The vestibular organs consist of the semicircular canals (SCCs) that are stimulated by angular accelerations, and the otoliths that detect the vector sum of linear accelerations acting upon the head, known as the gravito-inertial acceleration (GIA) vector. The otoliths are the primary graviceptors of the vestibular organ by registering linear accelerations on the one hand, including gravity, and lateral tilts of the head on the other hand. Otoliths transmit their information to the brain to determine the spatial vertical, which is essential for controlling our posture and eye movements. An important otolith-mediated ocular reflex is the ocular counter-roll (OCR) that is generated when the head is laterally tilted, e.g., during centrifugation or while driving around a corner. The OCR tends to rotate the eyes in the opposite direction to the roll tilt and towards the GIA [2]. As a result, you will still be able to maintain postural stability and gaze stabilization when making sharp turns during locomotion.

2. *Effect of prolonged spaceflight*

Cosmonauts who are in the International Space Station (ISS), orbiting around Earth, are subjected to microgravity (< 10^{-6}g). The lack of gravitational input will cause a deconditioning of the otoliths by decreasing the gain (ratio of eye torsion over head tilt) of otolith-mediated reflexes [4]. Also, the assessment of the real vertical will be impaired when there is a loss of otolith input to the brain in microgravity [7]. Deconditioning of otolith-mediated reflexes following microgravity exposure has been proposed as one of the multiple causing factors of the postural, locomotor, and gaze control problems experienced by returning astronauts [5]. These symptoms are generally maintained until the otoliths are re-adapted to Earth's gravitational level [4].

The OCR has previously been used as a measure for microgravity's effect on the otoliths [7,8,9,10]. However, these studies overall provide conflicting results, which is most likely explained by variations in mission duration, methodological choices, and sample size. Our group has previously demonstrated a decrease in the OCR reflex after long-duration spaceflight based on 25 datasets, which returned to baseline on average 9 days after return to Earth.

The aim of this study was to examine the effect of prolonged spaceflight on the otolith-mediated OCR in a study sample of 44 datasets, extending the results from our prior work [4]. Considering the increasing number, longer duration, and more distant destinations of future planned space missions, it is necessary to know to what extent the otoliths are affected. There are only few studies examining long-term exposure to microgravity, so that the consequences of such exposure on otolith-mediated reflexes are still not well understood. This study may provide more insight, especially for the upcoming long-term space missions to the Moon and eventually to Mars.

2. Material and Methods

2.1. *Experiment timeline and subjects*

The Visual and Vestibular Investigation System (VVIS), located in the Gagarin Cosmonaut Training Centre in Star City near Moscow (Russia), was used to induce the OCR. We investigated 27 cosmonauts, of whom several were tested twice or even more times during consecutive spaceflight missions to the ISS. As a result, 44 experiments were performed in total, 31 were conducted for experienced flyers (N=16 second-time, N=8 third-time, N=4 fourth-time, and N=3 fifth-time flyers), while the other 13 experiments were conducted for the remaining first-time flyers (N=13 first-time).

The cosmonauts were tested before and after their 6-month space mission in the ISS between ISS increment mission 16 in October 2007 to increment 61 in April 2020. The pre-flight experiments consisted of 2 baseline recordings defined as *baseline data collection* (BDC), and the post-flight experiments consisted of 2 to 3 OCR recordings. The first post-flight measurement was taken 1 to 3 days after their return to Earth, defined as R+1/3. The second post-flight measurement was taken 4 to 7 days after their return, R+4/7. The third post-flight measurement was taken 8 to 12 days after their return, R+8/12. It was impossible to test all cosmonauts on the same day after their return, due to medical and logistical limitations.

The experiment protocol was designed in accordance with the ethical standards defined in the 1964 Declaration of Helsinki and was accepted by the Human Research Multilateral Review Board (HRMRB) and European Space Agency (ESA). Cosmonauts gave their voluntary informed consent prior to their participation in this study.

2.2. *Visual and Vestibular Investigation System*

The cosmonauts were securely fastened, by a five-point safety harness with a restriction of head movements, and seated upright on the rotation chair, 0.5 m away from the vertical rotation axis.

The experimentation room was darkened to avoid fixation or visual motion feedback during centrifugation. A visual display, mounted in front of the cosmonaut's face, was used to project visual targets during parts of the experiment. Binocular 3D video-oculography with infrared video goggles was used to enable continuous recordings of dynamic changes in ocular torsion.

At standstill, the calibration of the video goggles and a baseline recording were performed. After an acceleration phase of 30°/s^2, the cosmonaut was subjected to constant angular velocity of 254°/s resulting in an outward centripetal acceleration Ac of 1g first for 5 minutes in a Counterclockwise (CCW) direction. The chair was decelerated with a rate of 3°/s^2 to stand still. The chair was then manually 180° rotated, and subsequently the protocol was repeated for 5 minutes in a Clockwise (CW) direction. In between both centrifugation directions, the cosmonaut remains seated while the operator changes the centrifuge configuration to the subsequent (CW) direction. The cosmonaut faced the direction of motion, with the right ear outwards during CCW rotation and the left ear outwards for the CW rotation. The vector sum of the gravitational acceleration Ag and the centripetal acceleration Ac is called the Gravito-Inertial Acceleration (GIA). This GIA was perceived by the subject as the 'spatial vertical' and exerted a shear force on the otolith system which caused an illusory 45° perceived roll-tilt during rotation. As a result, an OCR was induced that tended to orient the eyes towards the GIA and thus away from the direction of the perceived tilt.

2.3. *OCR measurements*

The OCR measurements were taken before, during, and after centrifugation according to a fixed protocol. The first and fourth OCR measurements were respectively taken before and after centrifugation during standstill, where no centripetal force was acting upon the body and thus an OCR of 0° was observed as expected. The second OCR measurement was taken 40 seconds after the steady-state phase of constant rotational velocity was reached, because we only wanted to assess the contribution of the otolith system to the OCR. During the 40 seconds, the cupula of the horizontal semicircular canals (SCCs) returns to its original position and no longer contributes to the OCR. The third OCR measurement was taken 40 seconds before the start of the deceleration phase. The time interval between the second and third OCR measurements was 3 minutes and 40 seconds. During centrifugation, the second and third OCR measurement, an OCR of on average 5°-7° [18] was expected to be measured because of GIA stimulating the otoliths. Each OCR measurement was recorded for 20 seconds, while the cosmonaut observed a fixation dot on the visual display. The fixation dot was used to cancel out other eye movements, e.g., saccades, during centrifugation. The OCR was calculated as the difference of the average eye torsion over these 20 second recordings, consisting of 600-1000 frames, between rotation and standstill.

The video files obtained during the VVIS experiment contain recordings of the eye movements and were analyzed in a visual programming language (custom made by H.M. in LabVIEW - National Instruments -11500 N Mopac Expwy. Austin, TX, USA) to measure the OCR in degrees.

2.4. *Statistical analysis*

The OCR measurements were statistically analyzed in JMP® (version Pro 16. SAS Institute Inc, Cary, NC, 1989-2001), with $p<0.05$ as significance threshold, using linear mixed models. We first tested our main variables as fixed effects and then systematically tested all interaction terms. The variables included were *Timepoint* (BDC1, BDC2, R+1/3, R+4/7, and R+8/12), *Days After Return* (1 to 12 days), *Flight* (first-time vs experienced flyers). The significance threshold used for selecting the fixed effect was set at $p=0.001$. Non-significant terms were removed until all combinations were tested and only the significant ones remained. In all models, *Cosmonaut* was entered as random intercept to account for the non-independence between observations from the same cosmonaut. As random slope terms *Cosmonaut*Flight* and *Cosmonaut*Flight*Timepoint* were included according to their Likelihood ratio tests (p<0.0001). The residuals of all models were checked for normality and homoskedasticity.

3. Results

We evaluated the OCR measured across different time points (BDC1, BDC2, R+1/3, R+4/7, and R+8/12) and different experience levels of the cosmonauts (first-time to experienced flyers). We showed an effect of time and previous spaceflight experience on the OCR (p<0.001) (**Figure 1**). There was also a significant interaction effect of time and previous flight (p<0.001). A post-hoc Dunnett's correction was performed to compare the OCR between BDC1 and all subsequent measurements. BDC2 did not differ from BDC1, proving a good test-retest reliability of the data. The OCR significantly decreased early postflight at R+1/3 and R+4/7 compared to BDC1. At R+8/12, OCR was back to preflight level. Overall, these results show that the OCR is decreased early after spaceflight and that it returns to baseline within two weeks after spaceflight. Moreover, the change in OCR over time differs between first-time and experienced flyers, with experienced flyers being less affected (**Figure 2**).

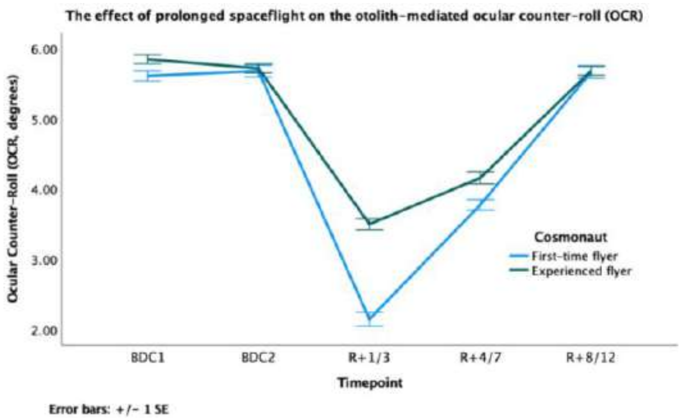

Figure 1 Difference between first-time and experienced flyers regarding the effect of long duration spaceflight on the OCR. Error bars represent standard errors of the mean with multiplier 1.

Using an independent sample T-test, as an approximation, we found a significant difference between the first-time and experienced flyer at R+1/3 (p<0.0001). The first-time flyers showed a decrease until 2.15±0.10, where only the experienced flyers showed a decrease until 3.50±0.08.

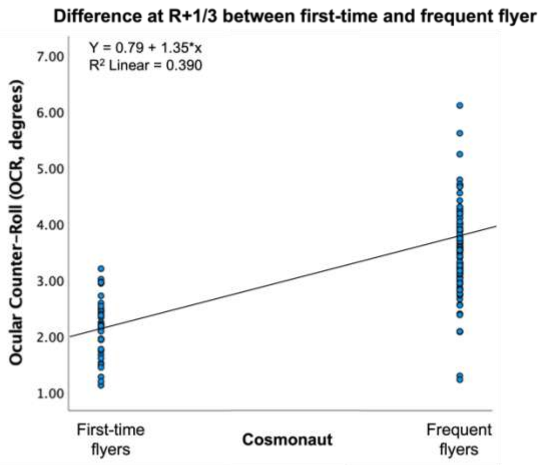

Figure 2 The difference between first-time and frequent flyers early post-flight (R+1/3).

4. Discussion

The aim of this study was to examine the effect of prolonged spaceflight on the otolith-mediated OCR in a relatively large study sample of 27 cosmonauts. The main findings of this study were that (i) the OCR showed to be consistent for test-retest as assessed by repeated preflight measurements, (ii) the OCR is decreased early post-flight compared to pre-flight, (iii) the OCR returns to baseline levels as measured on average 9 days after the space mission, and (iv) the OCR change over time is dependent on previous experience in space.

The decrease in OCR measured at R+1/3 reflects a deconditioning of the reflex as a result of a prolonged reduction in gravitational input during the space mission. It has long been established that the vestibular system is affected during space travel and that this causes various symptoms and functional changes during the first weeks in space, as well as the first weeks back on Earth. Specifically, postural control, locomotion, and gaze stabilization are affected during this time frame, which can be attributed to the vestibular system still being adapted to the condition of microgravity [6, 9, 10, 14, 16]. The decrease in OCR therefore strongly points to such an adaptation. Further establishing the association between OCR changes and functional changes will be essential for future missions to the Moon and Mars, where multiple gravitational level transitions will be made, forcing the vestibular system to adapt multiple times [13, 18].

Although a decrease in OCR after spaceflight has been demonstrated before [6, 16, 12, 17], some studies show conflicting results with ours. For example, one study showed no change in OCR

DOI: 10.5821/conference-9788419184405.122

after spaceflight [3]. This is potentially explained by the different methodological approach to trigger the OCR. In that study, the OCR was induced by static tilting of the head as opposed to the off-axis centrifugation used in our study. Moreover, the mission duration was less than two weeks as opposed to six months for our study. Possibly, the mission duration alone could explain why others have not observed OCR changes. Specifically, the vestibular system might only be slightly adapted compared to cosmonauts spending six months in space, meaning that the readaptation upon return to Earth takes place more quickly. In this case, the OCR is not found to be altered after spaceflight, possibly due to the otoliths being fully re-adapted at the time of measurement. This would highlight the importance of taking into account the mission duration concerning measurements of the vestibular system in space travelers.

Concerning the re-adaptation of the OCR when back on Earth, we found that the measurements taken on average 9 days post-flight did not significantly differ from pre-flight values. While this time frame has a reasonable correspondence with the time window in which cosmonauts present with gait, posture, and locomotion issues, we were not able to prospectively investigate such an association. On the other hand, our data corroborate with those of Kornilova and colleagues, who independently reported a similar time frame of OCR re-adaptation than we do. Interestingly, it has been shown that the vestibular system at the cortical level still presents with connectivity and activity changes 9 days post-flight compared to pre-flight [15,16,17]. This suggests that vestibulo-oculo reflexes are more quickly readjusted to Earth's gravity, while the brain needs more time, up to three months [17], for readjusting.

Lastly, we found that cosmonauts who flew in space before showed a lesser post-flight decrease in OCR compared to first-time flyers. This is a novel finding, as often sample sizes are not large enough in both groups. These data indicate that the otoliths of first-time flyers are more affected than in experienced flyers. We hypothesize that previous time spent in microgravity triggers learning behavior at the level of the neural reflex circuits, providing a resistance against OCR deconditioning. Previous spaceflight experience is known to have a beneficial effect for in-flight adaptation and post-flight re-adaptation at the level of sensorimotor function. For example, experienced flyers recover more quickly regarding locomotor function and are often not as susceptible to space motion sickness than first-time flyers [19]. Based on our OCR data, we demonstrate clearly that the OCR is less deconditioned in experienced flyers, advocating for sending humans to the Moon and Mars who have prior experience in microgravity. Due to the multiple gravity level transitions that will be characteristic for such missions, it would be beneficial to send experienced flyers due to their vestibular system seemingly adapting better to microgravity than first-time flyers. These findings might therefore open a new line of research into the exact requirements regarding experience for Moon and Mars missions.

5. Conclusion

Our study showed that the otolith-mediated OCR reflex decreases early post-flight, corroborating several other studies in long-duration mission cosmonauts. We further demonstrate a re-adaptation of the OCR to Earth's gravity levels around 9 days post-flight. Lastly, we show that prior experience in microgravity results in less deconditioned OCR reflexes, which may have beneficial consequences for functional adaptations during future space missions, such as to the Moon or Mars.

Acknowledgements

We would like to thank all participating cosmonauts and crewmembers. This study was funded by Belgian Science Policy (Prodex), ESA-AO-2004-093. CS is a Research Fellow of the Research Foundation Flanders (Belgium, FWO Vlaanderen).

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Assessment of a machine-vision-assisted test bed for spacecraft magnetic cleanliness analysis

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Abstract

Small satellites are becoming increasingly popular in several applications, in which attitude systems might require high precision performance. These spacecrafts are susceptible to magnetic disturbances in orbit, such as the interaction between the satellite and Earth's magnetic field. However, a major disturbance torque is generated by the residual magnetic moment. Therefore, a magnetic cleanliness analysis must be considered in order to meet the requirements for magnetic-sensitive instruments and subsystems. Studies on magnetic environment management are underway for the FORESAIL-1 and FORESAIL-2 missions using the optical magnetic test bed of Aalto University. This is particularly important for FORESAIL-2 which aims to precisely measure the orbital ambient magnetic field with a high sensitivity magnetometer

One of the parts of a spacecraft magnetic cleanliness analysis is the modelling of the residual magnetic moment as a set of magnetic dipoles. The dipoles are estimated from the measured magnetic field surrounded by the device-under-test (e.g., complete satellite, or its individual subsystems) using a stochastic estimation algorithm. The measurements are performed in a Helmholtz cage where the device and a low-noise magnetometer are placed, and detected by a smart camera using visual detection markers (ArUco). Information provided by the detection of the markers is then used for representing the position of the magnetometer and measured magnetic field points in the device-under-test coordinate frame.

The camera detection accuracy is improved with data fusion from several ArUco markers, and the system performance is assessed by verifying the estimated magnetic moment results using known permanent magnets. Using this methodology for calculating the residual magnetic moment, the system is able to estimate the dipole's position and magnetic vectors with a mean absolute error of 0.004 ± 9·10-7 m and 0.007 ± 1·10-4 A·m2 respectively. The test bed can be used for the characterization of the magnetic moment when measuring small satellites, or its components, in order to mitigate the residual magnetic moment.

Keywords

Magnetic dipole moment, Optical magnetic test bed, Residual magnetic moment, Small satellite, Spacecraft magnetic cleanliness analysis

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Nomenclature

B	*Surrounding Magnetic Field*
B_r	*Residual Flux Density of the magnet*
m	*Dipole Moment (magnetic)*
m_{EXXX}	*Dipole Moment of Magnet EXXX*
T_m	*Magnetic Torque*
V_{EXXX}	*Volume of the magnet*
μ_0	*Magnetic Permeability*

Acronyms/Abbreviations

ADCS	*Attitude, Determination and Control Subsystem*
CC	*Closer Configuration*
DUT	*Device-under-test*
FC	*Further Configuration*
FOV	*Field Of View*
MDM	*Magnetic Dipole Moment*
MF	*Magnetic Field*
OMTB	*Optical Magnetic Test Bed*
PA	*Pointing Angle*
RMM	*Residual Magnetic Moment*
S/C	*Spacecraft*
VA	*View Area*

1. Introduction

As the number of applications for small satellites increases rapidly, the mission goals can be more demanding. For example, the attitude, determination and control subsystem (ADCS) can require precise pointing and orientation management to meet the mission objectives. ADCS can be composed out of sensors such as magnetometers, gyroscopes, among others. The sensor data will influence the operation of the actuators, such as magnetorquers, reaction wheels, etc.

Some of these components can be affected by magnetic disturbances, which is the residual magnetic moment (RMM) of the spacecraft (S/C), and which can be one of the main perturbances. In order to minimize this, a magnetic dipole moment (MDM) need to be characterized accordingly, so mitigation techniques can be considered [1].

The MDM can be determined with a wide range of methods. Most of them involve mechanical magnetic test bed in which the device-under-test (DUT) is rotated in one or more axis during the measurement. However, some studies in this field are using new technology by incorporating a visual system which can be denoted as optical magnetic test bed (OMTB) [2][3][4]. This paper presents the performance of the OMTB used in Aalto university for small satellites' MDM characterization.

2. Magnetic dipole measurement

2.1. Pose and optical recognition

In this paper, the orientation of an object is represented by the Euler angles which represent the attitude of an object based on three rotations on each of the axes: x, y, z, named pitch, yaw and roll respectively. The final rotated frame depends on the sequence of the rotations. Note that pose is defined as the position and the orientation combined.

The OMTB uses optical recognition to detect the pose of the DUT by using ArUco markers stuck on the faces of the device. These markers poses are defined in the detection algorithm and then gathered using a smart camera using machine vision [4]. The markers have different patterns which differentiate them from one another.

2.2. Magnetic torque and characterization

As it was stated earlier, the main perturbance comes from the residual S/C's dipole moment, also known as RMM. This magnetic torque can be expressed as

$$\mathrm{T_m} = m \times B \qquad (1)$$

In order to reduce the RMM of the S/C and mitigate its disturbance, it is important for magnetic characterization techniques to be able to model the MDM. So, it can be compensated such that only a RMM remains. Some of these techniques are presented in [2], which include: direct torque measurements, ambient field mapping, mapping in a field-free region, etc. The last technique requires a region where the ambient MF is nearly zero, so small size devices are normally measured using this technique.

This paper will focus on the last technique, where the different poses of the DUT are measured inside a field-free region. In mechanical magnetic test beds, the DUT is rotated using mechanical systems to gather the pose information. These systems can be complex, even making the measurement tedious. Using a OMTB though, the process of gathering the information needed is automated and it does not require complex mechanical systems for taking the measurement.

3. Permanent magnet verification

3.1. Magnetic measurements

The physical setup of the OMTB at Aalto University is composed of: a 3-axis Helmholtz coil cage, a magnetometer, the DUT, ArUco markers, camera and support, background isolation paper, and control software; as can be seen in Figure 1. The magnetometer is placed inside, at the center of the Helmholtz cage which generates a near-to-zero MF. The camera and the paper shall be placed in the near background, and stay in the same position throughout the measurement. The same applies to the computer. Then, the field-free region is generated inside the cage. Note that the DUT is placed when the measurement starts and is being rotated within the camera's field of view (FOV).

The visual from the camera is also available, where the orientation of the detected markers is displayed (Figure 2). The magnetometer has the marker '0', and the DUT is a cube of 50 mm x 50 mm x 50 mm where all faces are covered with markers from '1' to '6' of the size of 37.7 mm x 37.7 mm. The camera used is a Jevois-A33 smart video camera [5]. On the plane of the marker, the X-axis is horizontal towards the right, Y-axis is vertically upwards, and Z-axis follows the right-hand rule. Inside the DUT used, a permanent magnet is placed underneath marker '1' as shown in Figure 3. Note that its location shall be defined in the script [4].

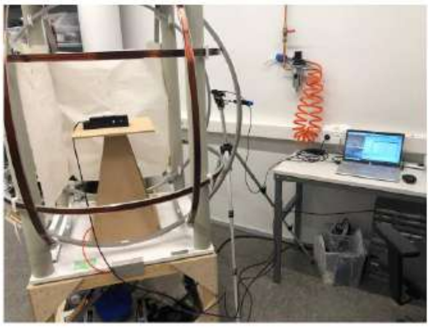

Figure 1. OMTB setup at Aalto University

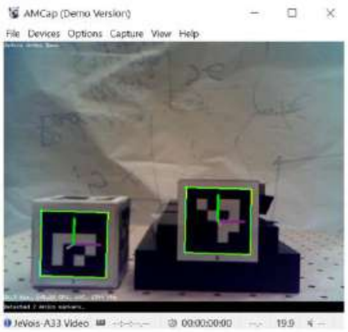

Figure 2. Marker detection from the camera

Figure 3. Permanent magnet E200's placement

Three magnets are evaluated. Their dipole moment can be calculated based on Eq. 2; where $\mathrm{B_r}$ is in Tesla, μ_0 in Henries per meter, and $\mathrm{V_{EXXX}}$ in cubic meters. The magnets are labeled with the codes E122, E317 and E200 (EXXX is generic). The characteristics of these magnets are displayed in Table 1. Note that the first magnet is cylindrical, and the rest are cubical.

For each of the magnets, the camera has been placed in a closer configuration (CC) and in a further configuration (FC), varying the distance from the markers and the camera. These two configurations can be seen in Figure 4 and Figure 1, respectively.

$$\mathrm{m_{EXXX}} = \frac{B_r}{\mu_0} \cdot V_{EXXX} \tag{2}$$

Table 1. Permanent magnets' features

Magnet label	Unit	E122	E317	E200
Radius	m	0.0017	-	-
Width		-	0.0050	0.0050
Depth		-	0.0050	0.0050
Height		0.0017	0.0020	0.0050
Position X-axis		0.0000	-0.0011	0.0000
Position Y-axis		0.0179	0.0180	0.0195
Position Z-axis		-0.0230	-0.0250	-0.0250
MDM X-axis	A·m2	0.0000	0.0000	0.0000
MDM Y-axis		±0.0039	±0.0509	±0.5093
MDM Z-axis		0.0000	0.0000	0.0000

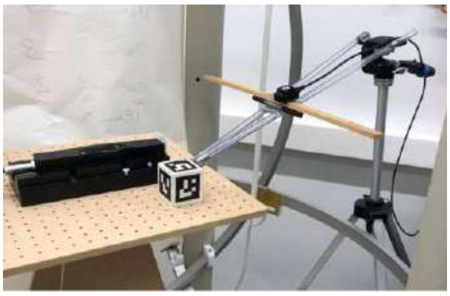

Figure 4. CC camera-marker

3.2. Modified magnetic measurements

some problems when detecting the markers were observed After taking the first round of measurements: momentarily undetected or intermittent marker detection, and orientation flipping. The way the software managed the collection of the marker's information was modified in order to minimize the effect of these problems. The next step was to analyze which poses provided improved accuracy. A better detection of the pose is proportionally related to a better reading and calculation of both position and MF. Thus, improving the detection of the markers' pose was the main focus, and a field-free region was not needed for this work.

For this evaluation, two markers were placed on a flat surface simulating one marker each for the magnetometer and one face of the DUT. Note that the markers do not move in relation to each other, the flat surface is rotating at different poses while the camera detects the markers. The position and orientation of the DUT marker '4' respect to the magnetometer marker '0' remains constant. Since markers' pose is well defined, the detected position and orientation directly provides the error; since the detection should match the defined value.

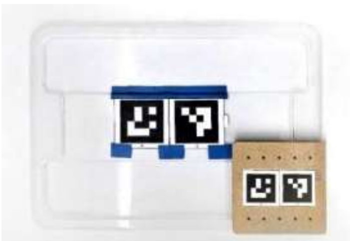

Figure 5. Markers '0' and '4' on a flat surface

It is worth to point out that several distances from the camera have been measured for different yaw and pitch angles of the flat surface. Roll angle has been proved not to disturb the detection when yaw and pitch angles are kept constant [5]. Notice that there are two sizes of markers, two markers for each flat surface. Markers are the same: '0' and '4' in both cases, but in different size: 37.7 mm x 37.7 mm, and 58 mm x 58 mm. Different size measurements have been considered to correlate the results in their detection's accuracy. The flat surfaces and the setup for this evaluation can be seen in Figure 5 and 6.

Figure 6. Accuracy evaluation set up

For analyzing the results, two generic concepts are created: pointing angle (PA) and view area (VA). PA refers to the axis angle of the DUT marker's Euler angles with respect to the camera z-axis pointing towards the markers, and VA is the percentage of marker's area viewed over the camera's FOV area. Based on this analysis, the algorithm has been modified to prioritize the detection of the markers in which pose the accuracy is higher. The three magnets and same camera configurations have been re-measured in order to see the new performance of the OMTB.

4. Results

The results from the first six measurements are displayed in Table 2, 3 and 4. Followed by the accuracy detection map based on the PAs and VAs, and their detection errors in position and orientation (Figure 7 and 8). Lastly, Table 5, 6 and 7 present the results of the modified magnetic measurements using the same magnets and configurations.

Table 2. Actual, CC and FC results

Magnet E122	Unit	Actual	CC	FC
Position X-axis	m	0.0000	0.0012	-0.0018
Position Y-axis		0.0179	0.0186	0.0143
Position Z-axis		-0.0230	-0.0237	-0.0256
MDM X-axis	A·m2	0.0000	-0.0006	0.0004
MDM Y-axis		±0.0039	-0.0061	-0.0045
MDM Z-axis		0.0000	0.0002	0.0002
MDM Module		0.0039	0.0062	0.0045

Table 3. Actual, CC and FC results

Magnet E317	Unit	Actual	CC	FC
Position X-axis	m	-0.0011	-0.0023	0.0007
Position Y-axis		0.0180	0.0205	0.0176
Position Z-axis		-0.0250	-0.0259	-0.0241
MDM X-axis	A·m2	0.0000	0.0013	0.0039
MDM Y-axis		±0.0509	-0.0469	-0.0345
MDM Z-axis		0.0000	-0.0002	-0.0013
MDM Module		0.0509	0.0469	0.0350

Table 4. Actual, CC and FC results

Magnet E200	Unit	Actual	CC	FC
Position X-axis	m	0.0000	0.0041	0.0000
Position Y-axis		0.0195	0.0152	0.0211
Position Z-axis		-0.0250	-0.0263	-0.0269
MDM X-axis	A·m2	0.0000	0.0627	0.0019
MDM Y-axis		±0.5093	0.3986	-0.4564
MDM Z-axis		0.0000	-0.0210	0.0064
MDM Module		0.5093	0.4041	0.4565

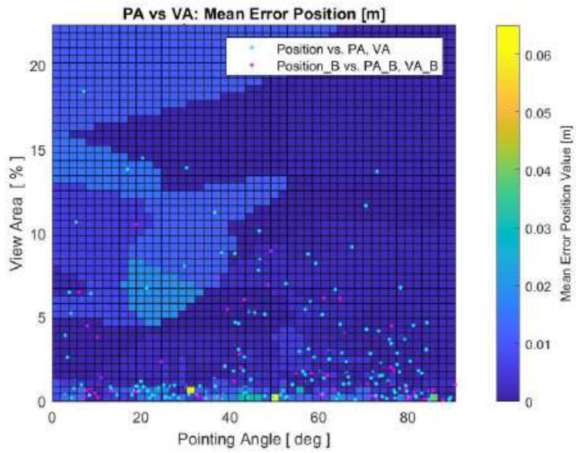

Figure 7. VA vs PA, mean error in position

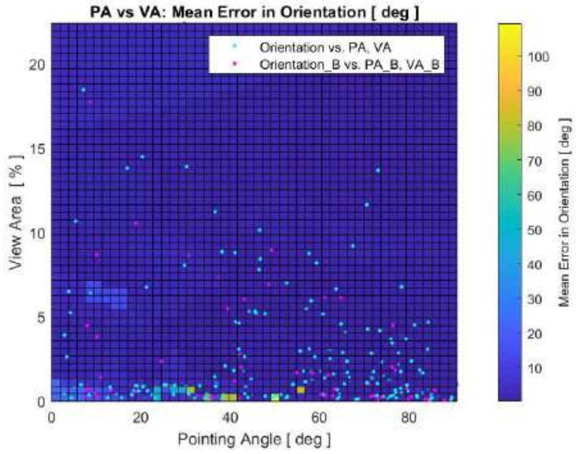

Figure 8. VA vs PA, mean error in orientation

Table 5. Actual, CC and FC after modification

Magnet E122	Unit	Actual	CC	FC
Position X-axis	m	0.0000	0.0017	0.0000
Position Y-axis		0.0179	0.0195	0.0090
Position Z-axis		-0.0230	-0.0239	-0.0257
MDM X-axis	A·m2	0.0000	-0.0005	0.0005
MDM Y-axis		±0.0039	-0.0061	-0.0033
MDM Z-axis		0.0000	0.0003	-0.0004
MDM Module		0.0039	0.0061	0.0034

Table 6. Actual, CC and FC after modification

Magnet E317	Unit	Actual	CC	FC
Position X-axis	m	-0.0011	0.0009	-0.0027
Position Y-axis		0.0180	0.0200	0.0175
Position Z-axis		-0.0250	-0.0245	-0.0225
MDM X-axis	A·m2	0.0000	0.0012	0.0011
MDM Y-axis		±0.0509	-0.0499	-0.0420
MDM Z-axis		0.0000	-0.0005	-0.0036
MDM Module		0.0509	0.0500	0.0422

Table 7. Actual, CC and FC after modification

Magnet E200	Unit	Actual	CC	FC
Position X-axis	m	0.0000	-0.0018	-0.0008
Position Y-axis		0.0195	0.0219	0.0182
Position Z-axis		-0.0250	-0.0282	-0.0334
MDM X-axis	A·m2	0.0000	0.0079	0.0162
MDM Y-axis		±0.5093	0.4258	-0.3872
MDM Z-axis		0.0000	-0.0103	-0.0126
MDM Module		0.5093	0.4041	0.4260

5. Discussion

From the first round of measurements, it can be said that the estimation in both configurations is similar.

The problems in the detection were observed and minimized by using the modified script based on the accuracy evaluation. In this evaluation, it can be seen that the detected orientation is homogeneously accurate at different distances from the camera but detection struggles around a PA of 40 degrees. Regarding the detection of the position, the accuracy is higher when the marker is oriented at a PA greater than 45 degrees; the accuracy also seems to vary with distance, but not by a significant amount. Comparing the modified magnetic measurements to the first round of measurements, there is a 2% increase in accuracy in the overall estimation results.

Based on these measurements and analysis, the OMTB is able to estimate the MDM's position and properties with a mean absolute error of 0.004 ± 9·10-7 m and 0.007 ± 1·10-4 A·m2, respectively. Moreover, it can be stated that the OMTB has an overall percentage error of 13% for position and 23% for magnetic properties, in the MDM estimation results.

More detailed information about the methodology, evaluation of the accuracy and measurements can be found mainly in [5]; regarding the particle swarm algorithm used to model the MDM, see [4].

6. Conclusions

The OMTB at Aalto University is able to model and estimate the MDM properties of the three permanent magnets used. The system was successfully assessed by measuring different magnetic dipoles before and after an evaluation and improvement of the accuracy in the markers' pose detection.

Future measurements could involve components of small satellites, or the spacecrafts themselves, in order to adjust and reduce the RMM. Also, the possibility of improving the results by carrying out improvements to the smart camera, lighting conditions, location of the OMTB and automatization of the DUT's rotation.

Acknowledgements

I would like to thank Jaan Praks and Bagus A. Riwanto for their help and guidance throughout the project. Also, to Daniel Garcia-Almiñana for the support for participating at the SSEA 2022.

Note that the participation in this conference (SSEA 2022) has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 737183. This reflects only the author's view and the European Commission is not responsible for any use that may be made of the information it contains.

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Competition, Research and Extension: The three approaches to the Popularization of Small Satellites in the Alto Paraopeba region in Brazil.

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Abstract

There are several approaches to the diffusion of the space technologies, three of them are in this work: competition, research, and extension. Thus, the objective of this work is to focus on presenting the results of the Brazilian nanosatellite team called NoizOrbita, and also to qualify quantitatively the impact of using these approaches in popularizing the topic of small satellites for space educational purposes. The team was founded on September 29, 2020, by three people: an alumni of Telecommunications Engineering at Federal University of São João del-Rei (UFSJ), Alto Paraopeba Campus (CAP), currently pursuing his Ph.D. in CubeSat Antennas at UFSC; a student currently in the 6th period of the Telecommunications Engineering undergraduate course (class of 2019); and a professor in the Department of Telecommunications and Mechatronics Engineering (DETEM). This initiative is intended to be a gateway to the space/satellite technologies in the institution and is based on three main pillars: Competitions, Research, and Extension in Nanosatellites. The team aims to obtain and develop small satellite technologies involving CAP undergraduate and graduate students, which enables them to learn the concepts of Space Engineering with the methodology of "learning by doing", covering the entire lifecycle of a spacecraft, even in a less complex way, through Systems Engineering approach. It also encourages the students to carry out scientific studies, prepare and publish papers, participate in conferences, and through extension, spread all the knowledge acquired in the various layers of society in the Alto Paraopeba region. Team members are all undergraduate and graduate students. Considering that one of the main characteristics of the team is its multidisciplinary nature, it leads to the advantage that students from all courses offered at CAP can join the group. This is reflected a lot by the concept of satellite engineering, since professionals from various areas of knowledge are sought for working with satellites and small satellites. Thus, in this work the main numbers related to the team were gathered, collected and presented in order to assess the impact and/or reach of the activities in its first year of existence. Data were extracted from databases, histories, and records on the various knowledge and information dissemination platforms. Regarding the research approach, the team obtained a significant number of scientific productions; regarding extension, presentations with satellite subjects were performed; and a great achievement with the competition aspect was obtained, which shows the effectiveness of these three approaches.

Keywords

Alto Paraopeba, NoizOrbita, Small satellites, Space education.

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Acronyms/Abbreviations

AEB	*Brazilian Space Agency*
CAP	*Alto Paraopeba Campus*
DETEM	*Department of Telecommunications and Mechatronics Engineering*
INPE	*National Institute for Space Research*
MCTI	*Ministry of Science, Technology, and Innovation*
OBSAT	*Brazilian Satellite Olympics*
SNCT	*National Science and Technology Week*
STEM	*Science, Technology, Engineering and Mathematics*
UFSJ	*Federal University of São João del-Rei*

1. Introduction

The Federal University of São João del-Rei (UFSJ) was founded on April 21, 1987 [1] with the name of Higher Education Foundation of São João del-Rei (FUNREI), being recognized in 2002 as a university. Currently, UFSJ has 6 campi: Alto Paraopeba Campus (CAP), Dona Lindu, Dom Bosco, Santo Antônio, Sete Lagoas, and Tancredo Neves Campus, covering a total of 5 cities. The Alto Paraopeba Campus, in particular, is located at the division of the cities of Ouro Branco and Congonhas in the region called Alto Paraopeba. The campus, whose main view is illustrated in Figure 1, was implemented in 2008, seeking to fulfill an important government policy of education [2]. It was conceived to be an engineering center [3], and among other objectives, it stands out to provide economic growth with quality of life in the Alto Paraopeba region, which for many, was another important step towards promoting sustainable development in the region.

Figure 1. Main view of the Alto Paraopeba Campus [3].

The group/team called NoizOrbita, whose logo is illustrated in Figure 2, was founded in 2020, and to the best of our knowledge, it can be considered the first initiative in the field of space engineering at UFSJ.

Figure 2. Logo of the UFSJ competition, research and extension team in nanosatellites.

More specifically, the team was founded in September 29, 2020, by three people: a former student who graduated in Telecommunications Engineering at CAP in 2018 and until then a Master's student in Space Engineering and Technologies at the National Institute for Space Research (INPE); a student currently in the 6th period of the Telecommunications Engineering course (class of 2019); and an effective professor in the Department of Telecommunications and Mechatronics Engineering (DETEM). This initiative can be a gateway to the space/satellite theme at the institution and is based on three main pillars: Competition, Research, and Extension in Nanosatellites, as illustrated in Figure 3.

Figure 3. The three approaches proposed to the popularization of small satellites.

The team aims to develop technologies related to small models of satellites in order to train the members of the team, which enables them to learn concepts of Space Engineering, covering the entire space lifecycle, even in a less complex way, through techniques of Systems Engineering project management. Some of the objectives of the team are to carry out scientific studies, prepare papers, improve and develop new technologies, and through extension, disseminate all the knowledge acquired and developed by the team in the various layers of society in the Alto Paraopeba region. The team is formed by students from the different engineering courses available at CAP. This fact emphasizes the multidisciplinary tendency of the NoizOrbita team, and can be compared to a "real world" satellite engineering group, in which professionals from various areas of knowledge are required for the design, development, assembly, integration, testing and operation of satellites and small satellites. Table 1 shows all the undergraduate courses offered by UFSJ at CAP.

Table 1. Undergraduate courses offered at CAP[1].

Campus	Undergrad. courses
Alto Paraopeba (CAP)	Civil Engineering
	Bioprocess Engineering
	Telecommunications Engineering
	Mechatronics Engineering
	Chemical Engineering

Regarding the organization of the team, each member is allocated in their division of choice and later, they are interconnected based on objectives, that can either be focused on the competitions, or in extension activities, which allows everyone to participate in the three main aspects of the team, each with its own specialty in an interdisciplinary and collaborative environment. In Table 2 it is possible to visualize the hierarchy of the internal divisions of the team.

Table 2. Hierarchical team divisions.

	Team Council	
	Team Leader	
Divisions	Management	Systems Engineering
	Content creation and social media	Embedded Electronics
	Human Resources	Mechanics and Structure
		Payload

The popularization of satellites through the three aspects of competition, research, and extension has already been extensively explored. It can be cited as a successful example of popularization of satellites in Brazil and Latin America the competition called CubeDesign[4], which is a small satellite development competition [4]. The competitive aspect, however, is not exclusive when we talk about the popularization of satellites, since projects and ideas can be born through various approaches, being able to migrate or generate works in other approaches, as is the case of [5]. In this example, after participating in the CubeDesign competition in 2019, they carried out a study and published a scientific paper at the Workshop on Space Engineering and Technologies[5] (WETE) in 2019, contributing to the dissemination of the research developed. Another example to be mentioned is the case of the team of students from the Cempre Benedito Ferreira Lopes middle school in Mogi das Cruzes - SP, who also participated in the competition in the same year and won the 3rd place in the Mockup category [6]. These students were awarded a lecture on "Introduction to Space Technologies" and also a CubeSat educational workshop. Figure 4 shows the CubeSat workshop in Mogi das Cruzes city on March 12, 2020, which was carried out by the CubeDesign organizing members.

Figure 4. CubeSats workshop held as a CubeDesign award [7].

The influence between the three approaches (competition, research and extension) to popularize small satellites in Brazil is evident, as a work that can begin as a small project, then it can evolve into research, and later it can become other extension activities, as mini-courses, lectures, and workshops, which reinforces the inseparability of these three approaches. The gap between the general society and space technology is notorious, at least in Brazil, however, it is shown in this work that through the presented approaches, it is possible to bring the general public closer to the technology and research in the space area [8] and also to the STEM areas (Science, Technology, Engineering, and Mathematics) [9]. The NoizOrbita team is also part of the Space Engineering Research Group, which is currently formed by two more teams: Rocket technology (NoizDecola) and amateur radio communications (PY4CAP), but they aren't discussed in this paper. Figure 5 shows the group logo.

Figure 5. Space Engineering Research Group logo.

Therefore, the main objective of this work is to show the approaches used to obtain the presented results (competition, research, and

[4] http://www.inpe.br/cubedesign/2021/

[5] http://www.inpe.br/wete/2019/

DOI: 10.5821/conference-9788419184405.124

extension) for the popularization of small satellites in the Alto Paraopeba region.

2. Methodology

The methodology used in this work is based on the analysis of the main metrics that are directly or indirectly related to the NoizOrbita team in order to evaluate the impact or the reach of the group's activities over its first year of existence. Data was extracted from the group's databases, histories, and other records on various platforms that disseminate knowledge and information.

3. Results and Discussion

In this section, the metrics related to the three approaches (competition, research, and extension, respectively) are presented.

3.1. Results of the competitive approach

The team's first approach to the popularization of small satellites brings with it the competitive bias, in total harmony with the "learning by doing" methodology. In this case, the small satellites competitions, which the team can participate in, allow students to gain experience by covering part of the lifecycle of satellites, providing them experience in the design, development, assembly, integration, testing, and operation of these artifacts. The main numbers or results of the team related to this approach came from two competitions: the 1st OBSAT (Brazilian Satellite Olympiad MCTI - Ministry of Science, Technology, and Innovation) and CubeDesign. Table 3 shows the obtained results from these competitions.

Table 3. Participation in small satellite competitions.

Category	Description	Year
CanSat	CubeDesign, 2nd virtual edition (INPE) – Interrupted.	2021
CubeSat	1st place [10] (mission to monitor agglomerations of people in remote areas - AGLOSAT-1), 6th place (mission to monitor greenhouse gases (EEG) using a constellation of CubeSats - ÉOLOSAT-1) and 8th place (mission to monitor ionizing radiation in the lunar environment - CURIESAT-1) in the first regional phase (state of Minas Gerais) at the 1st Brazilian Satellite Olympiad MCTI (OBSAT2021), receiving as a prize 3 CubeSats kits from the Brazilian startup PION Labs.	2021

Moreover, Figure 6 shows the final results (from the first regional phase of the 1st OBSAT), where three out of four sub teams of NoizOrbita (that won the 1st, 6th, and 8th places) were awarded one PION CubeSat kit each. Figure 7 shows the PION CubeSat kit.

Figure 6. UFSJ teams patch missions for the first phase of the Brazilian Satellite Olympiad.

(a) (b)
Figure 7. One of the three PION CubeSat kit awarded in the OBSAT: (a) Perspective view of the subsystems and (b) Top view.

3.2. Results of productions connected to the research approach

Regarding the approach related to research, team members have the opportunity to get started in the scientific environment in several ways: undergraduate final work, scientific research, and other academic works with space themes. Support and tutoring are offered by more experienced team members and advisors, so even any initial research can evolve into quality scientific papers at events and conferences inside and outside the university. Table 4 presents some papers and works that have been developed with the collaboration of team members.

Table 4. Main scientific productions.

Category	Description	Year
Undergrad. final work	Victor Henrique Santos Soares. “Deriving requirements for the design of a CanSat Launch Vehicle (VLC) through a Systems Engineering approach”. UFSJ - In progress.	2021
	Isabela Tavares Silveira. “Applications of machine learning techniques in telemetry data from the Brazilian satellite SCD-2”. UFSJ - Finished.	2021

Scientific research	Project entitled "Ground-Board Communication Earth Station for Stratospheric Balloons and Small Satellites" [11]. Student: João Pedro Polito, Advisor: Antônio Cassiano Júlio Filho (INPE), Co-supervisor: Marconi de Arruda Pereira (UFSJ).	2021
Articles accepted for publication	Title: "Denialism in the Popularization Satellites Use". E-book against science denialism, PUC-MG.	2021
Articles published in congress	Title: "Deriving requirements for the design of a CanSat Launch Vehicle (VLC) through a Systems Engineering approach". In WETE 2021.	2021

3.3. *Extension numbers*

One of the aspects that can differentiate the NoizOrbita team from other competitive teams at UFSJ is the extension approach, as the group also aims to extrapolate the limits of the university in order to impact different layers of society. The objective is to provide to the population in general a simpler and closer look to space themes, and show them the consequences and impacts of space research on everyday life. Activities carried out by the group are presented in Table 5.

Table 5. Main numbers extension results.

Category	Description	Reach
Presentation for students	Introduction to Telecommunications Engineering	50 students
	Introduction to Mechatronics Engineering	50 students
	CAP-UFSJ New students Welcome Week	195 students
Event organization	1st Space January	285 participations
	1st Week of Space Immersion of CAP.	180 Participations
Podcasts	Noiz Em Órbita	21 reproductions
	Space Philosophical Coffee	54 reproductions
Academic weeks	Telecommunications Engineering Week at UFSJ	35 Participations
	Mechatronics Journey	20 participations
	Mechatronics Engineering Week at UFSJ	18 people
Social media	Instagram	718 followers
	Facebook	101 likes
	Youtube	693 views
Professional media	LinkedIn	159 followers

In order to support the various projects under development and, at the same time, support the effectiveness of the popularization of small satellites, the team has resorted to several possible funding sources inside and outside UFSJ, as detailed below, in order to raise financial resources for the feasibility of some of its projects.

3.4. *Project financing*

Regarding fundraising, the objective is to continuously reach funding opportunities inside and outside UFSJ to support the development of small satellites for competitions, including subsystems to assist in the research and development of the work. Moreover, another objective is to purchase electronic components for extension activities purposes, such as the elaboration of mini-courses on CubeSats. UFSJ had a funding opportunity (UFSJ/PROEN/009 2020) in which the team raised the amount of R$15,505.69 (€2814,22) to be used for purchasing components.

3.5. *Future works*

As a future work plan, the group has already obtained several educational materials (which are listed in Table 6) to support extension activities at schools of different levels of education in the cities of the region of Alto Paraopeba. The material was provided by INPE (National Institute for Space Research). Other activities proposed for classroom teaching are also detailed in Table 6.

Table 6. Future works.

Category	Description
Nanosatellite Learning Kits	Introduction of small satellite concepts to elementary and high school students, with lectures and assembly practices, integration and testing of CanSats and CubeSats.
INPE teaching materials	Publicity material from both INPE and AEB (Brazilian Space Agency), in the form of stickers from INPE, from the Brazil-China CBERS partnership satellite, puzzles, booklets, folders, etc.
Plastic bottle rocket workshops	"Development of plastic bottle rocket" workshops for presentation at the National Science and Technology Week (SNCT).

4. Conclusions

Based on the numbers presented in this work, related to the first year of the existence of the NoizOrbita initiative, it is evident the importance of the three approaches presented to achieve the objective of the popularization of the small satellites theme in the Alto Paraopeba region, mainly. The competitions, through the exchange of experiences between the teams, and with the union of students to overcome challenges, prove to be an efficient way to motivate and encourage team members to improve themselves technically, and also develop and improve teamwork. The research, in turn, encourages students to participate and prepare academic works and, with that, generate scientific productions for the dissemination and improvement of space technologies. Finally, the extension approach makes it possible for the space theme to find a way outside university and reach various layers of society, initially in the local region of Alto Paraopeba, but also beyond (due to the virtualization of activities amid the COVID-19 pandemic), obtaining national visibility. The presented results support the methodologies applied by the team (competition, research, and extension) for the dissemination of the small satellites theme, resulting in a significant number of people impacted by the team.

Acknowledgements

This work was supported in part by the Foundation for Space Science, Applications and Technology (FUNCATE), by CAPES under grant 88887.638852/2021-00, and also by CNPq. The authors would like to thank NoizOrbita team for the data provided.

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Trade-Off between Concurrent Engineering Software Tools for utilisation in Space Education and beyond

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Abstract

Concurrent engineering is an approach to the development of complex systems that is characterised by direct communication between the disciplines involved. Instead of processing the individual disciplines one after the other, as in sequential design, or processing via a single contact person, as in centralised design, all systems work simultaneously. Learning this interaction and understanding what information needs to be communicated between disciplines are among the central learning objectives of the course "Spacecraft Design" at Technische Universität Dresden, Institute of Aerospace Engineering. In this course, the students represent different disciplines and work out a mission study that is commissioned by the lecturers. The lecturers thus participate in the development process in the role of customers.

Key to the concurrent engineering approach is that each discipline has access to the most current design data at all times. This can be done via a dedicated software solution. Both commercial and open source software tools are available. Within the frame of the above-mentioned course, several tools have been tested. The covered software solutions comprise ESA Open Concurrent Design Tool (OCDT), RHEA Concurrent Design Platform (CDP), Valispace and IBM Rhapsody.

This contribution presents the experience that we gathered with these concurrent engineering software tools. First, the tools are described and their commonalities and distinctions are highlighted. Subsequently, a detailed trade-off between the tools is being presented. This trade-off will particularly focus on the utilisation of these tools within the scope of course work at universities, as this entails special requirements and boundary conditions, such as very limited time for introducing the software, highly heterogeneous user group, limited utilisation of the software in terms of depth and functionality, to only name a few. Within this contribution, we will also explore alternative approaches, such as using no software at all.

The aim of this contribution is to offer other teachers and students some guideline for selecting a concurrent engineering software solution and implementing it in course work, in a way that using the tool itself does not become the central learning challenge of the course. The results might be of interest beyond university courses, as some requirements, like short times to get familiar with the software or certain interface requirements, also apply to other environments in research and development.

Keywords

Concurrent engineering, concurrent design, software tools, education

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1. Introduction

Concurrent engineering (CE) is an approach to the development of space systems and mission. It is characterised by direct communication between subsystems and parallel working of the involved disciplines. Learning this interaction and understanding how the different subsystems are connected to each other (i.e. which interfaces there are and which in- and ouputs have to be transmitted) might be just as important for students as learning about the individual disciplines (e.g. propulsion, thermal, communication). At Technische Universität Dresden (TUD), there is a dedicated course to introduce them to the CE philosophy [1].

At the beginning of the course, the characteristics as well as advantages and disadvantages of design processes are taught. Special focus is put on concurrent engineering. In addition, an introduction to the utilised CE software is given. The remaining time is used to carry out a concurrent engineering process for the conceptual design of a space system (e.g. a Mars probe or a Moon rover). For this purpose, a mission objective is issued by the teachers and the role of the customer/client is assumed. The mission is first discussed by the students and initial solution concepts are postulated, which are then evaluated. We / the students divide themselves into different roles/disciplines. Each discipline develops the corresponding subsystem (e.g. for energy supply or communication) or carries out the tasks belonging to the corresponding role (e.g. cost or risk analysis).

The CE process implementation is usually done with a dedicated infrastructure, which involves hard- and software. Latter is nowadays represented by a multitude of tools, including commercial and open source solutions. This contribution presents our experience with a selection of the available software tools. The aim of this contribution is to offer other teachers and students some guideline for selecting a concurrent engineering software solution and implementing it in course work, in a way that using the tool itself does not become the central learning challenge of the course.

Therefore, the tools will be described in section 3. The actual trade-off will be executed in section 4, before concluding the paper in section 5.

2. Concurrent Engineering Tools

Numerous tools to aid the concurrent design process are available. The tools tested here were chosen due to previous experience with them from workshops, projects or similar usage. This list is not meant to be a complete overview of all software tools that could be utilised, but represents the tools that we actually investigated both theoretically (*Rhapsody* and *OCDT*) and practically (*Rhea CDP* and *Valispace*). Note that further tools are being used in concurrent design facilities (CDF), such as the *Virtual Satellite* [2] tool used at the German space agency (DLR) or the tool *Poseidon* developed by NASA [3].

2.1. Valispace

Valispace [4] uses a browser-based web-interface to access a central database (so-called single source of truth) in which the actual design is been stored and advanced. Depending on the chosen license, this can be either a cloud-based database or a distribution on a local server. The database can be accessed by any user at any time from any browser system, which guarantees wide compatibility and low software requirements. However, this can also be a challenge due to the wide range of available browser types and active browser versions.

The design itself is based in a so-called product tree, which is a hierarchic representation of components and subcomponents with its representing parameters (so called Valis) that define the component. Valis can be dependent of each other, allowing automated calculations as well as budgets over different layers of the component structure. This allows, for instance, quick and easy parametric studies when varying single Valis.

Many quality-of-life-features are included, like alternative containers ad system modes. A complete unit calculation is implemented, including non SI-units. Furthermore, a history graph allows to follow the evolution of any Vali value over time. Datasets can be implemented as lookup table or for. Lastly, a network of interactions between Valis can be plotted, to name a few.

Valispace has implemented many more features that revolve around the product tree and allow for a more convenient design procedure. Although featuring all these capabilities, Valispace strife’s to be slick in its interface and

DOI: 10.5821/conference-9788419184405.125

intuitive to understand and use. Short introductions to the tool proved to be sufficient for students to get a grip of its functionality and start designing. The tutorial, that is available at the website [5], allows to get started in a rather short time. This allows for easy and convenient access for any user, which may be in particular beneficial for not as experienced user like beginners (i.e. students) or customers.

2.2. *Rhea CDP*

The Concurrent Design Platform (CDP) by Rhea [6] is a detailed design tool with high focus on implementation of space standards like the ECSS-E-TM-10-25A [7]. Here, we want to share our experience with mainly the CDP3.12 as well as the CDP4 versions. However, we need to consider the fact that the tool has since been developed further and is now available under the product name “Comet”.

One unique aspect of CDP is the design procedure, which avoids real time changes in favor of a discrete approach of forwarding changes. If any user adds or changes existing parameters, these changes are stored in a dedicated routine. Although every user may see indications that changes have been done, these are not activated right away. A user with a higher level of authority, for instance the team leader of the study, has to manually publish these changes so that it may be live in the actual design. Although this may seem like a highly inconvenient feature at first, it significantly reduces the continuous noise of changes occurring in the earliest design phases. This lowers the risk of potential performance issues of the tool, since it does not require permanent updating. Also, a very high number of additions and changes may only be expected during the initial phase, fast publishing can avoid any problems. In later stages of a design, changes mainly update initial values, in which the exact value may not be critical for other components, as long as they are connected correctly. In any case, this design procedure requires additional tasks and communication, which can negatively affect the development process particularly in a setting with students that are first-time users of the software.

The design itself is stored in a product tree that consists of components and subcomponents with dedicated parameters. Latter are defined in large detail. Furthermore, a strict ownership is established that defines who will be able to adjust a certain parameter, depending on who created it, respectively how it was defined initially. These aspects can make it very difficult for a new user to quickly get into creating objects and design content. However, once getting used to this technique and understanding the important aspects, it is easy to very clearly define all the aspect of any parameter.

2.3. *IBM Rhapsody*

From the tools discussed in this paper, IBM Rhapsody [8], may be the one with the fewest correlations to space mission design, as it is developed as a general model-based system engineering (MBSE) tool for any application. Still, it provides crucial features to enable the concurrent design approach. In our evaluation, SysML is used as modelling language.

The general idea of Rhapsody is to have different types of views onto one central model, where each view is optimized for different aspects of specification of the model. The central model itself can again be represented in a product tree, allowing an easy hierarchic structure of the major components. The different views, also called diagrams, focus, for example, on the structure of the subsystems, the definition and connection of requirements, the interaction with users, the definition of states of the system, the definition of actions and data exchanged in the system and so on. Consequently, an initially simple hierarchic structure of a model gets multiple layers of complexity, but the different diagrams keep it comprehensible.

Since the focus of Rhapsody is not on the guidance of calculations and therefore the implementation of parametric studies, but rather on the best possible modelised representation of the design, the user has the possibility/task to define any data up to the highest level of detail. For anyone new to the program and its implementation, this may very well be overwhelming, which can be, to the authors experience, a significant hurdle for anyone starting to model in order to exchange data. On the other hand, since much of the set up of data may be multiple layers bellow the initial level of the diagrams, this can make it much easier for any spectator to get the general grasp of the structure and functionality of the model in a top layer view.

2.4. *ESA OCDT*

Used in the CDF of ESA, the Open Concurrent Design Tool (OCDT) is a client/server software package that was developed for ESA. It shares most commonalities with Rhea's CDP. As CDP, it implements a standard semantic data model based on ECSS-E-TM-10-25. The database, which is stored on a server, is accessed via an OCDT client, which is based on the Microsoft software Excel. Therefore, analyses and calculations can be done directly in Excel, that utilises various spreadsheets that can be added to the workbook as needed. Thus, the work is done locally and the data is then shared via the OCDT interface. [9]

This exchange of information is not done automatically and therefore not instantaneously. Parameters need to be "pushed" to the database by their creator, who is responsible to keep it up to date. Users who wish to use this parameter need to subscribe to it, which defines the interrelations inside the model. Afterwards, they still need to pull the parameter to their local Excel interface. Moreover, like in Rhea's CDP, the team leader or system engineer needs to publish data sets after checking the values for consistency. [9]

Apart from that, users are free to create elements/components and attach parameters to them. Those parameters can have advanced characteristics, such as state or option dependencies. Former are used to model system modes or mission phases. Latter are used to model different system options, e.g. to compare an electrical with a chemical propulsion solution and the system effects thereof. [9]

2.5. Analogue tools

All tools presented here have great advantages for particular areas supporting the concurrent design process. However, the tool needs to be intuitive and easy to learn in order to be used by the students in the academic scenario presented. If the software is to complex, students will fall back to familiar alternatives. We observed that students will avoid the software interface and rather just note and share disconnected information on a common board in the room or facility they are in.

For a course in presence, this may be an option since everyone is working at the same time and means of exchange and communication can be very short. And indeed, we normally started of our courses with a discussion about the general concept idea together on a whiteboard. And even at later stages of the study, this became a pivotal point for the evolution of the design. For general and basic design, this may even be the best option, since students don't have to learn how to write information on a board, and can focus solely on the design of the respective subsystem responsible.

However, since the design will get complex by itself in no time, the design would quickly get unorganized. In addition to that, for any non-centralized design study over a longer period of time, as it was required in the resent years, this cannot be an option, and the dedicated opportunities for exchanging data needed to be required to be used.

While the analogue option surely has rather narrow limitations, it remains a viable option to learn the CE Methodology. And for any system with low complexity it may still be the way to go.

3. Trade-off

The following trade-off will particularly focus on the utilisation of described tools within the scope of course work at universities, as this entails special requirements and boundary conditions, which might not apply to other environments, such as the industrial utilisation of CE. Within this trade-off, we summarise our experience with and assessment of the tools. We didn't conduct this trade-off a priori and then implemented the most promising solution into our course, but we actually tested different options to see what works for us and what not.

3.1. Evaluation Criteria

This section contains the selection of the evaluation criteria for the trade-off with a short description of each criterion to clarify what it represents and how it is assessed. The following criteria will be used:

Usability: A key factor for using a CE software in a course is the time the students need to make use of it, as there is only limited time available. Therefore, the software should be easy to understand in its basics, but not necessarily in its full potential. This including the availabiltiy of freely accessible manuals and tutorials.

Complexity: While enabling very complex models is surely a key aspect for most CE users, it is of secondary concern for the use in an educational framework. However, it is still important to consider. A less complex software could prove beneficial for the course work. However, it would be even better if the software provides complexity, allowing interested students to dig deeper, but not unleashing the full complexity all at once at the new user.

Interface: Aside from the usability and complexity, the design of the user interface also plays an important role, as it defines how the user interacts with the software. While some tools rely on the use of Excel as an interface, other software use browser-based interfaces. While it is clear that the borders to usability and complexity are fluent, this criterion shall put focus on how easily, or better naturally, the user can engage with the software.

Performance: Another criterion is the software's performance. Not only too much complexity or a bad user interface can turn the student away from the screen, also performance issues can. We experienced that as soon there are problems with the stability of the software or serious latency in the data synchronisation, the acceptance drops. Thus, the software and it's implementation in the hardware must ensure not the highest, but flawless performance for a representative user group.

Manageability: This criterion represents the administrational effort for the lecturers, which themselves have limited time and want to put as much focus as possible on the students and their learning processes. Still, they have to set up the software and take care of any troubleshooting along the way. Therefore, this criterion highlights the knowledge that is needed and how much effort it takes to get and keep the software running.

These five criteria (usability, complexity, interface, performance and manageability) will be used for our trade-off. However, the analysis could be extended by further criteria. This could involve the supported interfaces for the implementation of further software solutions (such as design and simulation software). Another aspect might be the requirements of the software towards the hardware infrastructure. Lastly, some might consider available licenses and corresponding prices important.

The five criteria presented are all significant in their very own aspect, which concludes that the failure to fulfill any one of these may have severe influence on the usage by the students participating at the course. Therefore, it was decided to not add any additional weighting factors between these evaluation criteria.

3.2. Evaluation

Due to the limited time available during the course, easy accessibility of the functionality of the tool is of significant importance. Since most students are fairly firm with basic Excel operations, it does not take long to get acquainted with the OCDT tool. It is easy to start and available on most PCs. The availability of a browser for Valispace is even more so given to any user, making it highly accessible. However, some time to understand the setup of the tool is required to get the principal idea. Still, the tool is kept rather simple and intuitive, and catching the tutorials available will only take a few hours and has proven to be well suited to get started. For CDP and Rhapsody, additional software has to be installed. Some knowledge about server setup may be required, but access itself is easy. Once this one is covered, it can be challenging for beginners to get used to the tools, due to its very detailed options available. With both tools, significant time has to be invested to understand how information is created, connected, and to be stored in the model. From our experience, the level of expertise and therefore the level of usage will differ much stronger for CDP and Rhapsody than for Valispace and OCDT, simply due to the different background and interests of the students. This higher difference makes it more challenging for the tool to be actually used by the students during the course.

The OCDT, Valispace as well as CDP are particularly designed to aid the design of space related missions. Although other studies may also be conducted, numerous features support this general field of study, including the handling of units. For new users, this can be quite an important feature to guide the addition of information. Furthermore, a well-known or intuitive interface will also be beneficial for starters. Guiding the user step by step to add more information is best implemented in Valispace, where only basic information needs to be defined initially, but more detailed parameters can be added at a later intuitively. Although updating of parameters is also feasible with CDP and Rhapsody, the user will be confronted with these parameters already at the initial definition of an object, which results into a much slower process of adding information and more hesitance by the unexperienced users. Particularly with Rhapsody, a lot of information has to be added up front, but an experienced user can present this information later visually very appealing and sorted by use of different types of diagrams.

The functionality of updating the model differs for the tools. Naturally, Excel comes to its limits once a system gets more complex and will consequently take more time to update. Similar challenges have been observed using Valispace, since the update of a multitude of parameters can be resourceful and take a moment. For the CDP, the model will only be updated by a top-level user, making the system more discrete, but also requiring less data being exchanged continuously, improving the performance significantly. For Rhapsody, the aspect for downloading a recent part of the model und uploading it again to the cloud can be a nuisance, in particular when starting from a blank slate and many changes by many different users are to be expected.

From the educator's point of view, the setup of the tools is similar for all options, since respective accounts/access rules have to be added with all of them. However, making use of widely available access points like Excel for the OCDT and a browser for Valispace makes for more flexibility in planning the courses and allowing decentralized work. In the end, installing additional software and setting up the respective server for data exchange has always to be respected as a certain time factor, if no dedicated design felicity can be used.

4. Conclusion

Multiple tools have been used by the authors to conduct concurrent design studies in a university level course with students. Still, this is definitely not a full list of tools, as there are more available. In addition to that, the user experience by the authors is obviously also limited, and experienced users may be able to cover many more tasks with the dedicated tools. After all, the authors want to encourage any reader to at least give these tools a try, since they all are very capable and powerful in their very own way. Also, the tools are under constant development, which means that certain aspects may have changed since the writing of this paper.

For the course at hand, the software implementation by Valispace is our preferred solution so far. The tool grants easy access and requires only a minimum of initial training, which also can be self-taught, to enable students to work with the tool and start designing. Since the results of our design is not the main priority and the design itself will not get as complex, we can respect possible limitations quite well. Additional tools like time management and the implemented requirement management and report tool are additional benefits for our course. From our experience, the tool provided the best introduction to the general CE approach for the students and resulted in the greatest amount of data shared within such a tool.

Acknowledgements

We would like to thank all participating students for their adaptability, commitment, understanding and feedback.

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Designing Avionics for Lasers & Optoelectronics

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Abstract

Unlike imagery-based Earth observation (EO) which has become very widely and cheaply available, gravity sensing EO has not yet emerged from its fundamental science roots. The challenge therefore is to develop gravity sensing instruments that can replicate the success of widespread imagery based EO. There are three main gravity sensing mechanisms under investigation: laser ranging (e.g., GRACE-FO [1]); atom interferometers, which measure gravitation perturbations to the wavefunctions of individual atoms; and 'relativistic geodesy' which uses atomic clocks to measure the gravitational curvature of spacetime. All three of these measurement systems use stabilised lasers as their main enabling technology. However traditional laboratory laser systems struggle to meet the robustness, reliability, or low size, weight, and power (SWaP) requirements for use in space.

A demonstrator was build that adapted telecommunications industry COTS components, and software radio FPGA/DSP techniques, to develop a new all-fibre space-qualified stabilised laser systems for geodesy that have equivalent performance to laboratory systems. This instrument was used to develop a 780 nm laser system that is stabilised to the Rubidium D2 line - the stabilised laser most commonly required by the quantum and atomic sensing field achieving sufficiently high laser performance for the laser system to be immediately useful for quantum applications (stability: 1-10 kHz, accuracy: 1 MHz); and in an ultra-compact package that has the potential to be used in space (1 litre, 0.5 kg, 10 W) [2].

This paper reports on the current student work that advances the instrument further towards a flight payload – and key avionics design considerations for future researchers. This takes lessons learnt from the ESA ESEO software radio payload in utilising ECSS design practices [3] to fabricate a robust and modular avionics back-end board that can operate with numerous front-end laser or opto-electronics configurations for different quantum applications.

The new board consists of a single PCB containing circuitry for TT&C reporting of power supply and voltage conditioning, the current and temperature electronics needed to control a diode laser on orbit, interfaces for photo detectors and opto-electronics, and a high-speed analogue-to-digital conversion network centred around a FPGA. As an example, digital signal processing performed frequency-modulated spectroscopy on a warm Rubidium vapour using an all-fibre optical arrangement.

Keywords
Laser, Optoelectronics, Avionics, FPGA

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1. Background

Gravity sensing mechanisms that range from optical atomic clocks and quantum gravimeter to laser ranging, all require multiple stabilised lasers with Hz-to-kHz resolution over GHz as their enabling technology. Optical atomic clocks are the key payload to evaluate the gravitational time dilation effect by interrogating laser-cooled atoms at an ultra-narrow optical transition with highly stabilised laser [4]. Atom interferometry uses the wave-like properties of atoms to detect the impact of the gravity perturbation on the laser-cooled atoms [5]. Laser ranging interferometry (LRI) have been used to measure the changes of distance between two spacecraft to detect the mass changes of the Earth which contributes the changes of the Earth's gravity field [6].

The laser requirements of existing laser systems for above quantum applications are summarised in Table 1. Although the applications are different, what can be clearly seen in this table is the similar avionics requirements of kHz of frequency stability, MHz tuning for laser cooling and 10^{-2} to 10^{-3} of power stability.

However, the average SWaP of these systems is above 150 kg, 300 L and 400 W means that it is difficult to fit them into small satellites that enable low-cost missions, which are in the reach of research projects with limited budgets. The conventional design approach of these systems is to use multiple tunable laser sources to provide the optical frequencies used in different stages of the experiment. The tunability is achieved by modulating each laser with numerous narrow bandwidth optical modulator. Moreover, the control loop for frequency stabilisation of the lasers is implemented with fixed frequency and complicated analogue circuits. For instance, electronic component can be degraded by the space radiation effect. With the low flexibility in such control loops, the control settings cannot be optimised according to the degradation of the components. Thus, it becomes a challenging task to convert these systems into space payloads.

2. LEGO Configuration

2.1.1. Overview

The Lasers for Earth Gravitational Observation (LEGO) project was a CEOI 12th Call Fast-Track project to develop compact rubidium stabilised lasers for gravity sensing Earth observation undertaken by Surrey Space Centre at the University if Surrey and Twin Paradox Labs.

Table 1. Laser system requirements for quantum applications

Application	Laser System	No. of Lasers	Frequency Stability	Frequency Tuning	Power Stability	Weight (kg)	Volume (L)	Power (W)
	STE-QUEST [4]	5	~100 kHz	Cooling: 200 MHz Raman: 1 GHz	10^{-2}	220.7	469.5	608.1
	Trimeche [7]	7	NS	Cooling: 100 MHz Raman: 1 GHz	10^{-3}	264	635.145	849
Atom Interferometry	Luo [8]	1	30 kHz in 1 s	Cooling: 120 MHz Raman: 6.8 GHz	NS	150	540	500
	MIGA [9]	4	~100 kHz in $2 \cdot 10^4$ s	Cooling: 1 GHz Raman: 7 GHz	$1.7 \cdot 10^{-3}$	150	500	300
	Theron [10]	1	Below 100 kHz	Cooling: 200 MHz Raman: 1.7 & 6.8 GHz	NS	NS	NS	NS
Microwave Cold Atomic Clock	PHARAO [11]	6	~400 kHz	80 MHz	± 1% over 20 days	91	147.6	114
	SCAC [12]	3	~40 kHz	17 GHz	± 5% for 5 mon	NS	2.61	NS
Optical Cold Atomic Clock	ISOC [13]	5	Cooling:1 kHz Clock: 1 Hz	Cooling: 400 MHz	NS	75	116	62
Coherent Links	Chiodo [14]	1	NS	±12 GHz	NS	NS	NS	NS

DOI: 10.5821/conference-9788419184405.126

Unlike imagery-based Earth observation (EO) which has become very widely and cheaply available, gravity sensing EO has not yet emerged from its fundamental science roots. The challenge therefore is to develop gravity sensing instruments that can replicate the success of widespread imagery based EO. There are three main gravity sensing mechanisms under investigation: laser ranging (e.g GRACE-FO); atom interferometers, which measure gravitation perturbations to the wavefunctions of individual atoms; and ‘relativistic geodesy’ which uses atomic clocks to measure the gravitational curvature of spacetime.

All three of these measurement systems use stabilised lasers as their main enabling technology. However traditional laboratory laser systems struggle to meet the robustness, reliability, or low size, weight, and power (SWaP) requirements for use in space.

The project adapted modern telecommunications industry COTS components, and software radio FPGA / DSP techniques, to develop a new all-fibre space-qualified stabilised laser systems for geodesy that have equivalent performance to laboratory systems. These tools were used to develop a 780nm laser system that is stabilised to the Rubidium D2 line - the stabilised laser most commonly required by the quantum and atomic sensing field.

We set out to achieve two goals: 1) achieving sufficiently high laser performance for the laser system to be immediately useful for quantum applications (stability: 1-10 kHz, accuracy: 1 MHz); and 2) achieving this performance in an ultra-compact package that has the potential to be used in space (1 litre, 0.5 kg, 10 W). These goals were completed. The laser system, shown in the following figure, was fabricated.

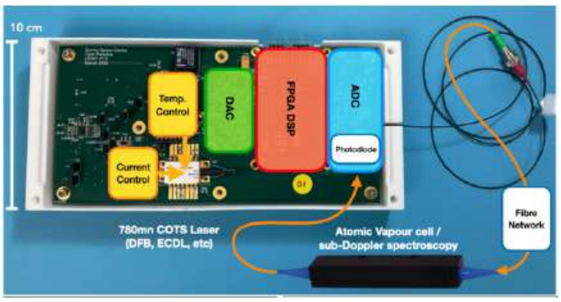

Figure 1. LEGO Digital & Fibre-coupled Payload

It consists of a single PCB containing a power supply and voltage conditioning circuitry, the current and temperature electronics needed to control a diode laser, photo detectors and opto-electronics, and a high-speed analogue-to-digital conversion network centred around a FPGA. Digital signal processing techniques were used to perform frequency-modulated spectroscopy on a warm Rubidium vapour using an all-fibre optical arrangement. The resulting Doppler-broadened, and sub-Doppler spectra are shown, along with the FM-demodulated error signal computed by the FPGA. FIIR filters were used to implement PID control to stabilise the laser to these signals achieving kHz stability.

2.1.2. Telemetry & Monitoring

One of the main features of the full control system is adding digital control into the firmware for live monitoring and control. To communicate with the temperature controller and provide serial data telemetry, an external UART interface is added. By designing a new I2C controller, it allows us to control and receive telemetry from Power rails monitoring ICS and current controller.

The I2C controller provides different modes for a specific purpose such as basic scanning of all channels and reading specific channel at full speed. End users could select the mode by sending a single specific command in the serial telemetry. Using a cyclic redundancy check (CRC) error checking routine, a robust and efficient serial data packet format allows us to obtain reliable telemetry points from numerous slave devices. Sending ID byte allows us to identify different telemetry points.

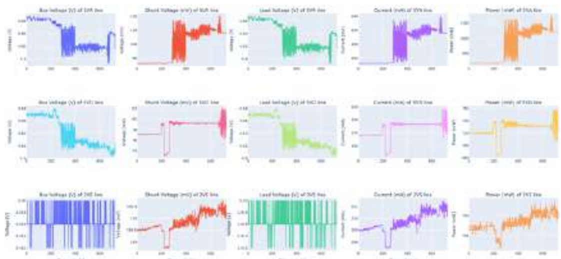

Figure 2. Offline data monitoring via UART

An offline data monitor shown in Fig. 2 is built for presenting streaming offline data from the firmware. Firmware with streaming data enables system health monitoring and control as a spacecraft payload. This real-time monitor is in development still. In the future, we would like to present real-time data with a custom-made GUI and SQL database.

3. Testing & Guidance

3.1.1. Frequency Stability

Frequency stability is one of the key parameters of laser used in gravity sensing applications.

DOI: 10.5821/conference-9788419184405.126

The in-loop frequency stability of LEGO is measured by monitoring the changes in amplitude of the error signals, that represents the laser frequency noise, in the laser current control loop. The laser frequency noise can be analysed with Allan deviation which is a useful statistics method to examine the long-term stability of a signal [11]. Figure 3 uses the Allan deviation to depict the in-loop frequency noise of LEGO during different operations. A 10 kHz of flicker noise floor at 100 ms is achieved with the laser locked to random perturbation.

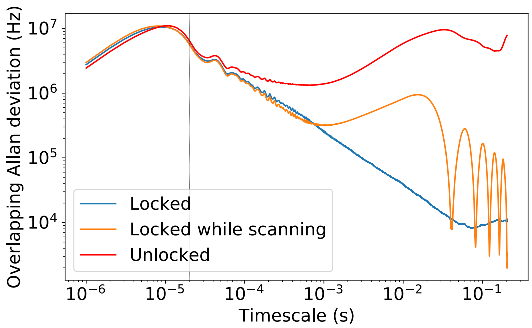

Figure 3. Allan Deviation of the Doppler-broadened stabilised laser's frequency noise during locked to random perturbation (blue), locked under a large 25 Hz perturbation (yellow) & unlocked (red).

3.1.2. Phase Tolerance Measurement

To maximise the gradient of the error signal, the photodiode signal is needed to be in phase with the sinusoidal modulation for locking. However, phase lag can be caused by the increased length of the optical path, reduced speed of the electronic components and FPGA calculations, etc. Therefore, if the phase lag exceeded the phase tolerances of the system, the gradient of the error signal will be reversed so the laser frequency won't be stabilised to the lock point. To assess the magnitude of phase lag that LEGO can cope with, a step change of magnitude of phase shift is introduced to the sinusoidal modulation shown in Figure 4 while the gradient of the error signal is measured

3.1.3. Beat note Measurement

When coupling two laser beams with different optical frequencies, a beat note, with a difference of two optical frequencies, can be observed in the frequency spectrum. The most common case is to evaluate the behaviours of the laser under test with a reference laser that has a known linewidth and frequency stability. Optical characteristics such as long-term frequency drift, linewidth, and power stability, can be obtained from the beat note.

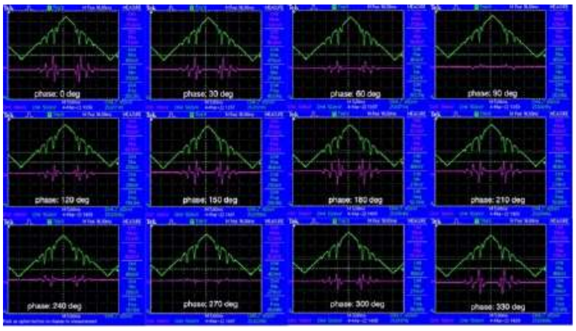

Figure 4. Changes in gradients of the error signals with a step change of 30º phase shift. Rb Spectrocopy (green) & coresponding error signal (purple).

3.1.4. Guidance

The top priority of conducting optical experiments is safety - LEGO has some safety features. Compared to the free space optics (FSO) approach, LEGO, which is a fibre-optic system, has a lower level of risks in health & safety. Moreover, the laser system can be remotely operated as USB controlled power relays are installed in power lines and operations of the laser can be commanded in the PC firmware. Thus, it enables frequency stabilised lasers related experiments within the reach of undergraduate students.

Apart from the advice for safety, when debugging optical setups, the first step is to make sure all connectors are well tightened and cleaned. The optical characteristics of optical components could be degraded with the presence of dust. Optical power meters are useful tools to validate the actual optical power with estimated values at the connections. Here are our selected Do's & Don'ts for optical measurement:

Do's

- Do turn off the laser when modifying the optical setup to avoid direct exposure of laser beams.
- Do wear laser safety eyewear during experiment.
- Whenever the fibre connectors are not plugged-in, protect the connectors with dust-caps.

Don'ts

- Don't point the laser beams vertically or toward anyone's head and eyes.
- Don't bend fibre cables under a radius of 3 cm.

DOI: 10.5821/conference-9788419184405.126

4. Avionics Considerations

ECSS refers to the European Co-operation for Space Standardisation. This organisational body have created a series of standards that aim to make space technologies more coherent and user friendly for all engineers working to send a project into Space. These standards apply to electronic hardware, all mechanical parts, communication protocols, material choices and even administrative applications such as management and product assurance.

Within the scope of the LEGO project our aim is to raise all compliance where applicable and verify that the current design is qualified for spaceflight based on the ECSS requirements for electronic hardware and PCB layout.

The board has been designed using Altium Designer, and so all specific tolerances and values that can be applied to the layout have been incorporated into the project's design rules, allowing for a design rule check (DRC) to be run at each stage of the layout's design to ensure it is correct and compliant for all hardware revisions.

Standards that have been referenced for creating the Altium rules:

- ECSS-E-ST-20 – Electrical and electronic [15]
- ECSS-Q-ST-70-12C – Design rules for printed circuit boards [16]
- ECSS-Q-ST-70-60C – Qualification and procurement of printed circuit boards [17]
- ECSS-E-ST-50-11C - SpaceFibre - Very high-speed serial link [18]

The above documents were best for populating the Altium rules as they contain specific values related to PCB design.

The design is also aiming to utilise SpaceFibre design practices, and so layout and routing has taken considerations from ECSS-E-ST-50-11C. For example, this document specifies that differential pair signals should be routed with an impedance of 100 Ω +/- 10 Ω.

4.1.1. Updated Design Rule Checking

The standard Altium DRC can allow for editing of 63 conditions, ranging from electrical constraints, manufacturing constraints or even signal integrity checks. 38 rules were configured in the original LEGO project to meet the design's needs and qualify the board in its first revision. Of these 38, 8 rules were edited and 5 added to match ECSS requirements.

When the DRC is run on the current LEGO board with 'regular' electronic design rules in place, no errors are flagged.

Figure 5. Altium Designer Output Success

This did not change when the new Altium rules were run on the PCB, meaning the current revision of the board is already compliant with the ECSS additions. Any further work on the PCB layout will aim to keep this DRC clear.

Future work on the board will prioritise adding protection on the ADCs to ensure hardware will be protected both in the space environment and for general operation, and then larger changes such as moving subsystems to improve signal routing and performance will be completed.

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Fly A Rocket! Programme: Assembly, Testing and Post-Flight Review of a Sounding Rocket Payload

Blanca Crazzolara[1], *Patrick Gowran*[2], *Jordi Vàzquez i Mas*[3]

Abstract

The *Fly a Rocket!* programme is a hands-on project offered by the European Space Agency's Education Office in collaboration with Andøya Space Education and the Norwegian Space Agency (Norsk Romsenter). The programme, which comprises an online pre-course and a hands-on launch campaign, represents a unique opportunity for european university students from different backgrounds to build, test, and launch a sounding rocket and obtain practical experience. The pre-course strengthened the understanding of rocket science of the students, and taught them about topics such as the rocket dynamics, propulsion, and orbital mechanics in preparation for the campaign. The students were divided into three teams, each with different responsibilities: *Sensors Experiments*, *Telemetry and Data Readout*, and *Payload*. The paper will focus on the work done by the team responsible for the rocket payload. The *Payload* team was responsible for the sensor placement of the rocket. They ensured the readiness of all the sensors and key components of the rocket. In addition, they were an integral part of the countdown procedure, the arming of the rocket and the performance of the sensors. After the launch, the data was analysed and presented according to four previously defined scientific cases. A GPS and a barometer were used in order to obtain the rocket trajectory. Both methods showed similar results. The GPS detected an apogee of 8630.11 ±2.4m. With an optical sensor it was possible to detect clouds which were verified with a humidity sensor. Additionally, the spin rate of the rocket could be detected with the optical sensor and a magnetometer by doing a Fourier Analysis. The rocket reached a spin rate of about 19 Hz after approximately 10 s after the firing. The results of the spin rate correspond to the results obtained with an accelerometer.

Keywords
Payload, Sounding Rocket, Student Programme

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Nomenclature

a	*Acceleration*
ν	*Spin rate frequency*
ν'	*Time derivative of* ν
t	*Time*

Acronyms/Abbreviations

AP	*Avionics Plate*
AT	*Avionics Tube*
ISA	*International Standard Atmosphere*
PAS	*Pad Supervisor*
PM	*Payload Manager*
RC	*Range Control*
TM	*Telemetry*

1. Introduction

In October 2021, 24 bachelor students from universities all over Europe gathered at Andøya Space to participate in the *Fly a Rocket!* programme. This educational programme was organised by the ESA Education Office, the Norwegian Space Agency and Andøya Space. It was targeted to Bachelor students studying a STEM field.
The first part of the programme served as a preparation for the practical work in Andøya; the students completed tasks using orbital dynamics and rocket trajectory simulations. During this preparation time, the students had access to various documents providing information about the properties of rockets and their associated engineering challenges. [4]

Figure 1. Rear airframe (above) and avionics tube (AT) with nose cone installed (below).

The second part and most important part of the programme took place at Andøya Space. During one week, *Aurora*, a Mongoose 98 sounding rocket (2.7m) was assembled and launched. Additionally, multiple lectures related to space research were held by personnel from the space industry working with Andøya Space.

The students were split into three different groups working on the payload, the sensors, and the telemetry [1]. This paper will focus on the work conducted by the *Payload* team.

The payload of *Aurora* consists of a combination of different sensors. The *Payload* team was responsible for the proper integration of all sensors. Depending on the objective of a specific sensor, a suitable position inside the rocket had to be chosen. The sensors were placed onto an aluminium avionics plate (AP) which was fixed inside the upper part of the rocket as seen in Fig.2. Using the transmitted data of the flight, four scientific cases were defined and studied:

a) Comparison of different trajectory determination methods.
b) Detection of clouds through light intensity variations.
c) Determination of the spin rate of the rocket with different methods.
d) Analysis of the temperature gradient in the atmosphere.

2. Sensor placements discussion based on scientific cases

The placement of the sensors on the AT had a crucial impact on the data collected and the validity of the results. Placement priority was primarily based on the importance of the scientific cases corresponding to each of the sensors. This considered the impact of misplacing sensors and the limitations imposed by cable lengths.

It was necessary to place the optical sensor at a location where it would be exposed to daylight, therefore it was placed at the rear of the AP, located underneath two holes in the surface of the avionics tube (AT). The sensor was aligned asymmetrically with respect to the holes in order to allow a difference in light intensity from each of the holes, enabling the direction of rocket rotation to be determined.

The rocket structure was primarily composed of carbon fibre composite, which blocks and absorbs GPS signals. The nose cone was made out of GPS penetrable fibreglass. Consequently, the GPS board was placed at

the fore of the AP, with the sensor located in the nose cone.
The internal air temperature and pressure of the AT were measured using a temperature array and two pressure sensors. The pressure sensors were aligned in the same direction, away from holes in the AT. They were located at the upper and lower part of the AT in order to determine whether there would exist a pressure differential during flight due to supersonic shockwaves or otherwise, which would have an impact on the altitude measurement.

Figure 2. Mongoose 98 with integrated aluminium avionics plate (AP) in the upper part of the rocket.

The temperature array board was located slightly above the centre of the AP, with the individual temperature sensors connected along the length of the AP. Ideally they would have been mounted to the AT, however this was infeasible due to the requirement for quick rocket disassembly for the purpose of pre-flight balance and stability checks/adding ballast. An additional temperature sensor was placed beneath a hole in the AT to measure the 'external' temperature as accurately as was feasible.

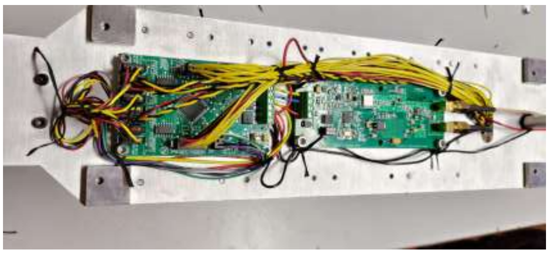

Figure 3. Encoder (left) and transmitter (right) on the back of the avionics plate.

The magnetometer required its measurement axis to be perpendicular to the longitudinal axis of the rocket. It was placed with the sensor as far as possible from the axis of rotation, at the aft of the AP.

The location of the on-board batteries and ammeter were determined by the position of the preinstalled battery mounts. The sensor data encoder and transmitter circuit board locations were predetermined, situated on the opposite side of the AP to the sensors (see Fig. 3), next to the transmitter ports in the AT and with access to the umbilical port for external power as seen in Fig. 6.

3. Sensors testing

Before testing the payload as a whole, individual tests were performed on each of the sensors, in order to determine the expected values during launch and to make sure that the output voltage would not exceed 5V, which was the upper operating range of the sensors.
The sensors in table 1 had the same testing set-up, as they all output analog information. The set-up consisted of a power supply of 5V (simulating the voltage input from the encoder) and an oscilloscope that read the voltage output. From these tests the following reference values were obtained, which were given to the telemetry stations to perform telemetry tests.

Table 1. Testing results for each sensor

Sensor	Expected Voltage Value when tested (Volts)
Accelerometer	2.5V at constant velocity (with a 0.04V and 0.02V raise per g on the x-axis and y-axis respectively)
Pressure sensors	4V at sea level pressure
Internal temperature sensor	1.16V at room temperature
External temperature sensor	2.82V at room temperature
Optical sensor	200mV: inside the tube 3.8V: exposed to natural daylight

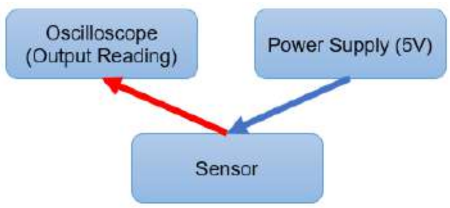

Figure 4. Testing set-up for analog sensors.

The three digital sensors (temperature array, GPS and IMU) had a different test setup from the analogue sensors. The sensors were connected to a board, which gave current to the sensor and received the output voltage, just as the encoder would do. Connecting the board to a computer, it was possible to analyse real-time data that the sensors collected.

The current sensor required another different test set-up; an oscilloscope detected the output from the current sensor, a power supply of both 10 V and 5 V simulated the internal batteries of the rocket, and a variable current load represented the intensity consumed by all the other payload sensors. The set-up is the following:

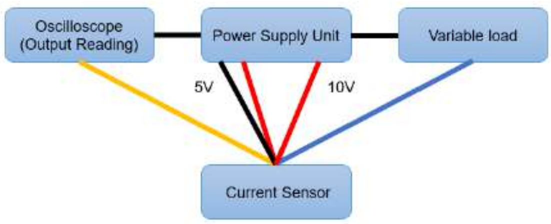

Figure 5. Testing set-up for the current sensor (In yellow the oscilloscope input from the current sensor, in blue the output of variable load to the current sensor and in black and blue connections between components)

4. Payload Assembly

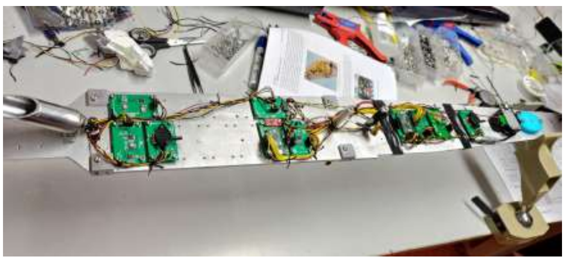

Figure 6. Payload plate with the sensors assembled. From left to right: magnetometer, optical sensor, pressure sensor (#1), IMU, temperature sensor, temperature array, current sensor, GPS, pressure sensor (#2), battery and GPS transmitter.

For all connections between different circuit boards, electric cables (AWG 26 wires) with suitable lengths were produced using a crimp tool and a female micro connector, and bound with cable ties [3]. The circuit boards were bolted into threads in the AP, with plastic washers placed between the AP and the circuit boards in order to avoid short circuiting between the sensor pins. The GPS sensor was secured to the payload assembly by bolting a 3D printed housing to the AP. After the sensors had been fixed to the AP, the AP was installed in the AT by Andøya Space staff prior to weight and balance checks.

5. Payload team role during launch

The payload manager (PM) was responsible for the functioning of the rocket's payload during launch. The PM was in constant communication with Range Control (RC) and the three Telemetry Stations (TM) ensuring smooth communication for a safe operation. The PM supervised the installation of the rocket on the launcher together with the Pad Supervisor (PAS), and asked for the confirmation checks of the sensors from the TM stations. Furthermore, the PM controlled the power supply of the rocket and armed the payload one minute before the launch [2]. No problems occurred during the operation and the launch was successful.

6. Results and Discussion

The four scientific cases presented in section 1 were analysed after the flight using the collected data.

6.1. Case a) Oliver Twist

Data from GPS, the top and bottom pressure sensor and IMU were used in order to calculate the rocket's altitude. It was assumed that the GPS data is the most accurate and was therefore used as a reference. The pressure data was converted to altitude using the International Standard Atmosphere (ISA) model. The data from the IMU was very noisy which is why it was not further included in the discussion.

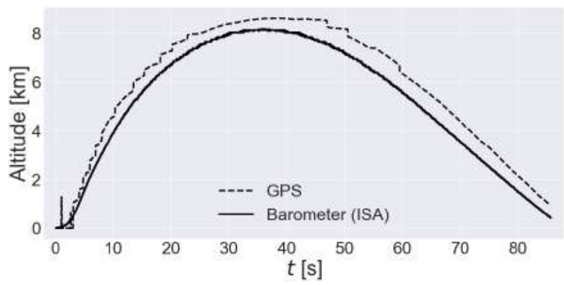

Figure 7. The rocket's altitude determined with GPS and two pressure sensors (averaged value).

Both pressure sensors showed similar results which suggests that the data is reliable. However, the aft pressure sensor in general showed slightly higher pressure values, which may be attributed to accumulated air at the rocket's payload bay. The fore pressure sensor showed similar results as the GPS.

6.2. Case b) Cloud Atlas

The objective of the scientific case Cloud Atlas was to detect clouds during the flight with three different methods. An optical sensor which detects the light density and humidity sensor.

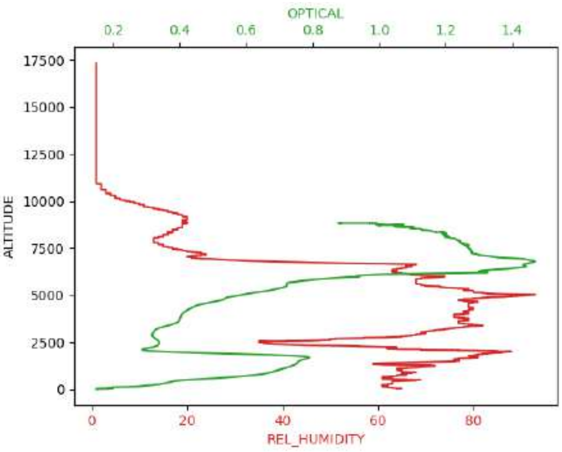

Figure 8: The humidity and the optical index as a function of the altitude. An optical index of 1 was used as reference for natural light. Data was obtained from a weather balloon released at Andøya Space.

A cloud should lead to high humidity values (close to 100%). The cloud would also lead to a lower light intensity since the cloud covers the sunlight.

Shortly before the rocket's flight, a weather balloon was released to measure the humidity and the light intensity. The humidity changed a lot until around 10 km as shown in Fig. 8. It was observed that the light intensity is small at altitudes between 3 km and 7 km. As expected the humidity is high in this range and therefore only little sunlight reached the optical sensor. The same explanation can be used between 7 km and 9 km where the humidity decreases and the light intensity increases.

The rocket did not have a humidity sensor and only detected clouds with the optical sensor. The obtained data during the rocket flight showed similar data curves as the data from the weather balloon shown in Fig. 8. Small abbreviations can be explained with a different flying direction and small changes during the 30 minutes of the launch times.

6.3. Case c) Rock And Roll

The spin rate of the magnetometer and the optical sensor were determined with a spectrogram shown in Fig. 9. The bright yellow line indicates the high amplitude of the corresponding spin rate.

The spin rate ν can be easier determined with an accelerometer perpendicular to the rocket's flight direction.

$$\nu = \frac{1}{2\pi}\sqrt[4]{\frac{a^2}{r^2} - (2\pi \cdot \nu')^2} \approx \frac{1}{2\pi}\sqrt{\frac{a}{r}} \qquad (1)$$

As an approximation, the second term in the root in the eq. 1 was neglected. The comparison to the results of the magnetometer and optical sensor showed that this approximation holds. Furthermore a distance between the accelerometer and the rotation axis of r = 3 cm was used. This value was estimated since it had not been measured before the flight. However, pictures of the payload and the comparison with the data obtained with completely different methods, validated this value.

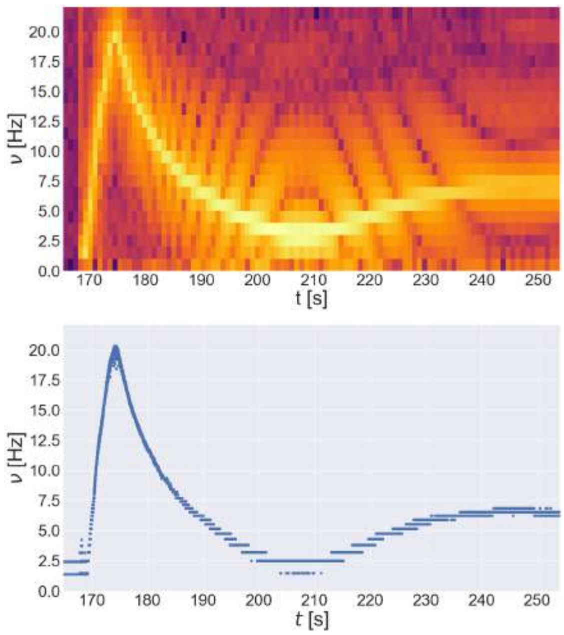

Figure 9: Visualisation of the rocket spin rate. Top: Spectrogram of the magnetometer data. Bottom: Spin rate calculated from the centripetal acceleration of the rocket.

The spin rate was the highest after the first 10 sec after the firing and reached a maximum value of around 19 Hz. The lowest spin rate of about 3 Hz was observed during the apogee. Using the method described in section 2 the spin direction was determined and it was shown that it stayed the same during the whole flight.

DOI: 10.5821/conference-9788419184405.127

The optical sensor showed a less clear spectrogram than the magnetometer. The main reason for this phenomena is that the spin rate could not have been detected precisely whenever the rocket flew through a cloud since the cloud creates a homogeneous light which makes it difficult to detect periodic patterns. Outside the cloud the sun as a point source was creating the periodic light peaks.
The sensor placement of the sensors was therefore well chosen by the payload team.

6.4. Case d) 451 Degrees Fahrenheit

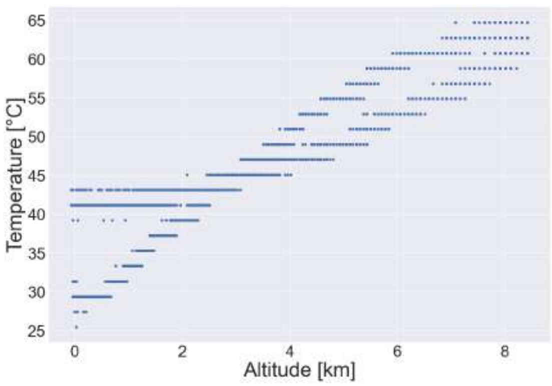

Figure 10: The external temperature as a function of the altitude of the rocket. The external temperature sensor was placed onto the fairing of the rocket.

An external temperature sensor and a pressure sensor were used in order to study the atmosphere. The altitude of the rocket was taken as pressure altitude. The 1993 ICAO Standard Atmosphere [5] was used but is not a perfectly suitable model since the location of Andøya in the upper northern hemisphere.

The results have shown that the temperature obtained from the *external* temperature sensor does not show any correlation to the 1993 ICAO Standard atmosphere model. The data in Fig. 10 shows that the temperature increased with increasing height which should be exactly the opposite using the ICAO model. The explanation of this behaviour is probably that the sensor encountered interference from the fairing of the rocket. The air resistance caused heating of the fairing during the flight and therefore an increase in detected temperature.
A weather balloon was released shortly before the rocket flight. The data showed a much better correlation to the ICAO model as shown in Fig. 11. Since the weather balloon flies much slower than the rocket, the results agree with the discrepancy of the rocket data.

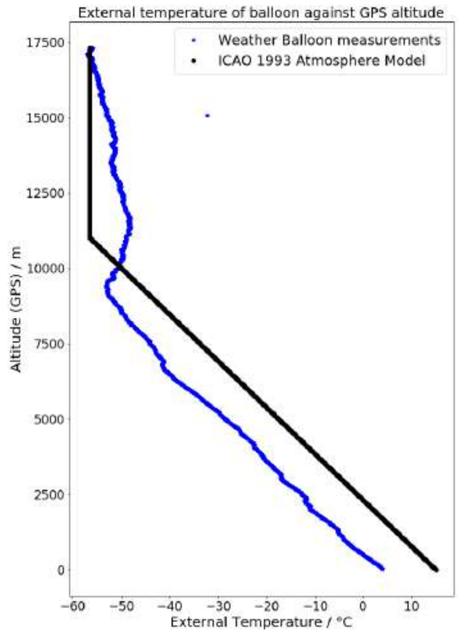

Figure 11: temperature measured from a weather balloon 30 minutes before the rocket flight.

7. Conclusions

During the launch campaign, the payload team's tasks included both soldering, making cables, and mounting and testing the sensors of the Mongoose 98 rocket. This required a wide range of knowledge as the payload had to work correctly in order for the telemetry team to receive data. The payload team also had the responsibility of verifying sensors, which was a big responsibility.

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QuantSat-PT: An Attitude Determination and Control System architecture for QKD

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Abstract

This article presents the QuantSaT-PT project, an effort to create the first Portuguese nanosatellite for space to ground quantum communication. Focused on the Attitude Determination and Control System, it describes the different elements that allow for the attainment of diverse accuracy levels required for separate mission stages. Given the harsh pointing precision necessary for establishing a quantum downlink, the implementation of this module presents a major challenge in the Cubesat field. Furthermore, the introduced architecture aims to reduce system cost by replacing the state-of-the-art star tracker with ground beacon detection.

Keywords

ADCS, Beacon, CubeSat, Downlink, QKD

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Nomenclature

$\mathbf{q}$	*quaternion*
$\mathbf{e}$	*rotation axis*
ϑ	*rotation angle*
$\boldsymbol{\omega}$	*angular rate vector*
$\boldsymbol{\beta}$	*bias*
A	*attitude matrix*
η	*noise variable*
ϕ, θ, ξ	*euler angles*

Acronyms/Abbreviations

ADCS *Attitude Determination and Control System*

ESA *European Space Agency*

FOV *Field-of-View*

GS *Ground station*

LOS *Line-of-sight*

MEKF *Multiplicative Extended Kalman Filter*

QKD *Quantum Key Distribution*

TRL *Technology Readiness Level*

1. Introduction

In the information age, it is crucial to create and maintain secure communications. One way of improving our current security standards is to use Quantum Key Distribution (QKD) methods, which allows two parties to exchange encryption keys with absolute confidence that any eavesdropping by a third party will be detected [1]. Given that this property of QKD stems from fundamental quantum mechanics laws, it is theoretically impossible to intercept the encryption keys without this interference being detected and will remain so even considering future technological developments.

QKD is based on photonic communication links. Ground-based links typically rely on optical fibers, which have non-negligible losses, thus limiting transmission distances to a few hundreds of km [2]. As such, satellite-based QKD is a promising approach to establishing a global quantum network. The development of a reliable and efficient space-to-ground link is an important first step, which has been demonstrated by the Micius satellite [3]. Implementing this technology in a CubeSat is a further step in the deployment of QKD technology, allowing for the low-cost deployment of large constellations.

Given the limited quantum link budget, extremely narrow optical beams must be used. This places strict requirements on the attitude determination and control system to guarantee pointing accuracy in the range of tens of microradians [4]. Furthermore, due to the fact that space-based QKD can only be performed while the spacecraft is in eclipse, significant temperature variations can be expected and present a challenge for the internal alignment of optical components. These constraints are addressed using a three-level pointing system which allows for internal angular corrections using Fast Steering Mirrors and for spacecraft-to-ground locking using a laser beacon.

1.1. QuantSat-PT

The Portuguese Quantum Communications Cube-Satellite Project (QuantSat-PT) is the first step of a larger and longer-term vision of developing quantum communication satellites and ground stations in Portugal, making the country autonomous in such sovereignty technologies, and integrating Portugal in the future European Quantum Communication Infrastructure.

This project is funded by the Instituto de Telecomunicações. The aim is to begin the development of a 3U CubeSat for a quantum downlink. Namely, the goals of project QuantSat-PT are:

- To develop a quantum payload for space-earth quantum key distribution in 2U.
- To test the quantum payload on earth over a distance of several kilometres.
- To develop the preliminary design of the space segment.

To attain these goals, the project QuantSat-PT brings together a unique and multidisciplinary team. It explores the complementary expertise of IT researchers from:

- The Physics of Information and Quantum Technologies Group responsible for the development of the first free-space quantum key distribution system in Portugal.

- The Network Architecture and Protocols Group and the Antennas and Propagation Group, both involved in the ISTSat One, a Portuguese classical communications CubeSat to be sent to space in 2022 through the ESA program Fly Your Satellite.
- The Optical Networking Group, expert in classical and quantum optical communications.

1.2. Cubesat implementation

Since the CubeSat platform is now established as an attractive alternative for education and research organizations that aim to bring innovative technology to space, at a lower cost than larger platforms, it was selected as the basis for this mission. These nanosatellites have a standardized form factor, allowing for quick and accessible low-risk testing of novel technological concepts, as well as access to commercial launchers. Nevertheless, this implementation constrains the QuantSat-PT outline in terms of Size, Weight, and Power, in addition to the severe environmental conditions during launch and in-orbit that already posed a challenge regarding the miniaturization and ruggedization of the payload.

This article is focused on the Attitude Determination and Control System (ADCS) which is responsible for determining the orientation of a satellite and then controlling it so that it points to the desired direction [5]. It also includes other functions, such as providing initial damping for the satellite angular motion after deployment. It is composed of sensors, actuators and an onboard computer. ADCS design is subject to strict constraints when it comes to size and mass, often limiting the pointing and slew-rate requirements.

With these restrictions in mind, the proposed solution repurposes the Optical devices from the Quantum payload to increase attitude estimation accuracy without the use of additional sensors. The Ground Station (GS) beacon is used as the Earth reference on an attitude estimation filter, when available.

2. Mathematic Models

The different mathematic models used are presented in this section.

2.1. Quaternion Kinematics

The quaternion is used as the attitude representation since it is the lowest-dimensional parameterization that is free from singularities [5]. The quaternion is defined in Equation 1.

$$\mathbf{q} = \begin{bmatrix} \mathbf{q}_{1:3} \\ q_4 \end{bmatrix} = \mathbf{q}(\mathbf{e}, \vartheta) = \begin{bmatrix} \mathbf{e}\sin(\vartheta/2) \\ \cos(\vartheta/2) \end{bmatrix} \quad (1)$$

The quaternion has the following attitude matrix representation given in Equation 2.

$$A(\mathbf{q}) = \left(q_4^2 - \|\mathbf{q}_{1:3}\|^2\right) I_3 - 2q_4[\mathbf{q}_{1:3}\times] + 2\mathbf{q}_{1:3}\mathbf{q}_{1:3}^T \quad (2)$$

where $[\mathbf{q}_{13}\,\mathrm{x}]$ is a skew-symmetric matrix for the quaternion vector components.

The quaternion kinematics are given in Equation 3.

$$\dot{\mathbf{q}} = \frac{1}{2}[\boldsymbol{\omega}\times]\mathbf{q} \quad (3)$$

where $[\boldsymbol{\omega}\times]$ is the skew-matrix for the angular rate.

2.2. Sensor Models

2.2.1. Gyroscope

The gyroscope measures the angular rate vector w and it is considered to be corrupted by a constant bias, as seen in Equation 4.

$$\widehat{\boldsymbol{\omega}} = \boldsymbol{\omega} + \boldsymbol{\beta} + \eta_g \quad (4)$$

where η_g denotes an independent zero-mean Gaussian white-noise process.

2.2.2. Beacon

For attitude determination purposes the beacon is modelled as a line-of-sight LOS sensor, instead of an optical device. Its output is subject to LOS to the GS and FOV restrictions. It is modelled as seen in Equation 5.

$$\hat{\mathbf{b}}_b = A_{\eta_s}\mathbf{b}_x \quad (5)$$

where A_{η_s} is a noise attitude matrix that corrupts the measurement with the structure and statistics as seen in Equation 6.

$$\begin{aligned} A_{\eta_s} &= A(\mathbf{e}_1, \phi_b)A(\mathbf{e}_2, \theta_b)A(\mathbf{e}_3, \xi_b) \\ E\{\phi_b\} &= E\{\theta_b\} = E\{\xi_b\} = 0 \\ E\{\phi_b\phi_b^T\} &= E\{\theta_b\theta_b^T\} = E\{\xi_b\xi_b^T\} = \eta_b \end{aligned} \quad (6)$$

where η_b the angle's covariance. This model is based on [6] converted from quaternions to rotation matrices

3. General Architecture

From the mission objectives, the attitude requirements are defined. In order to ensure Quantum communications, an attitude error in the range of tens of microradians must be obtained, whilst in eclipse.

Other CubeSats with optical communications missions have been designed to meet the attitude accuracy requirements through star-trackers [7]. In [8], a staged approach is proposed for the attitude determination, where the beacon, when received, is used to improve pointing accuracy in the fine stage.

A staged attitude determination system is proposed. The pointing, hence, estimation, requirements increase when more accurate sensors and actuators can be employed.

The first stage consists of using the common ADCS sensors to receive a signal from the beacon being transmitted by the GS. The attitude required for this stage is where the payload is pointed at the GS with an attitude error of 10°, equivelent to the FOV of the telescope that perceives the beacon.

The second stage uses the Earth's reference from the beacon to improve the attitude estimation, with the goal of obtaining a pointing error of 0.1°. This value is defined by the amplitude of actuation of the fast-steering mirrors (FSM).

A fine optical pointing stage is necessary to obtain the pointing accuracy required for quantum communications. The optical pointing system within the payload is in charge of this part of the mission. The laser beacon coming from the ground enters through the telescope and passes through an assemble of mirrors and lenses, guiding it to a quad-cell. The error signal generated from the difference between the measured and desired position of the beacon on the quad-cell is employed to drive a Fast Steering Mirror to actuate on the beacon attitude, augmenting the pointing accuracy without the need to move the satellite structure. This fine pointing process is executed continuously throughout the mission, designed as a closed control loop that runs in parallel with the other stages managed by the ADCS. The process, architecture, and implementation of this section of the pipeline for the Quantum-Sat project are illustrated in [9].

4. Attitude determination System

Even though the attitude determination system implemented in the ADCS progresses through two stages, the same estimation filter is used.

The filter used is a Multiplicative Extended Kalman Filter (MEKF) is implemented, based on [5].

The multiplicative attribute of the filter is due to the error quaternion expression that follows the Equation 7.

$$\mathbf{q} = \delta\mathbf{q}(\delta\vartheta) \otimes \hat{\mathbf{q}} \qquad (7)$$

The filter not only estimates the quaternion but also the gyroscope bias, such that the state is given in Equation 8.

$$\mathbf{x} = \begin{bmatrix} \mathbf{q} \\ \boldsymbol{\beta} \end{bmatrix} \qquad (8)$$

Since the attitude kinematics are non-linear, an EKF structure must be used, where the quaternion is not estimated but a "local" state vector, composed of a three-component $\delta\vartheta$ rotation vector and an estimation error for the bias, given in Equation 9.

$$\Delta\mathbf{x} = \begin{bmatrix} \delta\vartheta \\ \Delta\boldsymbol{\beta} \end{bmatrix} \qquad (9)$$

The structure of the MEKF and its equations are based on an EKF and are given in Appendix A and B, respectively, and are based on [5]. The discrete-time, non-batch version of the filter is used.

The measurement update uses attitude sensors to correct the state estimate. The measurement vector, sensitivity matrix, measurement covariance and Kalman gain vary in order to accommodate sensors availability. The reset step transports the local error state $\Delta\mathbf{x}$ to the global error state $\mathbf{x}$. The propagation step is based on the quaternion kinematic from Eq. 3 and for the gyroscope bias are given in Equation 10.

$$\dot{\boldsymbol{\beta}} = 0 \qquad (10)$$

5. Results (and Discussion)

The simulation is a self-made Simulink/Matlab 2020a model. It includes orbital and attitude motion, environmental disturbances and sensor models. The gyroscope used in the MPU9250 whilst the beacon was simulated based on [8].

In order to isolate the impact of the beacon in the attitude estimation, two different simulations are performed.

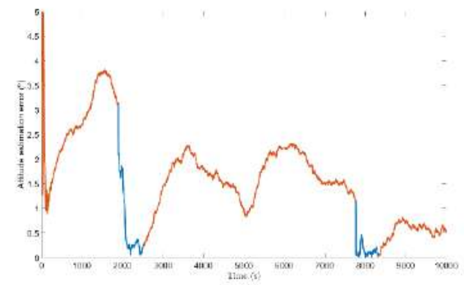

Figure 1 . Angular estimation error (°) with the beacon. Areas in blue represent the regions where the beacon is available.

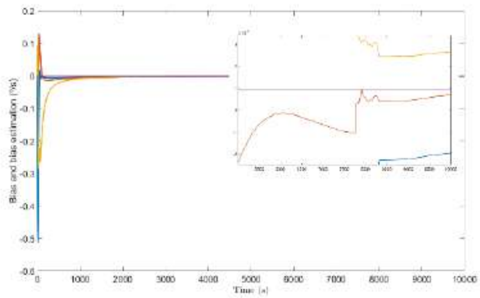

Figure 2 . Bias estimation error (°) with the beacon.

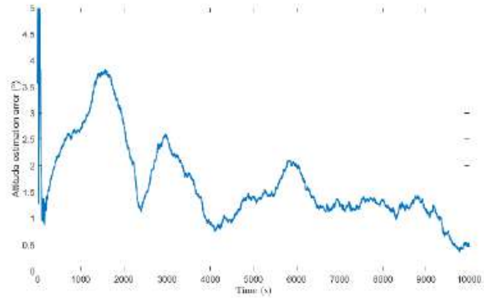

Figure 3 . Angular estimation error (°) without the beacon.

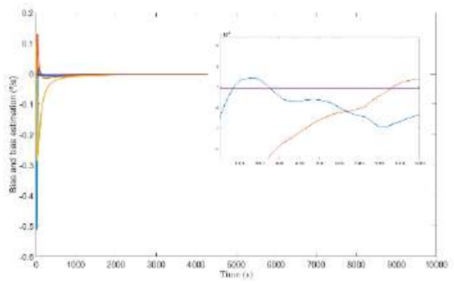

Figure 4 . Bias estimation error (°) without the beacon.

Figure 1 and Figure 2 show the estimation error and the bias estimate of the filter with the beacon whilst Figure 3 and 4 represent the estimation error and the bias estimate of the filter without the beacon.

When the GS is in LOS of the satellite, the estimation error is reduced, in some passes being able to reach the 0.1° estimation error.

When the beacon is not used, the estimation error is not low enough to meet the requirements.

Table 1 shows the mean of the estimate error of the attitude and bias. As it can be seen, the usage of the beacon drastically increases estimation accuracy in the downlink area.

The bias estimation doesn't suffer a drastic variation with the inclusion of the beacon.

Table 1. Estimation performance

Mean	With Beacon	Without beacon
Estimation error (°)	1.24	1.33
Estimation error (º) in FOV	0.3353	1.40
bias error (°/s)	0.0019	0.0018

6. Conclusions

An architecture for the ADCS, alongside with a filter was proposed in order to increase estimation performance. The GS beacon is repurposed as an attitude sensors.

Whilst within LOS, the beacon increases estimation performance since it provides an Earth reference.

Simulations show the effectiveness of the new sensor through the analysis of the estimation errors.

Acknowledgements

The authors thank the support from Fundação para a Ciência e Tecnologia (Portugal), namely through project UIDB/50008/2020, as well as from project QuantSat-PT.

Appendix

Appendix A - Multiplicative Extended Kalman Filter structure

Initialization: $\hat{\mathbf{x}}_0, P_0$
loop
  Propagation: $\hat{\mathbf{x}}_{k+1}^-, P_{k+1}^-$
  if observations ready: $\mathbf{y}_{k+1}$ **then**
    calculate kalman gain: K_k
    Calculate uncertainty: $\delta\hat{\mathbf{x}}_{k+1}$
    Update: $\hat{\mathbf{x}}_{k+1}^+, P_{k+1}^+$
    Reset: $\delta\hat{\mathbf{x}}_{k+1} = \mathbf{0}$
  end if
   return $\hat{\mathbf{x}}_k^+, P_k^+$
end loop

Figure A1. Pseudo-code for the MEKF

Appendix B - Multiplicative Extended Kalman Filter equations

$$\mathbf{K}_k = \mathbf{P}_k^- \mathbf{H}_k^T(\bar{\mathbf{x}}_k^-)[\mathbf{H}_k(\bar{\mathbf{x}}_k^-)\mathbf{P}_k^- \mathbf{H}_k^T(\hat{\mathbf{x}}_k^-) + \mathbf{R}_k]^{-1}$$
$$\Delta\hat{\mathbf{x}}_k^+ = \mathbf{K}_k[\mathbf{y}_k - \mathbf{h}_k(\hat{\mathbf{x}}_k^-)]$$
$$\mathbf{P}_k^+ = [\mathbf{I} - \mathbf{K}_k\mathbf{H}_k(\hat{\mathbf{x}}_k^-)]\mathbf{P}_k^-$$
$$\mathbf{h}_k(\hat{\mathbf{x}}_k^-) = \begin{bmatrix} A(\hat{\mathbf{q}}^-)\mathbf{r}_1 \\ A(\hat{\mathbf{q}}^-)\mathbf{r}_2 \\ \vdots \\ A(\hat{\mathbf{q}}^-)\mathbf{r}_N \end{bmatrix} t_k$$
$$\hat{\mathbf{q}}_k^+ = \frac{1}{\sqrt{1+|\ \delta\hat{\theta}_k^+/2\ \|^2}} \begin{bmatrix} \delta\hat{\vartheta}_k^+/2 \\ 1 \end{bmatrix} \otimes \hat{\mathbf{q}}_k^-$$
$$\hat{\boldsymbol{\beta}}_k^+ = \hat{\boldsymbol{\beta}}_k^- + \Delta\hat{\boldsymbol{\beta}}_k^+$$
$$\hat{\omega}(t) = \omega_m(t) - \hat{\boldsymbol{\beta}}(t)$$

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Design, Manufacture, and Validation of a Student-Made Ringsail Parachute for Sounding Rocket Recovery

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Abstract

In the previous years, the Parachute Research Group (PRG) of Delft Aerospace Rocket Engineering (DARE) has been relying mainly on cruciform, ribbon, or disk-gap-band parachutes for the retrieval of its capsules and smaller sounding rockets. However, heading towards a more sustainable future, with the prospect of full rocket recovery and reusability of larger flagship missions in the future, a new, high-performance main parachute had to be developed. As a result of these, a ringsail-type parachute was selected because of its excellent reefing capabilities, good drag performance, and flight heritage within the professional industry. This paper will focus on three main phases of the development of the new parachute type. Firstly, detailed designs and selection of these different designs created will be presented. Furthermore, considering the fact that this type of parachute is notoriously difficult to produce, new manufacturing methods will be proposed and discussed. Lastly, the results of the wind tunnel tests performed will evaluate and further elaborate on the drag performance, stability characteristics, inflation loads, and reefing capabilities of this parachute type.

Keywords

Ringsail, Sounding rocket recovery, Parachute production

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Acronyms/Abbreviations

DARE *Delft Aerospace Rocket Engineering*

PRG *Parachute Research Group*

OJF *Open Jet Facility*

1. Introduction

The Parachute Research Group (PRG) of Delft Aerospace Rocket Engineering (DARE) is a sub-team within a student rocket society located in the Netherlands. PRG develops new entry, descent and landing technologies for major flagship missions of DARE, such as the Stratos sounding rockets. DARE has relied mainly on cruciform and disk-gap-band parachutes as low-production-effort and high performance main parachutes respectively [1].

As DARE aims to increase the recovered payload mass to achieve a higher degree of reusability, a parachute with a higher drag coefficient than the current designs is more beneficial. Thus, the development of a parachute type previously unexplored by PRG was selected: the ringsail parachute.

Although large ringsails have been produced in the past for space missions, the characteristics of small scale ringsails are still relatively unknown [2]. The design, manufacturing and wind tunnel testing of four ringsail variants is presented in this paper - alongside the reflections and recommendations.

2. Design selection

Ringsail parachutes are notable for their geometric profile, consisting of annular cloth strips called sails which are spaced apart by slots around the crown, but adjacent towards the skirt. In addition to varying traits such as those offered by most solid parachutes (gore count, vent size, profile angle, etc.), variations may also be distinguished through features intrinsic to the ringsail, like sail fullness (leading and trailing edge widths of each sail), cloth and slot widths, and the angles of attack of each cloth-ring. The aforementioned geometric versatility hence allows for a more adjustable design to attain favourable drag, stability, inflation, and stress relief characteristics. Some ringsails have distinct design features that warrant specific names, these are for example disksails, starsails, and modified ringsails [3]. A disksail is a ringsail that replaces the inner rings around the canopy vent with a circular flat disk. The starsail is a ringsail where multiple gores are replaced by solid gores, which creates a star pattern. The modified ringsail uses wide slots with a conical or biconical profile. Considered separate from ringsail-like designs but within the slotted-parachute category, ringslot parachutes utilise concentric rings instead of individual sails.

The design requirements of a ringsail follow directly from the recovery or overall system requirements. This may include the required descent velocity, deployment conditions, system stability margins, payload weight, as well as internal volume and weight characteristics. These can then be translated into the constructed and geometrical parameters used in the parachute's design and are often based on past ringsail models. However, the scales of historical ringsails used in literature are significantly larger than the target designs in this paper.

Two standard, unmodified ringsails were initially designed by independent sub-groups. For Ringsail A, the team used Section 5: Design Procedures of the "Ringsail Parachute Design" by the Northrop Corporation [4] to calculate and select the necessary parameters to fully design the ringsail. Since the goal was to design a prototype ringsail, the nominal diameter was fixed to 1 m. A smaller diameter would lead to issues with cloth stiffness and a larger diameter would lead to an excessive blockage factor in the wind tunnel. The design guide in the Northrop Corporation book uses empirical relations and data from previous ringsails with nominal diameters between 6 m and 55 m. This means that several empirical relations did not scale well and assumptions had to be made. An example of this is the number of gores, which would be 3 when using the empirical relations, but was nevertheless chosen to be 8 to ensure a round, inflated profile while limiting the production time. Subsequently, the number of sails per gore was computed to be 9, the geometric porosity to be 8.5% and the profile to be 20° conical.

After finishing the first ringsail, the team noticed that a few steps of the manufacturing process could be simplified and therefore decided to create a simple ringslot hybrid parachute. The main differences between ringsails A and B are that the number of sails was reduced and the inner three rings were replaced by ringslots, which lack fullness and could thus be cut as single pieces without connections. Additionally, the sails had a larger relative fullness. As the development of the hybrid parachute progressed faster than expected, a disksail was also conceived and manufactured. This took the form of a modification to ringsail B by means of a disk attached over the vent and inner three rings, which resulted in minimal manufacturing time. The disksail has a lower geometrical porosity in the crown compared to ringsail B, increasing the expected drag.

Ringsail C was designed similarly to ringsail A: using the workflow described by the Northrop Corporation, but with some changes made to its geometry. The geometric porosity was increased to 11.5% by means of a larger vent and wider slots; 7 sails were selected to go with 12 gores to better resemble a hemispherical canopy profile. A slightly lower nominal diameter of 0.9 m and a larger cloth width size of 6 cm were selected to reduce manufacturing overhead. The increase in geometrical porosity close to the crown was chosen to reduce the shock factor associated with parachute inflation. However, it would also go on to aid with reducing the difficulty of attaching an extra ring of sails, with a narrower cloth width than the other sails. The gore templates and side profiles can be seen in Figure 1.

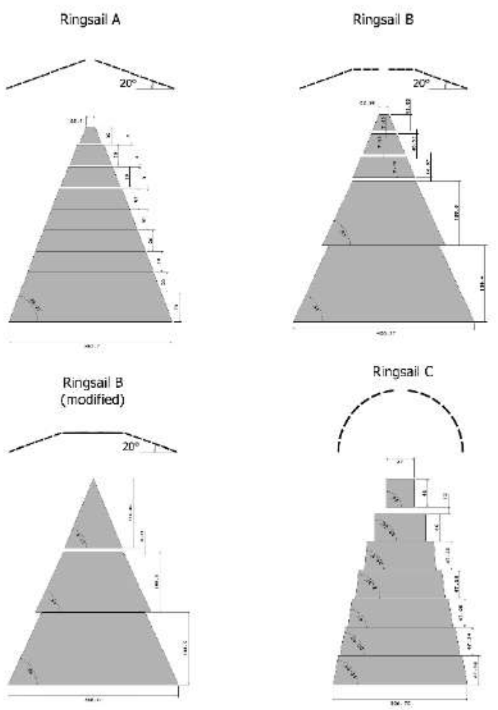

Figure 1: Side profiles and gore templates of the different ringsails.

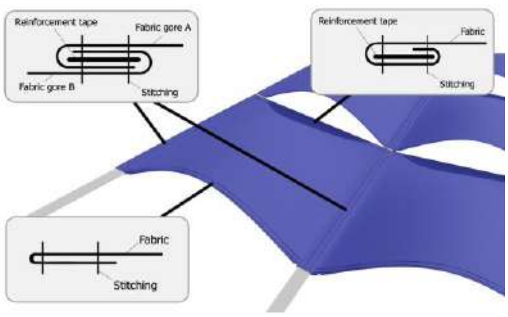

Figure 2: Graphical overview of the different reinforcements on each of the sails.

3. Manufacturing

Once the designs were selected, DXF files of all the sails were needed for use on the laser and fibre cutter. The DXF files, exported from CAD software, were used to cut the sails out of the fabric. This ensured that the dimensions of the sails were accurate and reduced manufacturing time compared to manually cutting the sails. Automating the cutting of fabric eliminated human error. An additional benefit was that the laser slightly melted the edges of the fabric, preventing fraying during the rest of the manufacturing process. Ringsail C was instead cut out on a computer-controlled fibre cutter, which had similar speed and accuracy benefits but did not prevent fraying.

The next step was to reinforce the edges of the sails. As more stress was expected on the trailing edge of the sails (the edge closer to the crown), this side was reinforced with a nylon reinforcement tape. The leading edge was simply folded over itself and stitched down. More reinforcement tape was used to connect neighbouring sails to each other and to function as a load path from the sails down to the suspension lines. These tapes were measured and marked at the correct locations for sail attachments, and then the reinforced sails were attached using the connections shown in Figure 2. The connections were secured using small clothing irons and heat-activated glue before being sewn together, rather than using pins.

Once the canopy was assembled, the lower ends of the vertical reinforcement tapes were folded back and stitched down over themselves to create loops. These loops were connected to the wind tunnel test riser using suspension lines, a link and a swivel.

In the end, each ringsail took between 50 and 100 man-hours to manufacture, except the disksail which was a simple modification of ringsail B. It should be noted that the manufacturing times are not necessarily representative as all ringsails, especially ringsail A, involved some measure of trial and error.

4. Testing

The key objectives of the wind tunnel tests are to quantify the drag, drag coefficient, shock load factor during inflation, and the stability of the ringsail parachutes. For ringsails the shock load factor is typically low, meaning that the inflation forces are not as high. Since this load factor is often the defining load for sizing the suspension lines, riser and structure, decreasing this factor could have a large impact on the design.

DOI: 10.5821/conference-9788419184405.129

Each ringsail was tested under multiple reefing conditions. The reefing percentage is defined as the restricted circumference over the unreefed circumference of the ringsail. All ringsails were reefed to 5%, 10% and 25%.

The tests were conducted in the Open Jet Facility (OJF) of the TU Delft. This wind tunnel has a throat width and height of 2.85 m and can reach speeds up to 35 m/s. The ringsails were attached to a load cell which was mounted to a test bench and can record measurements with frequencies up to 10 kHz, which has proven to be sufficiently fast to capture the inflation shock load for the current set-up. The latter was both bolted to a table in the test chamber and secured with steel cables.

The experiments performed in the OJF were subject to multiple test conditions. The airflow velocity in the wind tunnel was controlled and tests were conducted at speeds up to 27 m/s. The deployment method of the ringsails in the wind tunnel varied for each ringsail variation and test. Deployment could be manual where once the wind tunnel reaches the desired velocity, the ringsail was released into the airflow by hand. In order to test the inflation behaviour, the ringsails could also be deployed from a 3D printed canister using a parachute bag and a pilot chute. These tests could be actuated either by a remotely operated servo or by pulling a string.

All ringsails were tested between 4 and 8 times under reefed and unreefed conditions. During the tests, the ringsails were manually deployed at 10 m/s or out of the canister at 27 m/s. During certain trials, ringsails were deployed at lower speeds and the airflow velocity was progressively increased to test the ringsail at multiple velocities.

5. Results

For each ringsail, the drag coefficient is averaged over the different data points and different velocities at which the ringsails were tested. These average C_d values are presented in Table 2, along with the opening shock load factor of each parachute. This non-dimensional value represents the maximum peak load experienced at inflation, divided by the average steady state load at the deployment velocity. All deployment tests were performed by using a parachute bag and extraction by a pilot chute. Finally, the drag coefficient of the reefed ringsails is presented, expressed as a percentage of the average steady state drag coefficient of the non-reefed ringsails. The stability of each ringsail was tested qualitatively in a wind tunnel, results were recorded in the form of video footage and written observations. Initially, ringsails A and B appeared quite unstable, showing significant lateral movement. It was discovered that manufacturing defects and inconsistent suspension line length were probable causes for this instability. These defects were corrected by the team in between tests, and afterwards each ringsail showed a significant increase in lateral stability. Rotationally, the ringsails showed varying degrees of movement, with ringsail A rotating the most and ringsail B rotating the least. This can likely be explained by the fact that ringsail B is made up of fewer sails, thus containing fewer connections between sails meaning there is a smaller chance for manufacturing errors to occur. However, ringsail B did show more lateral movement than ringsails A and C after being corrected. It should be noted that both the lateral and rotational stability of the ringsails improved when the parachutes were tested in reefed configuration.

With the dynamic pressure and drag known for each wind tunnel test, the drag coefficient was calculated. The choice for reference area to calculate the drag coefficient is arbitrary, as long as the values are consistent with each other. In Table 2, the drag coefficient using the production area and projected area are used. The former area is that of the actual parachute fabric of the ringsail, while the latter area is that of a flat circle with the nominal diameter (mentioned in Table 1). The drag coefficient, using the production area, is very similar for all ringsails, in the order of 0.62 to 0.65, with the disksail (ringsail B modified) exhibiting the lowest performance by a small margin. According to literature [3], the drag coefficients of standard ringsails (such as ringsail A, C) is in range 0.75-1.00 whereas that of modified ringsails (namely ringsail B) is of order 0.65-0.70 [4]. The production and projected area of the ringsails are similar to each other, except for ringsail C due to the hemispherical profile. This also means that there is not a very large difference between drag coefficients using these two different areas for ringsails A, B and modified B, as can be seen in Table 2.

The opening load factor is an important parameter to consider when performing parachute trade-offs or when designing recovery systems, as the inflation shock is typically the highest load the system has to sustain. Ringsail A showed an exceptionally good inflation behaviour with no distinct peak value. Ringsail B and its modified variant had a significantly larger shock load of 1.74 and 1.86 respectively. This discrepancy in shock loading is likely caused by the lower geometric porosity and larger sails of ringsail B, compared to A. During the deployment tests of ringsail C, the pilot chute that extracts the parachute bag was entangled with the pull line. After several seconds, the pilot chute still managed to pull away the bag. No distinct inflation shock load was observed, however the data of this test is marked non-representative. Edgars et al. [4] states that the maximum opening load factor (for a cluster of 2 ringsails) is of order 1.5, for similar dynamic pressures.

The selected reefing ratios gave significant reductions in drag, however the reduction in drag was inconsistent between the different parachutes. Ringsails A and C, both with a relatively high number of sails, had similar amounts of drag reduction. For the two larger reefing line ratios this lines up with literature for ringsails, while for smaller reefing line ratios stiffness likely plays a role in small parachutes [5]. For ringsail B and its modification the drag reduction is significantly smaller. Here the drag reduces significantly between the larger two reefing line ratios, while reefed to 5% the drag does not reduce much further. The reefing behaviour is also largely not influenced by the disksail modification. For the 5% reefing line ratio for ringsail C it was observed that larger velocities were needed for complete inflation of the parachute. During the reefed operation of the different ringsails, flutter on the leading edge sails was observed. This was especially violent for the disksail variant, leading to two of the loops of reinforcement tape connecting to the suspension line failing.

The reductions in drag correspond well to the values for large ringsails according to literature with small deviations [5]. These are to be expected as literature also mentions fabric stiffness as a larger problem for reefing of smaller parachutes.

6. Conclusion

The design, manufacturing, and testing of four ringsails have been presented. The existing design guidelines for ringsails had to be adapted to smaller sizes, by defining a fixed nominal diameter and number of gores, and subsequently computing the geometry based on empirical data. This resulted in four parachutes being manufactured and tested successfully during a wind tunnel campaign. Ringsail A was developed as a prototype, with the goal of further understanding the empirical design relations required to manufacture a small ringsail. Ringsail B was designed to examine the characteristics of a ringsail/ringslot hybrid which was later modified to obtain a disksail. Ringsail C was distinct from the other ringsails by number of gores, crown porosity, and hemispherical profile. Manufacturing was carried out using new methods by cutting the fabric with a laser cutter or fibre cutter. Testing was done in a wind tunnel with speeds up to 27 m/s and varying deployment methods. The results showed that the parachutes were relatively unstable but that reefing improved stability. Furthermore, the drag coefficient for the parachutes was in the order of 0.62 to 0.65. Ringsail A displayed good inflation behaviour with no distinct peak shock load, while for ringsail B and ringsail B modified the inflation load factor was 1.74 and 1.86 respectively. Due to problems with the deployment method of parachute C, no reliable data was collected. Finally, a positive relationship was determined between the reefing ratio and a decrease in drag coefficient.

7. Reflection and recommendations

During the first wind tunnel tests, the team discovered that manufacturing errors were the probable cause for parachute instability. The two most significant deviations were the lengths of the suspension lines and the size of one particular sail. After these were corrected, the stability was noticeably improved. Small manufacturing defects have a large effect on the performance for small parachutes. Therefore, it is highly recommended to perform a more thorough quality control on smaller parachutes.

After consulting the design guides available in literature, it was found that the sails on the relatively small ringsail parachutes described in this paper had a large aspect ratio. During wind tunnel testing it was found that these experience a high-frequency flutter at the canopy's leading edge, both in a reefed and non-reefed configuration. It is recommended to either increase the number of gores or to reduce the number of sails per gore to decrease the sail aspect ratio. The former will however increase the production time significantly.

During the experiment possible sources of error occurred that made the data less representative compared to flight conditions. Two of these were the blockage factor of the parachute and turbulence caused by the test bench, which led to a lower measured drag force.

After wind tunnel testing, it is recommended to flight test a parachute under more representative conditions compared to the controlled environment in a wind tunnel. A test flight of ringsail C on board of PRG's Parachute

Investigation Project rocket is scheduled to launch in March 2022 [6].

Although the stability of the ringsails at reefed conditions was determined during the latest wind tunnel campaign, deployment tests at reefed conditions were not performed. However, it is recommended to characterise the opening load factors of a reefed ringsail in future testing.

Additionally, it is recommended to investigate whether different folding methods can decrease the inflation shock loads of the ringsails. Additional tests may be performed to investigate the effect of geometric porosity on the inflation behaviour.

Acknowledgements

The authors would like to thank the Faculty of Aerospace Engineering at the Delft University of Technology and its staff for their continued support in recovery system testing and the provision of the OJF wind tunnel.

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Table 1: Overview of the different ringsail designs.

Parameter	Ringsail A	Ringsail B	Ringsail B (modified)	Ringsail C
Type	Ringsail	Modified ringsail	Disksail	Ringsail
Gores	8	8	8	12
Gore composition	9 sails	2 sails, 3 slots	2 sails, 1 disk	7 sails
Nominal diameter [m]	1.0	1.0	1.0	0.9
Production area [m^2]	0.792	0.888	0.904	0.550
Projected area [m^2]	0.785	0.785	0.785	0.414
Profile	20° conical	Biconical (20°-0°)	Biconical (20°-0°)	Hemisphere
Suspension line length [m]	1.15	1.15	1.15	1.08
Material [-]	F-111	Kite fabric	Kite fabric	Kite fabric

Table 2: Overview of drag performance of the different ringsails under different conditions.

Parameter	Ringsail A	Ringsail B	Ringsail B (modified)	Ringsail C
Type	Ringsail	Modified ringsail	Disksail	Ringsail
C_d average w.r.t. production area [-]	0.64	0.64	0.62	0.65
C_d average w.r.t. projected area [-]	0.65	0.72	0.72	0.87
Opening load factor, deployed from parachute bag [-]	1.00	1.74	1.86	Unreliable data
Percentage of C_d, reefed to 25%	39.5%	55.2%	61.2%	37.5%
Percentage of C_d, reefed to 10%	15.8%	36.9%	34.9%	14.0%
Percentage of C_d, reefed to 5%	8.9%	31.0%	-	5.8%

Engineering and Management of Space Systems (EMSS) - an international joint Master's double-degree program

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Abstract

Dynamic development of the space sector of European, and especially of Polish and German economies results in a necessity for suitable Higher Education Institution graduates. The increasing digitization, distribution and networking of technical systems leads to the necessity of a degree programme teaching “the systems view” and “interdisciplinarity” methods and skills. Furthermore, it is necessary to consider the entire life cycle of the systems starting with the analysis of the requirements, through design, integration, verification, to operation and maintenance, with supplementation of management, social and intercultural skills.

Since interdisciplinarity and internationality are essential for engineering and management of space systems, the international project was launched early last year by two universities – Hochschule Bremen (Bremen City University of Applied Sciences, HSB, Germany) and Politechnika Gdańska (Gdańsk University of Technology, Gdańsk Tech, Poland) establishing an international interdisciplinary joint Master's double-degree program - Engineering and Management of Space Systems (EMSS). It consists of three different fixed three- or four-semester study paths of several mobility schemes, though individual educational pathways adjusted to students' preference are also allowed. Each path includesa joint academic year – first semester is conducted in Gdańsk, the second in Bremen. The remaining semesters can be studied at either of the universities. All of the EMSS curricula meet the highest education standards of both countries.

Several mandatory modules and many elective courses are included in the EMSS curricula. Upon graduation, students of the program are awarded two Master’s degrees - in Space and Satellite Technologies, issued by Gdańsk Tech, and, depending on the chosen study path, in Aerospace Technologies, Computer Science, or Electronics Engineering issued by HSB.

Work on the establishment of a new, international, joint field of study - Engineering and Management of Space Systems, run by both universities is currently in progress. The curriculum of the new study programme will be based on the recommendations of the International Council On Systems Engineering (INCOSE) and its German Chapter, Gesellschaft für Systems Engineering (GfSE), and will offer the possibility of certification as a Systems Engineering Professional, Associate Level.

This paper includes the lecturers’ and students’ perspective on the program and its future development.

Keywords

Engineering and Management of Space Systems, International joint double-degree program

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Acronyms/Abbreviations

Gdańsk Tech	*Gdańsk University of Technology (Politechnika Gdańska)*
EMSS	*Engineering and Management of Space Systems*
HSB	*City University of Applied Sciences Bremen (Hochschule Bremen)*

1. Introduction – the establishment of the EMSS program

To track the origins of the Engineering and Management of Space Systems (EMSS) program one should go back to year 2017, in which 3 Polish universities from the Tri-City region of Gdańsk, Sopot, and Gdynia, joined their forces to run a novel, intercollegiate Master's studies in the field of Space and Satellite Technologies [1][2]. These universities were: Gdańsk University of Technology (Gdańsk Tech, formerly GUT, Fig. 1), Gdynia Maritime University, and the Polish Naval Academy in Gdynia). Gdańsk Tech, the leader and coordinator of this action, is the second-best research university in Poland (in the 'Initiative of Excellence - Research University' competition of the Ministry of Science and Higher Education, currently, Ministry of Education and Science Poland), classified in the most prestigious international rankings, including the Shanghai Ranking. The HR Excellence in Research logo of the European Commission places Gdańsk Tech among the institutions creating the best working and development conditions for researchers in Europe. With over 15 000 students, 37 fields of study, 2 doctoral schools, 13 scientific disciplines, and nearly 1300 academic teachers, Gdańsk Tech is the biggest technical university in the Pomeranian region, most frequently chosen by Polish and international candidates. Its partner, Gdynia Maritime University, is the largest state school of higher maritime education in Poland, and one of the largest universities of this type in Europe. Its programs of study satisfy not only the Polish educational standards set by the Ministry of Education and Science, but also the highest requirements of the International Maritime Organization – IMO. The last party of the initial project, the Polish Naval Academy, is a naval university operating under the Ministry of National Defence of Poland. It educates officer-cadets, commissioned officers and officers of naval forces of the European, North African, Middle and Far East countries, as well as civilian students. Joint studies of these institutions were supported by the Polish Space Agency and co-financed by the National Centre for Research and Development under the project entitled: Adaptation of the second-degree studies Space and Satellite Technologies to the needs of the labour market.

Figure 1. Gdańsk University of Technology

Under the umbrella of the Space and Satellite Technologies program, several related fields of study, namely the Information and Telecommunications Technologies in Space and Satellite Engineering (offered by the Faculty of Electronics, Telecommunications and Informatics of Gdańsk Tech), Mechanical and Mechatronic Technologies in Space Engineering (run by the Faculty of Mechanical Engineering of Gdańsk Tech), Marine Satellite and Space Systems (organized by the Faculty of Electronics of Gdynia Maritime University), and Space and Satellite Applications in Security Systems (of the Faculty of Command and Naval Operations of Polish Naval Academy) were merged to offer a truly interdisciplinary branch of graduate studies. As a result, not only a highly professional program with the best input of all the universities involved was launched. Another unquestion-able benefit of such a collaboration was turning the institutions that used to be competing for graduate students into partners, sharing their knowledge, good practice, and efforts in recruiting the best candidates. Thanks to the financial support of the external bodies, experts from the space industry were invited to deliver part of the courses. In such a partnership, side by side with the Polish Space Agency, the universities were able to face the challenges of a new innovative industry sector of space exploration and utilization technologies emerging in Poland, and Pomerania - a manifold of companies and other related entities. These new entities were both Polish branches of well-established international corporations, along with smaller local firms offering various services, including satellite telecommunication, satellite navigation, Earth observation, as well as the Geographic Information Systems (GIS).

However, rapidly-growing European and global markets set high demands that could be met only under international collaboration. Since similar issues were faced by the German Higher Education Institutions, another partnership strengthening the Space and Satellite Technologies program was made. Seeing great potential of international collaboration and complementarity of the institutions within the field of space sector, the City University of Applied Sciences Bremen (Hochschule Bremen, HSB, Fig. 2) and Gdańsk University of Technology decided to launch a joint interdisciplinary double-degree Master's program, supported by the expertise of the old members of the Space and Satellite Technologies alliance.

Figure 2. City University of Applied Sciences Bremen

The Bremen City University of Applied Sciences is the largest university of applied sciences, the second largest Higher Education Institution in the federal state of Bremen. It offers almost 70 degree programs in engineering for about 8,500 students. The HSB offers a reliable framework for all students to gain international experience during their studies. A cornerstone of internationality at HSB are the more than 360 cooperation agreements with universities and diverse companies and organisations worldwide. The partnership with the Gdańsk Tech is especially valuable, since Bremen and Gdańsk are twin cities. Thanks to long-standing contacts with industrial partners, enabling strongly practice-oriented teaching and research, HSB offers a broad spectrum of future-proof and innovative study programs. Thus, it is regarded as driver of innovation for the surrounding region. Having so much to offer, HSB entered the agreement with Gdańsk Tech with three fields of study, i.e. Aerospace Technologies, Computer Science, and Electronics Engineering, giving rise to 3 possible branches (study paths) of the initial Space and Satellite Technologies program, collectively called the Engineering and Management of Space Systems program. The first pilot run of the program was started in April 2021.

2. Program details

2.1. Program management

Dr. Marek Chodnicki for the Polish part and Prof Jasminka Matevska for the German part are responsible for the management of the program. Along with Prof Zbigniew Łubniewski (Gdańsk Tech) they are local coordinators of the program. Supported by a team of academic teachers from both of the universities, they are responsible for all the program curricula, course contents, learning outcomes, supervision of students, and all other matters related to the quality of education, and organization of the program.

2.2. Student admission

Candidates eligible to apply to the program are the holders of Bachelor's or engineering degrees meeting the admission criteria of both universities. Students are recruited separately by both institutions into respective fields of study: Aerospace Technologies, Computer Science, and Electronics Engineering at HSB, or Space and Satellite Technologies at Gdańsk Tech. The university that recruited students becomes the Home University for these students. Next, each institution selects highly motivated candidates that are evaluated by local coordinators from HSB and Gdańsk Tech, i.e. by Prof Jasminka Matevska (HSB), Dr. Marek Chodnicki (Gdańsk Tech), and Prof Zbigniew Łubniewski (Gdańsk Tech), heads of the program. Positive evaluation of candidates results in their nomination to the international double-degree EMSS program, and their enrollment at the second university that becomes the Partner University for these students.

2.3. Program structure and curricula

The EMSS program is a joint interdisciplinary international Master's double-degree program of an Erasmus Mundus type. It is designed for completion in three or four semesters of full-time study, depending on the chosen study path and study pace. All students enrolled to the program follow one of a predefined two-semester joint study paths. The first semester is conducted in Gdańsk, the second semester in Bremen. The place of study for the remaining one or two semesters is the Home University, unless decided otherwise by students and coordinators of the program.

Tab.1 Detailed curriculum of one of the study paths is shown in Tab.1. Space and Satellite Technologies (Gdańsk Tech) + Electronics Engineering (HSB)

MODULE NAME	ECTS
First semester, Gdańsk Tech	
Mechanics and mechatronics in space technologies (includes: Robotics for human health and performance, Gravity-related research, Heat and mass transfer in lack of gravity)	6
Satellite technologies (includes: Satellite navigation, Satellite remote sensing, Spatial data processing technologies)	6
Interdisciplinary project – part 1 (includes: Interdisciplinary project, Management in space industry)	6
Law and security in space (includes: Space law, Cybersecurity, Crisis management)	6
Electronics Engineering – elective (Choose 3 from 4: 1. Antenna technique in space applications, 2. Autonomous (systems) vehicles control, 3. Objective programming, 4. Electric drives	6
Polish as a foreign language – only for German students	1
Second semester, HSB	
Space Systems Engineering (includes: Systems engineering foundations, Systems engineering methods and processes, competences and roles, Classical and agile approaches, Requirements engineering, Technical realisation processes, Operational aspects)	6
Project Management (includes: Project management activities and methods, Classical vs. agile project management, Project management in the space application domain, Teambuilding and communication)	6
Interdisciplinary project - Part 2 (includes: CubeSat development, Engineering and management)	6
Metrology and Instrumentation	6
Laser systems and applications	6
Electronics Engineering – elective modules (Choose 1 from 6: 1. Satellite Communications, 2. Unmanned Aerial Vehicles, 3. Image Processing and Pattern Recognition 4. Fundamentals of Machine Learning, 5. Non-Chemical Space Propulsion Systems, 6. Optical Communications	6
German as a foreign language - only for Polish students	1
Third semester, HSB or Gdańsk Tech	
Master thesis (includes: Diploma seminar, Master thesis)	30

The EMSS curricula include various mandatory modules, such as Mechanics and Mechatronics in Space Technologies, Satellite Technologies, Interdisciplinary Projects, Law and Security in Space, Space Systems Engineering and Project Management. Additionally, many elective courses depending on the chosen specialty, like Design and Modelling of Space Propulsion Systems for Aerospace Technologies, Methods for Development of Complex Software Systems for Computer Science, Metrology and Instrumentation for Electronics Engineering are available to adjust to students' individual interests and preference. A detailed curriculum of one of the offered study paths is shown in Tab.1. Individual study plans may also be taken into account, if appropriately motivated, and verified in terms of the diploma requirements and approved by both institutions. Students enrolled to the program choose their specialization by signing a proper Learning Agreement stating the program of their studies and degrees awarded.

Apart from regular classes, students of the program may also participate in traineeships, language, adaptation, and intercultural trainings. Such course diversity should result in highly skilled specialists that will meet the demands of the European as well as the global job market related to various space programs.

2.4. Graduation criteria, Master's thesis, degrees awarded

All of the curricula offered within the EMSS program meet the most rigorous higher education standards of both countries. They are consistent with Polish, German and European Qualification Frames, as well as, with internal study regulations of both universities. As it is not a trivial issue, all of the actions of the local coordinators of the program are supported by Dr. Justyna Szostak, a specialist in international multiple-degree programs from Gdańsk Tech.

A minimum of 30 ECTS credits has to be collected at each of the institutions. Credits acquired at one university in accordance with the Learning Agreements are recognized by the other university. The International Offices of both universities are offering support considering the organizational aspects. To confer both of the final qualifications, students have to meet the graduation criteria of both universities - both fields of study they are enrolled in. They have to collect the minimum number of ECTS credits and learning outcomes specified for a chosen study path, write and defend a Master's thesis.

To make sure that the Master's thesis follows the standards of the two fields of study and both universities the student is going to graduate from, each Master's thesis has to be co-tutored by professors from both institutions. In addition, a reviewer validating the quality of the submitted thesis has to be assigned. If the main supervisor of the thesis is from HSB/Gdańsk Tech, a Gdańsk Tech/HSB professor has to be chosen as a reviewer, respectively. The defense of the thesis, run in accordance with the internal regulations of both universities, will take place only once if the Examination Board includes the representatives of both partners. Otherwise, the defense will be organized separately at each of the universities. If necessary, the defense may be conducted on-line or in a blended form.

Graduates of the EMSS joint program will be awarded a Master in Engineering Degree in Space and Satellite Technologies issued by Gdańsk Tech, and a Master's Degree in Aerospace Technology, Computer Science, or Electronics Engineering, depending on the specialization, issued by Bremen University of Applied Sciences.

2.5. Language policy

During the first, joint year of study, all of the classes, exams and trainings of the EMSS program are held in English. To this purpose students are required to prove a satisfactory (minimum B2, according to C.E.F.R.) level of both spoken and written English. Master's thesis has to be written in English, that is the language of the defense as well.

In order to support and implement the multilingualism policy of the European Union, it is advised for non-native students to acquire a basic level of proficiency in the Polish/German language (A1, according to C.E.F.R.) before the end of the joint semester of study held in Gdańsk/Bremen, respectively. In order to implement this recommendation, language courses are offered to students.

2.6. Financing

The first run of the EMSS program was supposed to be financed from a KATAMARAN grant awarded to the partners by Polish National Agency for Academic Exchange. Unfortunately, due to COVID-19 pandemic, and other related issues, it was impossible to make use of these funds. Nevertheless, HSB and Gdańsk Tech decided to run the program despite the lack of additional funds. Both universities will apply for national and international, e.g. DAAD or Erasmus Mundus funds, to support the realization of the program in the future.

Students participating in the EMSS program, though enrolled at both institutions, pay tuition fees, and any other fees but HSB semester contribution, to their Home University only. They are also required to cover any personal expenses incurred by them during the exchange period, including travelling and lodging. Their international mobility is supported by the Erasmus+ program funds. Within the frame of this program, Home University of the EMSS program is considered as the Sending Institution, and is responsible for the financing of the Erasmus+ mobility of that student.

3. Discussion – the results of the first pilot run

3.1. Teachers' perspective

The first batch of students, consisting of 13 international participants of the EMSS program, has just started their 3rd semester of study, while 13 best candidates out of 47 applicants have been selected for the second pilot run.

At the end of the second semester at HSB a retrospective session was organized by Prof. Matevska. All the students, many lecturers and supporters of the study program participated actively. A very honest and open discussion took place and very valuable information considering the experiences on both sides could be collected.

As a summary, it can be stated that the first run of this international interdisciplinary study program was a great experience for all involved parties. This is the right direction and way to follow during the establishment and accreditation of the new joint study program. The very good availability, friendly communication, good team work and helpful lecturers / organizers were much appreciated. Also, the accompanying guest presentations held by experts from the space industry organized during the winter semester at HSB were a great opportunity to get an inside of the actual practical work.

Nevertheless, there is some improvement that can be done for the second run and considered for the new study program. For example, the better coordination of the contents of the first and the second part-module for the interdisciplinary project shall be achieved. Furthermore, the specialization of each single student shall be checked in more detail and if necessary, some additional specific modules shall be defined as mandatory, so everybody can follow the lectures in the best effective way.

3.2. Students' perspective

The offered program, with its designed learning outcomes spanning from engineering domain to management, soft skills and intercultural competences is very attractive for students choosing their master studies. Experience gained during the first pilot run of the EMSS project proves the real interdisciplinary character of the studies, what is very well backed not only by the offered subjects and study paths, but is also supported by very diverse background of students from their

DOI: 10.5821/conference-9788419184405.130

bachelor studies, what could be best observed utilized during the interdisciplinary project classes. As the pioneers of the pilot run, students were aware of possible imperfections of the implementation of that ambitious program, willingly sharing their remarks, ideas and conclusions during the retrospective session, to make future editions an even better experience. What was perceived by students among the best that they experienced during the program, was the work in a big interdisciplinary team on the research cubesat project and submitting it the ESA Fly Your Satellite! program, as well as the international experience of cooperation with people from different backgrounds and living abroad, which unfortunately was a bit limited due to the COVID pandemic. What could be developed in the future, would be the possibility of building a prototypes of developed designs. Finally, tThe studies are very demanding and time consuming, but students were aware of that upon matriculation.

3.3 Future plans

After a very intensive and successful first year of educational and organizational collaboration, HSB and Gdańsk Tech decided to further strengthen their partnership regarding the “Engineering and Management of Space Systems” (EMSS) program. A novel, joint interdisciplinary field of study at both institutions shall be established. The existing study paths on HSB side shall be combined under one main master’s degree EMSS including three different specializations according to the three already established paths. The final curriculum will be adapted accordingly. The accreditation of the new study program is planned for the year 2023 and will be performed on both universities in parallel following the accreditation and quality requirements of each country. The final result is subject to approval of the different boards and committees. The INCOSE certification will be the next step upon successful accreditation.

Students in the new field of study will be able to carry out many joint projects, including those organized by ESA Education.

4. Conclusions

The new international interdisciplinary study program of Engineering and Management of Space Systems is a very promising approach. It is strongly supported by both partner universities and by the local space industry partner companies.

The successful first run has shown, that the team is on the right way. Furthermore, the necessary improvements could be recognized so they will be considered for the second run and for the establishment the final new joint study program. We are happy to continue our cooperation work and very confident that it will result in a successful accreditation of the new study programme.

Acknowledgements

This program would not come into fruition if not the support of many academic and non-academic staff members of both universities, as well colleagues from the space industry namely:

HSB: Yana Yerofeyeva, Prof Antonio Garcia, Prof Lars Braubach, Prof Uwe Apel, Prof Friedrich Fleischmann, Prof Ludger Kempen, Christian Dierken, Prof Andreas Teufel, Prof Thomas Trittin, Dr. Anne Brümmer-Kock, Hagen Dix, Joachim Beyer, Prof Sören Peik, Prof Thorsten Teschke, Prof Uta Bohnebeck, Prof Volker Pälke, Prof Indulis Kalnins, Peter Feldbrügge, Birgit Averbeck, Hanno Feidicker, Jürgen Niemann

Gdańsk Tech: Prof Edmund Wittbrodt, Dr. Aleksandra Wiśniewska

Industry support:

Airbus (incl. Airbus Defence & Space): Maik Purrmann, Dr. Temenushka Manhtey, Hauke Ernst, Christina Jetzschmann

Ariane Group: Dr. Alexander Schwientek, Celen Nil

OHB: Dr. Anna Chrobry, Dr. Ferdi de Bruijn, Juan C. Bastante

DSI Aerospace Technologie: Dr. Marco Bacaro

The City of Bremen Space Coordinator: Siegfried Monser

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Space education activities at the Romanian Science Festival

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Abstract

Eastern European countries, in particular Romania, offer much fewer opportunities for science and space outreach and informal science education compared to the West. Romanian Science Festival was founded in 2018 with the aim of answering questions raised by the inquisitive minds of children all over Romania. In 2019, we reached over 20,000 people with our live events: open-air science festivals, space talks and astronomical observations. During the COVID-19 pandemic, we organised 58 live webinars of over 75 hours in total, one of the largest scientific resources in the Romanian language. Moreover, we visited 150 schools across the country, including rural areas, providing an opportunity for students to meet scientists online.

Space-related topics are a key focus of the science festival as they are not included in the Romanian school curriculum. That is why the resources in the form of the expertise and career orientation offered by our mentors are so valuable to the students. The topics we address include Astronomy (asteroids, black holes, extrasolar planets, etc.), Space Exploration, Satellite Design and Earth Observations. In 2021 and 2022 we organised the 'Space month' during which thousands of students had the opportunity to discover careers in space, participate in competitions, meet the only Romanian astronaut, Dumitru Prunariu, in celebrations of 40 years' of his space flight and a former NASA director of Astrophysics. Through mentorship, students discover opportunities to study and do research in astronomy. All these activities expose the public to the latest discoveries in the field, thus highlighting the importance of investing in fundamental research. This is just the beginning. The Romanian Science Festival story will continue because our team is determined to create a systemic impact in education. We will continue to add new chapters, stimulating the curiosity and imagination of people fascinated by science and space.

Keywords

astronomy, space education, science festival, webinars, meet-a-scientist

1. Introduction

With the mission to inspire, encourage and challenge children and people of all ages and from all walks of life to get to know and understand the world surrounding us, the Romanian Science Festival (RSF) team aims to provide an engaging platform for bringing together science enthusiasts. Drawing on two similar initiatives, RSF was established in the city of Timișoara, Romania, in 2018.

As part of the brain drain phenomenon, the last two decades have seen a massive emigration of young motivated Romanian scientists to the West. The RSF's main objective is to build bridges between the expertise within the Romanian diaspora and the educational system at home. For this purpose, RSF has a growing community of over 100 'mentors'[4], from the academic diaspora who interact directly with students. The mentors are researchers from top universities from all over the world: USA (MIT, Harvard, Chicago, etc), the UK (Oxford, Cambridge, Imperial Collage, Manchester, etc), the Netherlands, Switzerland, Sweden, Germany, Australia etc. RSF mentors have been involved in STEM outreach programs in the universities they have attended, so they already have experience in presenting science according to various levels of understanding.

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RSF also cultivates partnerships with local organisations, clubs, and educational institutions and develops new initiatives, workshops, and national projects to benefit STEM academic curriculum development.

Initially established as a two-day event focusing on an open-air science festival, RSF was faced with the impossibility of organizing the event in 2020 due to the pandemic. However, the new social context opened the door to new online initiatives which aimed to support online teaching and learning.

The main goals of RSF are:

(a) to offer high school students career models in the STEM fields

(b) to build links between the academic diaspora and the Romanian education system

(c) to build a platform where different STEM projects can display their portfolio

(d) to encourage lifelong learning

(e) to develop skills such as creativity and critical thinking which are needed in STEM but rarely taught

(f) to promote accessibility and inclusion in science by targeting traditionally underrepresented communities.

Space is a key focus of the RSF. It is a popular field, not included in the Romanian school curriculum, that is why the resources in form of the expertise and career orientation offered by our mentors are so valuable to students. Through mentorship, students discover opportunities to study and do research, while the public is fascinated by the latest discoveries in astronomy and space science and learn about the importance of investing in fundamental research. In the next section we describe in detail the activities of the science festival over the last three years.

2. Activities

2.1. Open-air science festival

The first and foremost activity of RSF is the open-air festival, organised in different cities of Romania. In 2019 we organised three such events, in the cities of Timisoara[5], Baia Mare[6] and Pitesti[7] (see Figure 1 for images from these events). The open-air science festivals attracted 20,000 members of the public and involved 450 volunteers (school students, university students, researchers, professionals) showcasing science experiments to the public. The idea behind the open-air festival was to make science accessible, fun and enjoyable. Each festival had a dedicated space component consisting of (1) an astronomy stand, (2) solar observations, (3) telescopes for demonstration, (4) astronomy showcases (such as the gravity tablecloth experiment) and (5) Space Talks[8]. We partnered with local astronomy societies, planetaria and ESERO-Romania who joined our events as demonstrators and provided educational materials to the public. In 2020, because of the COVID-19 pandemic, we had to interrupt the in-person events and the activity of the RSF moved fully online.

Figure 1. Open-air science festivals in 2019 in Timișoara (*top left*), Pitești (*top right*) and Baia Mare (*bottom right*). Paxi with the astronomy educational materials that were handed out to the public (*bottom left*).

2.2. Science webinars

The pandemic proved to be an excellent opportunity for the RSF for online activities. Since the majority of the RSF scientific community lives in the diaspora, the online presence allowed us to have a wider reach in

[5] Timișoara Science Festival
[6] Baia Mare Science Festival 2019
[7] Pitesti Science Festival 2019

[8] https://spacetalks.net/event/exoplanets-artificial-intelligence-and-citizen-science/

DOI: 10.5821/conference-9788419184405.131

the country and to connect scientists to students across Romania, including in remote areas. In partnership with British Council Romania, in April 2020 we launched a series of weekly science webinars, live on the Facebook page of the festival[9]. Through these live online events, the scientists from the RSF community were able to present their field and science to a broad public, including teens and adults.

To date, 64 RSF mentors presented 58 live webinars, totalling over 75 hours of scientific content aimed at Romanian secondary schools. We promote the classical STEM disciplines such as Maths, Chemistry, Physics, Geography and Biology, as well as 'new' sciences which are not part of the Romanian school curriculum, but which are very much in trend globally, such as: Astronomy, Space Science and Exploration, Artificial Intelligence, Neuroscience, Earth Observation etc. Hence, we are encouraging the students to look beyond the classical approach to sciences, challenge them to keep pace with the current research and scientific discoveries, and be interested in science content which is relevant for tomorrow's world.

So far, there were 13 webinars on Space topics such as Solar System objects, Black Holes, Extrasolar Planets, our Galaxy, Pulsars, Mars Exploration, Building Cubesats, Planetary Habitability and Earth Observation. A list of our space webinars and speakers is below:

- Sandor Kruk (ESA, Netherlands) - "Three astronomical hypotheses for the end of the world"
- Aurora Simionescu (SRON, Netherlands) - "An expedition to the edge of a black hole"
- Cristian Ignat (UCL, UK) - "The hunt for exoplanets"
- Paula Gherghinescu (University of Surrey, UK) - "Galactic archaeology: stars as cosmic fossils"
- Alexandra Bonta (University of Manchester, UK) - "Pulsars: the chronometers of the Universe"
- Cristian Lazăr (Airbus, Germany) - "Space exploration: from ExoMars to SpaceX"
- Adrian Dumitrescu (University of Southampton, UK) - "The history of miniaturisation of satellites"
- Cristina Vrînceanu (University of Nottingham, UK) - "A journey through Earth's geosystems"
- Cătălina Mirițescu (Imperial College London, UK) - "Habitability in the Solar System"
- Alina Vizireanu (SGAC, UK) - "The role of geographic informational systems in the society"
- Marcel Popescu (Astronomical Institute of the Romanian Academy) - "To asteroids"
- Ioana Ciucă (Australian National University) – "Galactic Archaeology: A great journey through our Galaxy"
- Norbert Zicher (University of Oxford, UK): "What are exoplanets?"

The webinars were advertised on social media (see some of the advertisements in Figure 2) and have totalled over 100,000 views on Facebook, LinkedIn and Youtube. The entire content is freely available on the RSF Youtube[10] page and the webinar archive is probably the largest resource featuring scientific content presented by various experts in the Romanian language.

Figure 2. Examples of RSF live science webinars on space: Cristian Lazar (Airbus), Aurora Simionescu (SRON), Sandor Kruk (ESA).

[9] https://www.facebook.com/RomanianScience Festival

[10] https://youtube.com/playlist?list=PLtTu_O-DejhE7CpXU6hpDtzbOc1RTBUfk

2.3. Online school visits

The period of the COVID-19 pandemic has been a challenge for both teachers and students. In April 2020, we launched a new Romanian Science Festival programme - ***Invite a RSF mentor to your online class***. Inspired by the highly successful Skype-a-Scientist[11] project, we aimed at connecting scientists from the Romanian diaspora with schools in Romania. Through this programme, the scientists had the opportunity to share their passion for science and space with children and students from the country. They also discussed about their career paths in science. The teachers could sign up via Google Forms and we paired them with scientists from the RSF community. In total, we visited 150 schools online, approximately half of them being from rural communities (see in Figure 3 a map of Romania with the locations of the schools visited). Through this activity, we reached over 2000 students from all over the country.

In Romania, half of the students study in rural settings. These have fewer opportunities to expand their knowledge horizons through extra-curricular science activities.[12] Hence, many children from underprivileged backgrounds, who otherwise would not have had such an opportunity, listened to and interacted with scientists for the first time.

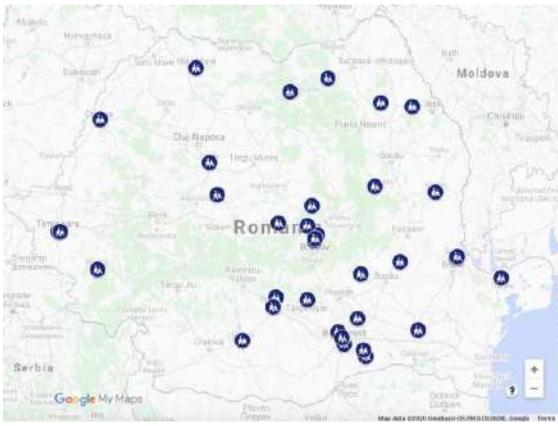

Figure 3. The location of the schools where our mentors visited online classes, during the first round of the programme.

2.4. Space Month

Using a unique moment as a window of opportunity, we organised the "Space Month at RSF" in April-May 2021. This campaign launched on the 12th April 2021, celebrating 60 years of the first man in space, Cosmonaut Yury Gagarin, and ended on 14th May 2021 with the celebration of 40 years since the first and only Romanian Cosmonaut, Dumitru Prunariu, flew in space.

During this campaign, the RSF team enabled space exploration lectures and creativity sessions for children from primary and secondary schools. 100 children were able to interact and ask questions live to Dumitru Prunariu[13]. Additionally, we created new partnerships that allowed children from Romania to participate in international creative sessions as part of the Projects Kids to Mars (InnovaSpace, UK) and Project Beyond (Space for Art Foundation, US). As part of Project Beyond, we organised a space drawing competition whose winner's, Alesia Ardelean's painting was displayed together with paintings from other countries on a spacesuit at the UN Climate Change Conference (COP26) in Glasgow.

Figure 4. The Romanian winner of the Beyond project, Alesia Ardelean, and her drawing that was displayed on the astronaut suit by the Space for Art Foundation[14].

[11] https://www.skypeascientist.com/
[12] https://worldvision.ro/wp-content/uploads/2020/11/Raport-de-Bunastare-a-Copilului-din-Mediul-Rural-2020.pdf
[13] Recording: https://youtu.be/n46EWpq_Pb0
[14] https://www.spaceforartfoundation.org/space suit-art-project

Figure 5. The programme of 'Space Month' 2022.

During April 2022 we once again organised the 'Space Month' at RSF. This time, we planned for a series of three webinars on Earth and Space and one panel discussion with five guests on the topic of 'Astronomy as a hobby' (see Figure 5). As a special event to celebrate the 32nd anniversary of the launch of the Hubble Space Telescope, we invited Dr Charlie Pellerin, former director of NASA Astrophysics, to tell our audience about building and repairing Hubble, as well as how NASA builds teams. Finally, we organised an engaging essay competition with prizes on the topic of 'space travel' for middle school students.

2.5. Plans for 2022

As the pandemic slowly goes into the endemic phase, we plan to return to in-person events. In 2022, we have partnered with the Romanian American Foundation and are planning for three new open-air science festivals in Romania. These will be complemented by 'science caravans', with mentors visiting schools in remote communities, where they make science presentations, talk to children about a career in science, interact with the teachers.

Additionally, we have partnered with the Romanian Space Initiative (ROSPIN) to organise the ROSPIN School[15], the first space school project, asking students in teams to design a Lunar Rover. Owing to the success of the online activities, we will continue to deliver high quality webinars and to visit online classrooms.

3. Discussion

RSF is the first national science festival in Romania. Through various initiatives, we aim to inspire, encourage and challenge children of all ages and from any social background to explore and understand the world around them from a scientific perspective.

Sciences are taught in Romania in a theoretical way. This has two immediate consequences. Firstly, it limits the student's level of understanding of the applicability of science. Science surrounds us and is part of our daily lives. While a theoretical way is focused on information delivery, an interactive way to experience science helps children understand its ubiquity in everyday life. Secondly, a theoretical approach triggers a student's negative attitude towards sciences. Therefore, the vast majority of students find sciences to be difficult disciplines, hard to understand and not very appealing. In the long term, this has an impact on the careers the students choose.

At RSF, we aim to reverse this trend of 'running away from science'. In our four-year experience we have noticed that students' relationship with sciences lacks two main elements. The students lack both role models and opportunities to discover various STEM disciplines. RSF aims to address these two needs. Through various initiatives, we aim to create opportunities for students to discover science in a new way, to challenge them to understand science beyond the theoretical framework, to encourage them to be inquisitive and creative and express themselves through science, to guide them in their endeavour to pursue a scientific career.

4. Conclusions

This is just the beginning of our knowledge exploration. Space education is just one exploratory mission from a series of diverse initiatives. The Romanian Science Festival story will continue to expand the knowledge horizons of children by launching new STEM initiatives, because our team is determined to create a systemic impact in education. We will continue to add new chapters, stimulating the curiosity and imagination of people fascinated by science and space.

Acknowledgements

We acknowledge funding and support from the Romanian-American Foundation, from the Fundatia Comunitară Timișoara and from numerous private and public entities that made our live events possible. We also acknowledge the tremendous work of 450 volunteers in the events of the science festival.

[15]https://rospin.org/rospin-school/

A 3-axis Stabilisation Platform to Improve Experiment Conditions in Parabolic Flights

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Abstract

There are different ways of providing free-fall conditions on Earth in order to test a component, perform an experiment or demonstrate equipment before it can be included in a space mission. One of these options is a parabolic flight: briefly, the aircraft flies on a parabolic trajectory with the on-board payload experiencing several seconds of weightlessness. These flights have been performed since the 1950s to simulate space conditions for experiments as well as astronaut training.

The project objective is to develop a cubical platform to perform 3-axis attitude stabilisation for experiments during the microgravity phase of a parabolic flight. The goal is to stabilise the platform and thus reduce perturbations and vibrations that diminish the quality of the microgravity achieved. To do so the attitude control system, composed of three reaction wheels in orthogonal configuration, will counterbalance the disturbances measured by the attitude determination system, an inertial measurement unit. The platform will be tested using a small aircraft in a self-organised flight campaign.

Comprising nine students, this project is currently in the preliminary design phase. However, the prototyping and testing of the platform structure has already been initiated using a small-scale design and several hardware components have been ordered. The platform will be printed using additive manufacturing due to the numerous benefits of this process. The component integration is expected to be completed in time in order to facilitate the laboratory testing of the various subsystems before the flight campaign in May 2022. After the flight campaign, the collected data will be analysed, processed and published to ensure that it is accessible to the scientific community.

Keywords
Attitude control, microgravity, parabolic flight, reaction wheel, student experiment

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Acronyms/Abbreviations

ACS	*Attitude Control System*
ADCS	*Attitude Determination and Control System*
ADS	*Attitude Determination System*
ASTER	*Attitude STabilized free falling ExpeRiment*
CAD	*Computer Aided Design*
DLR	*Deutsches Zentrum für Luft- und Raumfahrt (aka. German Aerospace Center)*
ESA	*European Space Agency*
EPS	*Electrical Power System*
FASTER	*Flying Attitude Stabilized ExpeRiment*
FFU	*Free Falling Unit*
IMU	*Inertial Measurement Unit*
LTU	*Luleå University of Technology*
NASA	*National Aeronautic and Space Agency*
OBC	*On-Board Computer*
OBDH	*On-Board Data Handling*
PCB	*Printed Circuit Board*
PDU	*Power Distribution Unit*
PL	*Payload*
UAV	*Unmanned Aerial Vehicles*
REXUS/BEXUS	*Rocket/Balloon EXperiment for University Students*
SED	*Student Experiment Documentation*
SD	*Secure Digital*
SPI	*Serial Peripheral Interface*
SNSA	*Swedish National Space Agency*

1. Introduction

Verification and testing of a component or experiment that is going to operate in space is a vital step during the development phase. For that reason, several methods of simulating space conditions on Earth have been employed during the last century, including thermal vacuum chambers and different ways of reaching free-fall conditions on Earth.

During the second half of the 20th century, parabolic flights became a rather popular and easy way of testing space components and training astronauts before space flights. However, such flight campaigns organised by the European Space Agency (ESA) or the National Aeronautic and Space Agency (NASA) use large aircraft[1]. In recent years, there has been an increasing interest in performing this kind of flights with smaller jets, single engine aircrafts, gliders or Unmanned Aerial Vehicles (UAVs) [2]. Using these platforms, the access to microgravity becomes easier and the preparations and precautions that need to be taken, such for example the closure of the air space, are simpler.

There are, however, some disadvantages such as the quality of the microgravity achieved is not as good as on a large aircraft, the vibrations and external noises appear while performing the parabolic trajectory and the microgravity time achieved by the aircraft is shorter.

Team Flying Attitude STabilized ExpeRiment (FASTER) is developing a platform to operate in a fully autonomous way during parabolic flights using light planes or UAVs. The experiment aims to prove that these disadvantages can be overcome by using a 3-axis stabilisation system using reaction wheels, in a similar way as satellites perform attitude control manoeuvres but on a shorter time scale. The project objectives are as follows:

Primary objectives:

- build an attitude stabilisation platform for parabolic flights,
- validate that Attitude Control System (ACS) reaction wheels can be used for manoeuvring the platform during the microgravity phase of the flight,

DOI: 10.5821/conference-9788419184405.132

- verify that the ACS improves the microgravity conditions of the payload during the flight.

Secondary objectives:

- demonstrate that the ACS can reduce vibrations and perturbations caused by the aircraft,
- design for future adaptability of the system to parabolic flights using a small aircraft.

The team will consider that the experiment has been successful if the primary objectives are proven and a total success if both primary and secondary objectives are reached.

The student experiment is an adaptation of project Attitude STabilized free falling ExpeRiment (ASTER) [3], an experiment to improve the microgravity conditions of payloads during the free-falling phase of a Free Falling Unit (FFU) ejected from sounding rockets, which has been part of the 30th student Rocket/Balloon EXperiment for University Students (REXUS/BEXUS) campaign organised by the Deutsches Zentrum für Luft- und Raumfahrt (aka. German Aerospace Center) (DLR) and the Swedish National Space Agency (SNSA) and the experiment was designed and developed by Luleå University of Technology (LTU) students, which settled the base for a multi-application platform that could be adapted for other types of microgravity setups such as parabolic flights, centrifuges or drop towers.

Project FASTER was founded in September 2020 at LTU, and during its first year the design and adaptation phase was performed, which was finalised with the publication of a Student Experiment Documentation (SED) reviewed by the supervisors from LTU. During Spring 2022, the team will integrate and test all the components of the experiment aiming to test the platform during Summer 2022 in a self-organised parabolic flight campaign in Kiruna, Sweden. This flight campaign is being organised together with one of the LTU supervisors, Mr.Olle Persson, who will act as pilot of the light Cessna that will perform the parabolic trajectories.

Since the goal of the project is to make parabolic flights more accessible to all parties involved in the space industry, the project will be made publicly available. This will be done by publishing the source code under a free software licence and publishing all the design files for the hardware.

2. Overview of the platform

In the following section a brief description of the platform will be presented following the department structure in which the team has been working.

2.1 Mechanical design

The design has been done using Solidworks software. The platform dimensions are 205 mm x 205 mm x 205 mm, and the total mass of the structure is estimated to be 2.0 kg.

As shown in Figure 1, the platform main structure consists of glass fibre reinforced composite panels assembled into a cube. Three of the panels carry the reaction wheel setup, with the motors placed outside the platform to enable extra space for payload. Two of the panels will carry the batteries and one panel will carry the Printed Circuit Board (PCB) and Power Distribution Unit (PDU). The structure is designed to distribute the stresses and vibrations that the platform is subjected to during the operation both from external sources and from the ACS. The structure is constructed to be lightweight and have high structural strength that meets the structural requirements of the project.

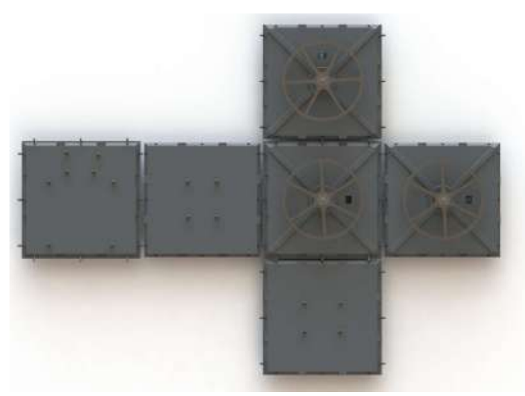

Figure 1: Computer Aided Design (CAD) design of the platform plates with the reaction wheels

DOI: 10.5821/conference-9788419184405.132

Additive manufacturing has become popular in the aerospace industry as a result of the rapid advancements in the technique and in the development of low cost computer aided design programs. It offers unique design solutions, lightweight components and reductions in cost and lead-time.

This manufacturing method is beneficial for FASTER for many reasons. Since the structure is only manufactured in a small quantity, the method is very cost efficient as it does not require special tools or moulds. The method also enables more prototyping, which gives valuable design feedback and helps finding issues in the design early in the process.

As FASTER is intended to benefit many different payloads, additive manufacturing also enables the cheap and fast adaptation of the platform to a new payload.

2.2 Attitude Determination and Control System (ADCS) design

The main objective of the ADCS is to stabilise the platform during the different microgravity phases of the parabolas. This is achieved by using a feedback control system that determines system rotations and actuates the reaction control wheels with electric motors.

The Attitude Determination System (ADS) comprises an off-the-shelf Inertial Measurement Unit (IMU) originally developed for usage with Arduino development boards. It uses a Bosch BNO055 chip which has a 3-axis accelerometer, a gyroscope and a magnetometer.

The ACS comprising three reaction wheels will perform manoeuvres and store or apply momentum to the platform in order to control the attitude during parabolas.

The reaction wheel setup consists of a 60 W brushless motor, a rotor made out of machined stainless steel, a mounting bracket and an adapter for the motor shaft. Manoeuvrability, manoeuvre time and size constraints were the primary parameters in determining the design of the reaction wheels.

An exploded view of the reaction wheel is presented in Figure 2.

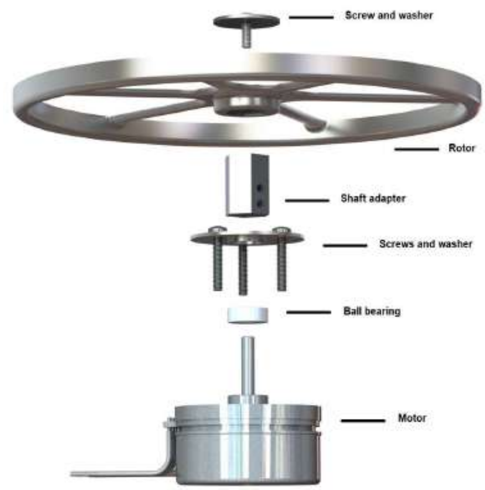

Figure 2: Exploded view of the reaction wheel setup

2.3 Electrical design

The electrical design of this project consists of four different subsystems, namely, the On-Board Data Handling (OBDH), Electrical Power System (EPS), ADCS and Payload (PL) and is implemented on two in-house PCBs. The Main PCB is responsible for the control and operation of the subsystems, motor controllers, IMUs and data storage. The PDU PCB is responsible for the regulation and power distribution of all the subsystems present on the Main PCB.

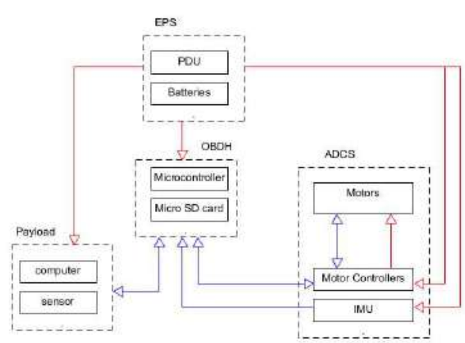

Figure 3: Block diagram of the electrical design

Figure 3 shows the interaction between the different subsystems. The power rails are coloured red and the data paths are in blue.

Each subsystem has a clear set of objectives to make the system work and, altogether, reach the objective of the platform.

The OBDH is the brain of the system. It reads all the sensor data and receives the output signalling and power to ensure proper operation of the system. On the data side, all the data that the microcontroller reads and generates will be directly saved into the double (redundant) micro Secure Digital (SD) cards, via Serial Peripheral Interface (SPI).

The ADCS subsystem is in-charge of the stabilisation of the platform during the parabolas. It determines the orientation via the 9-axis IMU and calculates the new set of speeds for the motors to spin. These speeds are translated to power via the MAXON controllers to the MAXON motors. This subsystem is the most power hungry and one of the reasons why there is a dedicated EPS.

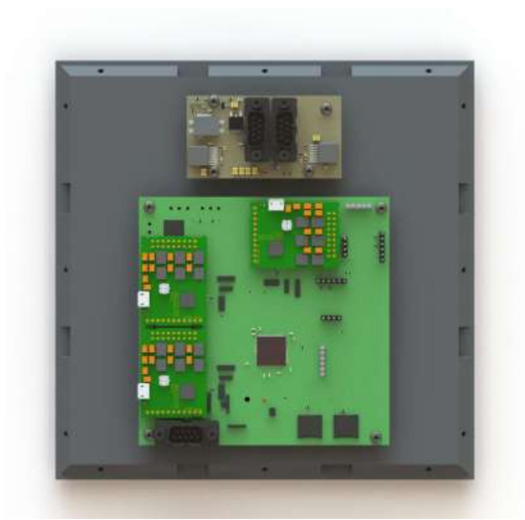

Figure 4: CAD design of the platform with the PCB and PDU

The EPS is the conjunction of the PDU and batteries that store the energy for the instrument during the complete operations. This subsystem will use six Lithium-ion batteries (18650 type) in series, with a voltage of 3.6 V each allowing a total voltage of 21.6 V. The PDU is converting the original battery voltage to all the rails needed on the different subsystems -3.3 V and 5 V. Additionally, it also contains the possibility to switch off and on any of the rails from the On-Board Computer (OBC).

Finally, the PL subsystem is designed in a way that will be able to fit many different kinds of possible experiments. For the first flight, another IMU is designed to be the payload in order to test that both IMU provide the same accuracy in the data and calibrate the one that is on the platform.

2.4 Software design

The platform has been designed to operate on a fully-autonomous basis during the flight so that the flight operator will only switch on the experiment and make sure that the safety requirements are fulfilled. The software team has developed an algorithm in which the platform will ensure nominal operations during the whole duration of the flight. On top of the autonomous operation, a wireless communication system between the platform and the computer of the flight operator has been developed to enable the retrieval of real time data and to send telecommands. In addition, the team has performed simulations and calculations to ensure that the ACS will perform as expected during the flight campaign; these calculations will be used during the post-flight analysis of the data to see how accurate the experiment has operated.

The platform will then operate using the main OBC and will perform the stabilisation manoeuvres according to the gravity conditions that the aircraft encounters. For that reason, a process flow consisting of five main states has been defined:

- INIT: initialization after the platform is switched on
- IDLE: state between two parabolas
- HIGH GRAVITY 1: first part of the parabola (entering) with spin up of the reaction wheels
- MICROGRAVITY: second (top) part of the parabola with the ADS on

DOI: 10.5821/conference-9788419184405.132

- HIGH GRAVITY 2: last part (exit) of the parabola with a steady shutdown of the reaction wheels

The flow state diagram is presented in Figure 5, showing the nominal phases of the software during the flight.

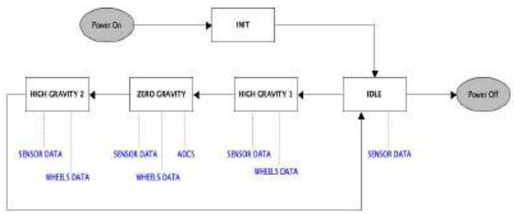

Figure 5: Flow chart of the different software states during a nominal flight

3. Discussion

Although parabolic flights are an exceptional tool to develop and test various technologies, there are certain limitations such as high cost, disturbing vibrations etc. There is also a decreased stability of microgravity conditions and in order to improve this, a platform that can control its attitude and reduce the external vibrations could make parabolic flights ideal for many experiments. In FASTER, such a platform has been designed and will be printed by using additive manufacturing technology. The wide range of benefits offered by additive manufacturing ranging from customisation, energy savings, accelerated prototyping, material waste reduction etc., makes it a desirable choice.

On the other hand, there are challenges that arise as a student project such as high production costs, restricted access to printing facilities and limited types of materials that can be processed with additive manufacturing. The technical support from the project sponsors in the additive manufacturing industry has enabled FASTER to benefit and also improve the design of the platform.

4. Conclusion

The rapid developments and advancement of technologies in the space industry as well as space-associated industries have been a great motivation for student projects. In FASTER, the platform developed using additive manufacturing processes accounts for the incorporation of latest technologies in student projects with industry support. The success of this project will highlight the collaborative effort of a team of motivated space students, guidance from university and support from the industries with advanced technologies. It will also benefit future space experiments in microgravity and motivate students to come up with innovative project ideas thereby contributing to the growth of the space industry.

Acknowledgements

We would like to thank our supervisors, the university and our sponsors for their support in the development of this project. We would also like to thank SNSA for providing us with a scholarship for SSEA 2022.

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Selection Criteria for Parachutes of Student-Built Sounding Rockets

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Abstract

Various parachute-type decelerators can be considered in the design of a sounding rocket recovery system. During the development of various flagship missions of Delft Aerospace Rocket Engineering (DARE), the Parachute Research Group of DARE has developed several methods and criteria to select the right parachutes for a given mission. This paper presents and discusses the operational envelopes, advantages, and disadvantages of different parachute types. The parachutes described in the paper are variations of cross parachutes, disk-gap-bands, ringsails, conical ribbon parachutes, and hemisflo ribbon parachutes. Variants of these parachute types have previously been developed in-house and flown, allowing for acquaintance with their design, manufacturing and performance. Apart from the more traditional parachutes used for student-built sounding rockets, this paper will also cover the opportunities and challenges that are associated with the use of less conventional parachutes, such as ringsails, ringslots, and parafoils. Each parachute is described in detail after which all are compared to one another based on several sets of typical requirements. Factors that influence the parachute selection process are, for example, the parachute flight envelope, stability behaviour, and manufacturing complexity.

Keywords

Parachute selection, recovery system design, sounding rocket

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Nomenclature

C_d	*Drag coefficient*
A	*Nominal area*
D_0	*Nominal diameter*
C_d*A	*Drag area*

Acronyms/Abbreviations

DARE	*Delft Aerospace Rocket Engineering*
PRG	*Parachute Research Group*
DGB	*Disk-Gap-Band parachute*
AR	*Aspect Ratio*
R&D	*Research and Development*

1. Introduction

Throughout the history of the parachute, many different types have been designed and flown. They all have different strengths and weaknesses, and one must be selected carefully for each specific application. A lot has been written about the characteristics of the many types of parachutes, but little literature exists that focuses on their use in student rocketry. As such, this paper aims to shed light on the selection process for the most suitable types of parachutes for student sounding rockets. As each mission is different, and no single parachute is suitable for every single mission, there is no definitive answer as to what the 'best' parachute is. General guidelines and criteria on performing a tradeoff to select one for a specific mission are instead highlighted.

2. Needs and requirements

In general, the main parachute should safely recover the rocket or payload. This is generally defined as a landing velocity for which the kinetic energy is low enough for landing. This sets the drag area of the parachute. It is up to the team to discover and specify requirements, however, some requirements, such as landing velocity are frequently found. Other common requirements are the maximum loading on the system and the maximum inflation conditions. It is therefore very important for the parachute engineer and systems engineer of the mission to discuss and discover all aspects of the flight.

Other requirements such as the inflation conditions of the parachute influence the possible need for an additional decelerator, for example, a drogue parachute.

Besides these requirements, there are potential requirements imposed by a launch site or mission regarding the flight time and ground range. Small and narrow landing zones might require a later parachute deployment or steerable parachute, resulting in smaller wind drift. Alternatively, when measurements are performed during the parachute phase, it might be that a minimum flight time is needed to ensure there is sufficient time for the experiment. Other requirements that originate from the payload include the maximum allowed oscillations during flight.

Besides requirements from flight, inflation and landing conditions, there might be restrictions when it comes to manufacturing and materials, as some parachutes are easier to manufacture than others.

3. Parachute types

This section provides an overview of what types of parachutes exist and are commonly used. A brief explanation of each type and its characteristics is provided. Moreover, their constructed profiles are illustrated in Figure 1.

3.1. Solid parachutes

Solid parachutes often consist of multiple sheets of fabric sewn together without many gaps or fabric discontinuities. A central vent hole is often the sole source of geometric porosity for these types of parachutes. The low porosity and poor porosity distribution make these parachutes less attractive for supersonic applications, compared to ribbon parachutes.

3.1.1. Cruciform

Cruciform parachutes are, as the name implies, cross-shaped and have been a very popular choice for subsonic recovery systems. Because of their ease of manufacturing, they are often used for amateur or student launched rockets. They have average drag coefficients around 0.7 and also experience average to poor stability during flight. There are many variations to cruciform parachutes possible - such as changing the aspect ratio (AR) of the parachute or making connections between the corners/sides of the cross shape to create a box parachute.

Cruciform parachutes have proven to exhibit unfavourable behaviour at supersonic speeds, and are thus best used as landing parachutes at low speeds [1].

3.1.2. Circular

A circular parachute's gore shape can be chosen such that the shape of the parachute is flat, conical, hemispherical, or a different profile. These parachutes are fairly easy to manufacture and have fairly high drag coefficients often ranging from 0.7 to 0.9. However, they suffer from significant oscillatory instabilities and large opening loads up to 2 times the steady state load. These types of parachutes are also not suited for supersonic flight. They are seldom used for space applications, because of their poor stability and inflation behaviour.

3.1.3. Disk-Gap-Band

Disk-Gap-Band (DGB) parachutes consist of a flat circular disk and a cylindrical band, separated by a gap. The gap and the vent hole in the disk give this parachute a significant geometrical porosity, which contributes to the parachute operating at supersonic conditions.

The DGB has proven to be reliable as a drogue and main parachute in both sub- and supersonic conditions. The ease of manufacturing a DGB parachute has also made it an excellent candidate for amateur and student rocket recovery systems. Although it has a wide operating Mach envelope, it has moderate stability and a low to moderate drag coefficient close to 0.5.

3.1.4. Annular

Annular parachutes have the shape of a half-torus, with their suspension lines attached to both the outer perimeter and the vent hole. These parachutes have higher than average drag coefficients, ranging from 0.9 to 1.0, exhibit moderate stability and show opening loads close to 1.4. Their flight envelope is, however, limited to subsonic regimes.

Annular parachutes have become very popular for military, recreational and other non-space related applications, however, have only been used very rarely for space missions.

3.1.5. Guide-surface

Guide-surfaces are parachutes that are constructed with a rounded crown and an inverted conical surface - running from the apex to the skirt. Ribs are additionally used to maintain their characteristic shape. These parachutes are known for their excellent stability behaviour, however, typically have very low drag coefficients in the order of 0.3 to 0.4. Hence these tend to be relatively heavy compared to the other solid parachutes, to achieve the same drag. The inflation behaviour of guide surfaces, especially ribbed guide-surfaces, is generally favourable with opening load factors as low as 1.1.

In past missions, these have primarily been relatively small, in the order of 1 metre diameter, and were used as stabilisers, pilot chutes, or main parachutes for small spacecraft. The fact that guide-surface parachutes are difficult to produce and used in subsonic conditions, makes them less advantageous compared to other parachutes, except when stability is of utmost importance to the mission.

3.1.6. Asymmetric drag parachutes

Asymmetric drag parachutes are a subset of the solid parachute on which asymmetric vent holes are placed. This allows for air to escape the canopy, creating a thrust-like force. The gliding can be controlled, allowing for control over the landing location. In general, the glide ratio of these parachutes is 0.5 to 0.7 and the aerodynamic coefficient is 0.85 to 0.9, which describes the resulting aerodynamic force on the canopy.

3.2. Slotted parachutes

As discussed in the previous section, solid parachutes are usually designed without many gaps. Slotted parachutes, conversely, consist of multiple individual or ring segments with gaps so that the geometric porosities lie in the 10 to 35% range. The first slotted parachute design was the flat ribbon parachute, after which the conical ribbon parachute was designed [2]. Furthermore, in order to reduce the cost of the parachute, the ringslot parachute design was introduced. Further improvement of the design resulted in the ringsail parachute.

3.2.1. Ribbon

There are a few different types of ribbon parachutes, including the flat ribbon parachute, the conical ribbon parachute, the hemisflo ribbon parachute and the variable porosity ribbon parachute.

Flat ribbons are circular and consist of concentric ribbons supported by smaller horizontally spaced tapes and radial ribbons at gore edges. The ribbons and tapes are accurately spaced to provide the desired ratio of open space to the solid fabric over the entire canopy. Gores are triangular and dimensions are determined in the same manner as for the solid flat circular parachute. The flat circular ribbon parachute has a lower drag per unit surface area than its solid-cloth analogue, but its stability is excellent and maximum opening force is low in comparison. The canopy is relatively slow in opening and its performance reliability depends on specific design parameters. Compared to solid cloth hemisflo parachutes, the flat circular ribbon canopy is more difficult to manufacture.

DOI: 10.5821/conference-9788419184405.133

The constructed shape of the conical ribbon canopy is similar to solid cloth conical parachutes. These show higher drag than the flat circular ribbon just as the solid cloth conical parachute does over the solid flat parachute of the equal construction area.

The canopy of a hemisflo ribbon is a spherical surface that continues a preset angle past the hemisphere at the skirt. The canopy design retains effective drag and stability performance over the range from Mach 1.5 to 2.5, although conical ribbon parachutes are as good or better at speeds below Mach 1.5. Hemisflo parachutes are used almost exclusively for drogue applications, which require stabilisation and deceleration at supersonic speeds. The hemispherical profile makes for reduced breathing and reduced high-frequency flutter - both proponents of fatigue and drag reduction - but are more susceptible to canopy rotation.

The last type of ribbon parachute considered is the variable porosity ribbon parachute. This modification to ribbon parachute profiles involves a variation in geometric porosity from the vent to the skirt. The steady-state drag coefficient can be increased without a large loss of stability using this change, but the opening load factor also tends to see an increase.

3.2.2. Ringslot

In an attempt to reduce the cost of the ribbon parachute, the ringslot parachute was developed. It has similar aerodynamic characteristics, however, it has an increase in drag, most often 10 to 14%. Using multiple individual segments in the design of the ringslot parachute, the horizontal ribbons of the ribbon parachute are replaced. They are then sewn together to create concentric rings which are afterwards joined using radial tapes. Similarly to ribbon parachutes, the aerodynamic performance is controlled by the total porosity and the allowable increase in effective porosity.

3.2.3. Ringsail

Developed as an improvement over the ringslot, the ringsail consists of many small sails arranged in concentric rings, often with a slotted section near the crown for increased geometric porosity. It is an attractive choice due to its high drag coefficient at around 0.8 to 0.9, moderate to good stability and suitability for reefing [3]. It is also a relatively lightweight parachute for the amount of drag it produces, has gentle inflation characteristics and is commonly used on manned space flights. Major disadvantages of the ringsail are the fact that it is a very complex and time-consuming parachute to manufacture. There is also little literature available for ringsails in the size range that would be appropriate for most amateur and student rocket projects. For these reasons, it is rarely used for such applications.

3.3. Parafoils

Commonly used in skydiving, a parafoil is mainly characterised by its airfoil shape, giving it its lift generating capability. A parafoil is often composed of only three different parts: the intrados, the extrados, and a series of ribs. The intrados and extrados are two rectangular pieces of fabric making up the bottom and the top of the wing. In simple designs, the ribs can all be identical. Two main parameters affect the flight: the rib's profile, linked with both lift and drag, and the AR of the parafoil. The AR is defined by the ratio between the span of the parafoil and its chord, and this is the determining factor in parafoil design. A larger AR lowers the strength of the wing vortices and improves the lift to drag ratio of the parafoil, but deployment becomes more difficult. In most cases, parafoil deployment requires the use of a deployment bag and an extraction parachute. These are used to tension all the lines in the air shortly before the parafoil is deployed, reducing the risk of line entanglement.

Another important parameter in the choice of a parafoil design for a given flight mission is the nominal airspeed. The airspeed of a parafoil can only be adjusted in a very narrow range, in comparison to a fixed-wing aircraft with the ability to pitch down to trade potential energy for kinetic energy. A higher nominal airspeed allows the parafoil to keep a forward ground speed, even when flying against a strong headwind. Higher performance parafoil wings looking closer to paraglider wings can also be used in cases where flight performance (glide ratio) and controllability is needed. However, the deployment of such wings is currently considered harder. It's also important to keep in mind that choosing a steerable parachute will require a significant effort of R&D for the control mechanism and algorithm.

3.4. Rotating parachutes

Some parachute types generate more drag than others due to their shape and behaviours. One example is the rotafoil. This parachute consists of asymmetric vent holes placed in the canopy which means the parachute will start to rotate. Alternatively a vortex ring parachute can be used. This rotation creates a centrifugal force on the canopy and lines, increasing the projected diameter. These parachutes are often small, no more than about 3 metres D_0.

DOI: 10.5821/conference-9788419184405.133

4. Comparison of parachutes

In this section, the different types of parachutes will be compared.

First, one should determine whether a parachute should be steerable or not. Ballistic parachutes are not steerable and thus have larger landing areas. Guided parachutes can be steered to a final landing location. Guided parachutes can be divided into lift generating parachutes and asymmetric drag parachutes, with the difference being that a lift generating parachute can fly further and has more control over the landing location.

Within the category of ballistic parachutes, rotating parachutes can be distinguished. The other two categories are high and low dynamic pressure at deployment. The high dynamic pressure systems are usually slotted parachutes which modify the geometric porosity to ensure the parachute can survive inflation. Low dynamic pressure systems are usually solid cloth parachutes and can range from crosses to circulars to ellipsoidal parachutes.

A table with the typical values of parachute performance parameters is provided in Table 1. Gliding parachutes are instead presented in Table 2. These tables serve as the first reference during a preliminary design study to gauge which parachute types are feasible and how they compare to each other. One of these, the angle of oscillation, is a parameter often used in literature to gauge the stability of a parachute. However, the stability of small-scale parachutes can be affected greatly by the manufacturing errors that for example give rise to asymmetry. Additionally, the wake-effects of a body in front of the parachute will also affect its stability behaviour in flight. Furthermore, parachute stability can be improved by increasing the effective porosity of the canopy, with the penalty of a lower drag coefficient.

5. Conclusion

When selecting the main parachute for a particular mission, the first thing to consider is the required landing velocity, as this immediately fixes the drag area C_d*A regardless of the type of parachute that is chosen. The maximum allowable force that the structure can take is next, as this may exclude certain types of parachutes that generate high shock loads, such as the circular parachute, or require the use of an additional decelerator such as a drogue parachute prior to the deployment of the main parachute. Another factor that may introduce such a requirement is the Mach number at deployment. This Mach number depends on when the parachute is deployed, which in turn may depend on several factors such as the size of the landing area and the consequent limit on acceptable wind drift distance. In case a precise landing location is required, choosing a steerable parachute will likely be necessary. A last important point to consider is whether the complexity of the parachute is feasible within the available manufacturing capabilities. A final comparison of the various types of parachutes may be found in Tables 1 and 2.

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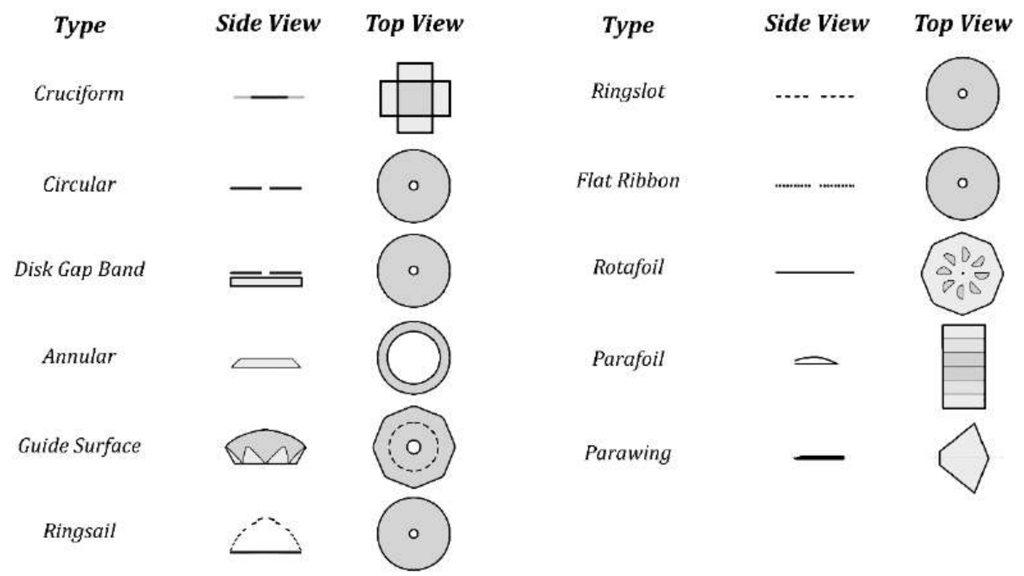

Figure 1: Constructed profiles of the different types of parachute geometries

Table 1: Typical values of performance parameters for different types of main parachutes [2,4,6,7,8]

Parachute type	C_d [-] subsonic	C_d [-] supersonic	Angle of oscillation [deg]	Shock load factor [-]	Manufacturing complexity	Supersonic capable
Cruciform	0.6 – 0.8	N/A	0 – 40	1.2	Very low	No
Circular	0.6 – 0.95	N/A	10 – 40	1.4 – 1.8	Very low	No
DGB	0.4 – 0.6	0.45 – 0.7	5 – 15	1.3	Low	Up to Mach 2.7
Annular	0.9 – 1.0	N/A	0 – 5	1.4	Low	No
Guide-surface	0.3 – 0.4	N/A	0 – 5	1.4	Low	Yes
Ringsail	0.75 – 1.0	N/A	5 – 20	1.1	High	Yes
Ringslot	0.55 – 0.65	N/A	0 – 5	1.05	High	Yes
Ribbon	0.45 – 0.65	0.25 – 0.6	0 – 3	1.0 – 1.3	Medium	Up to Mach 3
Rotafoil	0.8 – 1.0	N/A	0 – 5	1.05 – 1.1	Medium	No

Table 2: Typical values of performance parameters for different types of gliding main parachutes [4,5]

Parachute type	Glide ratio [-]
Asymmetric drag parachute	0.5 – 0.7
Low AR ram-air parafoil	2.5 – 3.5
High AR paraglider	5.0 – 13.0

Mechanical Design and Deployment of a Quasi-Rhombic Pyramid Drag Sail for Safe De-Orbit of a 3U CubeSat

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Abstract

Orbital debris is rapidly becoming a more prevalent and alarming obstacle that, without immediate intervention, will undoubtedly become disastrous for human activity in space. The University of Glasgow's microsatellite society, GU Orbit, has taken action to equip its 3U CubeSat ASTRAEUS-01 with a drag sail de-orbit device. This payload represents a simple and low-cost solution for the mitigation of debris in Low Earth Orbit (LEO) and is expected de-orbit the CubeSat within 12 to 24 months, depending on solar activity. These aspects are deemed fundamental for the mission and align with GU Orbit's ethics of promoting space sustainability and accessibility. As a student society, the aim of this research is to demonstrate the viability of a drag sail technology in the absence of large monetary investment.a

In this article, the studies on the structure, material and Hold-Down and Release Mechanism (HDRM) of the drag sail system are evaluated and briefly discussed. The discussion starts by illustrating the 7m² quasi-rhombic drag sail that will deploy to increase the satellite's atmospheric drag and allow the spacecraft to lose altitude and re-enter the atmosphere. Various aspects of the geometry and folding technique used to fit the drag sail on the CubeSat are analysed. Phenomena of material degradation such as thermal and oxygen degradation have been accounted for in the design to mitigate their effect over the duration of the mission. Tape spring booms coiled around a spool will release the drag sail from its folded state maintained throughout the mission. These have been dimensioned through a mathematical model in order to provide optimum deployment dynamics for the drag sail. The paper describes also how a simple and economic nichrome burn-wire HDRM has been integrated with the drag sail design to trigger the release sequence of the cover doors and the drag sail itself.

Keywords

GU Orbit, CubeSat, ASTRAEUS-01, drag sail, deployable, gossamer, space debris, LEO, student society, HDRM, sustainability

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Nomenclature

A	*Area*
r	*Radius*
B	*Base length*
L	*Length*
L_b	*Boom Length*
t	*Thickness*
α	*Apex half-angle*
β	*Subtended Angle*
R_T	*Transverse Radius of Curvature*
R_L	*Longitudinal Radius of Curvature*
R_e	*Reaction Efficiency*
Δm	*Mass loss*
ρ	*Density*
φ	*Incident Atomic Oxygen Flux*
t_E	*Exposure time*
A_E	*Exposed Surface Area*

Acronyms/Abbreviations

AO	*Atomic Oxygen*
CoM	*Centre of Mass*
CoP	*Centre of Pressure*
GPU	*Graphics Processing Unit*
HDRM	*Hold-Down and Release Mechanism*
IADC	*Inter-Agency Space Debris Coordination Committee*
LEO	*Low Earth Orbit*
PCB	*Printed Circuit Board*
QRP	*Quasi-Rhombic Pyramid*
UV	*Ultraviolet*

1. Introduction

ASTRAEUS-01 is a 3U CubeSat mission currently being developed by GU Orbit, a student society at the University of Glasgow. The objective of the four-year-long mission is to gather Earth surface data. The payload for Earth observation is composed of a camera and a Graphics Processing Unit (GPU), which utilises on-board processing as a novel method of optimising data processing and transmission to Earth. The operational altitude of the satellite will be between 500 and 600 km in a Low Earth Orbit (LEO).

The drag sail is a secondary payload that will be included on board ASTRAEUS-01. It consists of a deployable thin-film membrane whose purpose is to increase the satellite's atmospheric drag, allowing the spacecraft to decay and re-enter the atmosphere within two years instead of five. This happens due to the interaction of the drag sail with the Atomic Oxygen (AO) present in LEO. For this reason, the material of the drag sail must be selected by considering the effects of its interaction with the space environment, namely the drag area lost due to degradation from AO interaction and thermal radiation. Sail erosion can manifest within a matter of days post-deployment, culminating in a thickness loss of approximately 3.15 µm per year [1]. The sail is of quasi-rhombic pyramid (QRP) [2] shape and will be folded and stored within cartridges until the de-orbit phase commences.

The main purpose of equipping ASTRAEUS-01 with this payload is to make the mission as sustainable as possible. At the end of its life, the CubeSat will deploy its drag sail to begin the de-orbit phase of the mission. This will prevent the creation of additional orbital debris that it is well known to be an alarming obstacle to current and future human activity in space. Indeed, this debris poses a catastrophic threat to active space missions, hence leaving ASTRAEUS-01 in orbit would only contribute to accelerating the phenomenon of Kessler Syndrome.

2. Drag Sail Membrane

2.1. Material Selection and Stowage

The primary requirements of the drag sail membrane material are twofold. Firstly, it is required to be sufficiently resistant to AO and UV radiation degradation such that its area will not reduce by an amount that would compromise the de-orbit timeline. Secondly, the sail material should be transparent to minimise disturbance torques from solar radiation pressure that, in sun-synchronous polar orbits, perturb the spacecraft's attitude in such a way that lessens the sail's effective area [3]. Kapton film meets this latter requirement, however, it is susceptible to degradation. For this reason, it is proposed to employ a 12.7 µm Kapton film with a 300 Å aluminium protective coating as the sail material. Stowage of the sail is achieved by utilising a folding pattern with high packing efficiency – in this case, the Miura-Ori fold (see Figure 1).

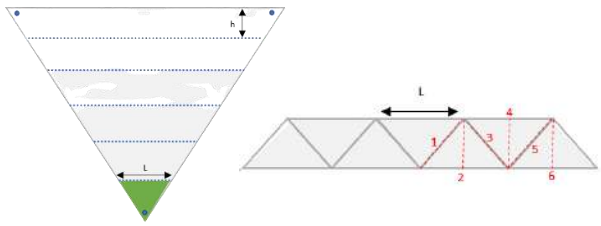


Figure 1: Drag sail folding pattern.

2.2. Dimensions

The effective drag area of the sail will heavily influence the de-orbit duration of the CubeSat. The size of sail required is itself highly dependent on the mass, altitude, and orbital inclination of the host satellite. Various studies have shown that, for a 3U CubeSat, a drag area of 4m² is sufficient to fall well within the IADC's 25-year de-orbit requirement [4]. In fact, a preliminary analysis by GU Orbit estimates a de-orbit time of slightly under two years for a 6kg 3U CubeSat with a 4m² drag area.

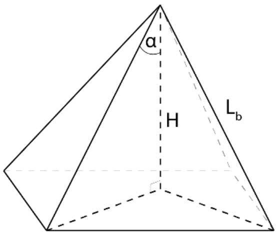
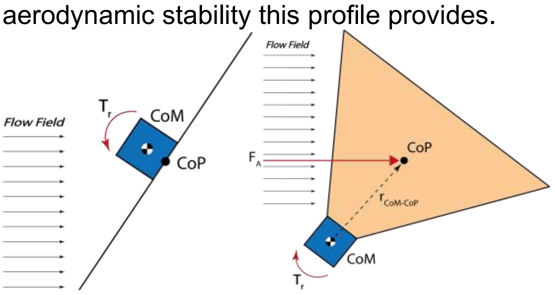


Figure 2: Geometry of a QRP drag sail with important dimensions labelled.

Figure 2 shows the geometry of a QRP sail, as proposed by Ceriotti et al [2]. Taking the base to be square, B is 2m for a 4m² sail (frontal drag area). The boom length L_b is determined by the apex half-angle α. Ideally, the booms should be as long as the CubeSat's volume and mass constraints permit in order to maximise the principal moments of inertia about the y- and z-axes, thus increasing the perturbation torque required to generate undesirable angular accelerations [5]. An apex half-angle of 30° gives the CubeSat an aero-stable profile and, to retain a 4m² frontal drag area, requires booms of length 1.87m, resulting in a 7m² sail area when projected onto a flat plane.

2.3. Aerodynamic Characteristics

When compared to a flat sail, the CoM and CoP of a pyramidal sail are significantly further offset from one another, as illustrated in Figure 3. This results in a far greater restoring torque T_r for the same applied force F_A. Moreover, the sail's QRP shape increases the effective drag area exposed to the flow field on the side of the angular offset, further augmenting the restoring torque [6]. The nominal reduction in frontal area is deemed a worth sacrifice for the additional aerodynamic stability this profile provides.



(a) Flat sail **(b) Pyramid sail**

Figure 3: Aero-stability comparison between a flat sail and a pyramid sail

3. Booms and Deployment Dynamics

To successfully deploy the drag sail, there must exist a deployable structure to which it can attach. A typical low-cost and relatively simple solution is the implementation of tape spring booms. Tape springs are thin strips of material with an initially curved cross-section and are of increasing interest for nanosatellite applications. To design a safe and reliable drag sail deployment mechanism, it is vital to have a firm understanding of tape spring deployment dynamics.

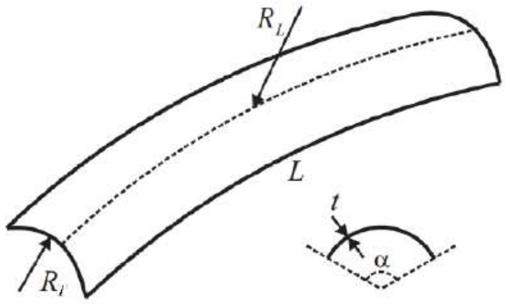


Figure 4: Geometric characteristics of a typical tape spring, adapted from [7].

The standard geometric parameters of a tape spring have been defined in Figure 4. These, in tandem with material properties, can be used to study tape spring dynamics (Beryllium Copper has been selected for testing purposes). The transversal radius of curvature R_T corresponds to the radius of the spool around which the boom is coiled. This radius of the spool around which the boom is coiled will determine how energetic the deployment is, with a smaller radius resulting in more violent deployment and vice versa. A balance must be struck to ensure the deployment is sufficiently energetic to full deploy the sail without risking tearing or detachment. Another important consideration is that the spool radius should be approximately equal to the boom's transverse radius of curvature R_T to avoid buckling during deployment. A mathematical model was developed to study boom deployment dynamics and optimise the geometry accordingly.

4. Deployment Mechanisms

4.1. Spool and Boom Mechanism

While in their stowed states, each tape spring boom will be coiled around a spool (see Figure 5). Once released, angular contact bearings will allow the spools to spin, resulting in extension of the booms and deployment of the drag sail.

DOI: 10.5821/conference-9788419184405.134

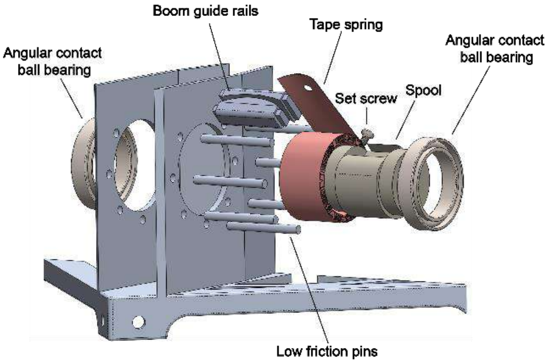


Figure 5: Exploded view of spool and boom CAD assembly.

4.2. Hold-Down and Release Mechanism

HDRMs are electromechanical devices used to deploy payloads on the satellite. These devices fall into two main types: pyrotechnic (explosive) and non-pyrotechnic. A first list of requirements was developed prior to the selection process of the best HDRM as reported in Table 1. In general, it was agreed that the HDRM task of stowing the drag sail was more important than its release because an accidental deployment would undermine the whole mission. For this reason, the HDRM of the drag sail shall meet some rigorous requirements in order to be employed on the CubeSat [10].

Table 1. List of HDRM high-level requirements

Requirement Number	Requirement	Description
1	*Redundant*	Back-up mechanism necessary
2	*Reliable*	>90% chance of successful deployment
3	*Synchronous*	Mechanism must activate at same time at different locations
4	*Controlled*	Actuation must be controlled by host spacecraft
5	*Safe for Space Environment*	No hazard shall be posed to space environment (debris, cords hanging, etc.)

Universities, private companies, and space agencies have developed different architectures of HDRMs, each one particularly suited for a specific application. In the case of ASTRAEUS-01, it was decided to maintain the drag sail in its stowed configuration using a set of cords, hence pyrotechnic HDRMs such as separation nuts were immediately discarded. The team therefore evaluated two of the most common devices used on CubeSats, namely the CYPRES™ Cutters and the Nichrome Burn-Wire Mechanism. Additional requirements were developed in order to proceed with a rigorous selection of the best HDRM for application on ASTRAEUS-01:

- Low Volume – the HDRM must occupy the least amount of space. The gap between the drag sail structure wall is very limited.
- Low Weight – the device must be as light as possible to limit the total mass of the CubeSat. This could have a significant impact on launch costs.
- Reliability – this requirement comprises redundancy, years of mission, percentage of successful deployment and humidity acceptance. The HDRM must prevent accidental deployments and account for a possible failure.
- Power Efficient - the power consumed by the mechanism must be compatible with the power supplied by the Electric Power System (EPS).
- Cost-effective – to demonstrate the accessibility of the technology.
- Complexity – manufacturing and integration within the drag sail structure.

CYPRES™ cutters have been proven to be extremely versatile devices by Cranfield University, who employed them on their TechDemoSat-1 [12]. These devices are extremely reliable since they are used as parachute tether-cutters in reserve chute deployment and therefore are commercially available and inexpensive. Despite the several advantages stated above, the cutter has a length of 48mm [8], which makes them unsuitable for installation within the drag sail structure of ASTRAEUS-01. The focus shifted to the Nichrome Burn-Wire Release Mechanism, developed at the Naval Research Laboratory (NRL). This mechanism uses a nichrome burn wire, which heats up when activated and cuts through a Vectran cord effectively used as a hold-down mechanism [2]. This HDRM has been tested in both air and vacuum, also with Vectran cords of different thickness. The significant advantages identified in this mechanism are its simplicity, high customisability and low cost that make it more accessible to university CubeSat projects. Tension in the cord and cutting time (dependent on operating conditions) are however key aspects that need further investigation.

The final design of the burn-wire mechanism took inspiration from a device developed by the Naval Research Laboratory [9]. The size of the component was critical since the space in the drag sail structure is very limited. In order to successfully deploy the drag sail, a clean cut must be executed to sever the hold-down cord and release the booms. This can only be achieved by supplying a constant current of 1.60±0.05 A to ensure that a reliable cut will take place while preventing the nichrome burn-wire from overheating [9]. The design shown in Figure 6 uses two M1.6 bolts to fit the mechanism to the wall of the drag sail structure and two M2.5 screws hold the nichrome burn-wire in position and ensure that the electrical connections are in contact with the wire. The electrical connections will be fed directly from the PCB.

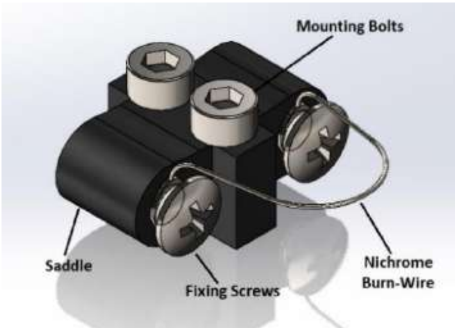


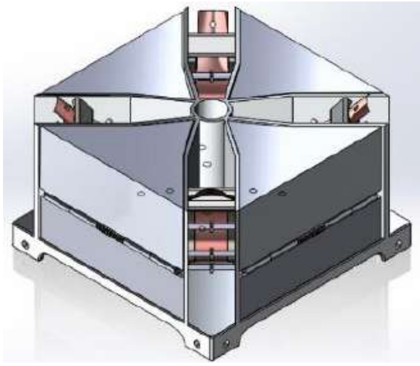
Figure 6: CAD model of initial nichrome burn-wire HDRM.

4.3. Housing Door Mechanism

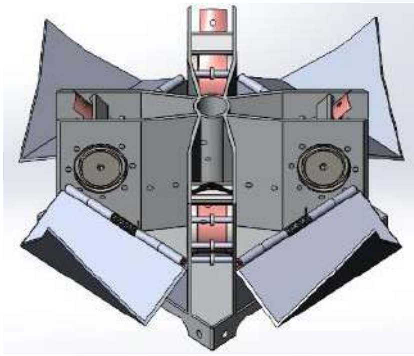
The drag sail membrane needs to be covered and protected throughout the mission to prevent any possible damage caused by environmental effects of LEO. In particular, the membrane cannot be exposed to AO and UV radiation as these would deteriorate its surface (erosion), eventually leading to holes and damage of the sail that would undermine its successful deployment and functioning [1]. A deployable cover compatible with the existing drag sail structure was therefore designed after having defined the main design criteria stated above. In addition to the environmental requirements, minimisation of weight and cost were also key elements to obtain the best design. Using the material selector Granta EduPack in combination with material data from NASA [1,13], it was decided to design the drag sail covers using anodized aluminium. According to NASA reports, the reaction efficiency of most metals is relatively low, with values approaching zero for aluminium and magnesium:

$$R_e = \frac{\Delta m/\rho}{\varphi t A} \qquad (1)$$

This implies that these materials do not show any macroscopic changes when exposed to LEO effects and are therefore suitable for application on ASTRAEUS-01 [1]. The design chosen for the cover doors consists of two sections, one fixed and the other able to open when the HDRM is activated. The two sections of the cover are connected by a hinge and the deployment is actuated by a torsion spring as shown in Figures 7. The doors will be held closed by a cord similar to the one used to hold down the booms. The same type of burn-wire HDRM will be used to trigger the deployment of the cover doors prior to the opening of the drag sail itself.



(a) Undeployed state



(b) Deployed state

Figure 7: CAD of drag sail assembly.

4.4. Final Configuration

ASTRAEUS-01 will be equipped with four burn-wire mechanisms that will be installed on the internal walls of the drag sail structure as shown in Figure 9. A Vectran cord will pass through the four doors, keeping them closed throughout the mission. HDRMs 1 and 3 in Figure 8 will be used to cut the cord and release the doors. Similarly, another cord will prevent the spools from deploying and it will be cut by HDRMs 2 and 4. With this configuration, the deployment of the doors is independent from the deployment of the drag sail and, by using two HDRMs for each deployment, the necessary redundancy is ensured to increase the reliability of the release system. This critical deployment will be extensively tested, also considering the addition of an extra two cords to prevent any premature deployment that would undermine the mission.

DOI: 10.5821/conference-9788419184405.134

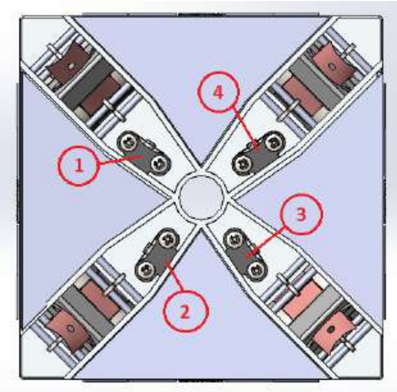


Figure 8: Disposition of HDRMs within ASTRAEUS-01.

5. Discussion

The next step on improving this technology is to make it a system useful not only for the end-of-mission phase, but also for tasks such as attitude control [11] or even orbital transfer without the need of a propulsion system. Moreover, with the development of materials engineering, optimised alloys will appear and set a new and improved standard in terms of performance and area-to-mass ratio.

Throughout the design process of the drag sail subsystem presented in this report, modularity and compatibility with standard CubeSat form factors has been a top priority. It is hoped that the development of this low-cost and versatile de-orbit technology can make space sustainability more widely accessible, particularly for start-ups and SMEs in the burgeoning nanosat sector.

6. Conclusions

This paper has presented the design selected for the drag sail of ASTRAEUS-01 and its deployment mechanism. This payload is extremely significant to GU Orbit for preventing the accretion of space debris that could undermine present and future human activities in space.

The quasi-rhombic design of the drag sail shall facilitate the de-orbit of the 3U CubeSat within 12 to 24 months by exploiting the interaction with the AO present at the CubeSat's operational altitude. Kapton has been selected as the constituent material of the drag sail membrane. Despite its known mechanical, thermal, and optical properties, the membrane will be extensively tested to ensure that the mounting points to the booms and structure do not pose any risk to its structural integrity (i.e. internal stresses). The deployment of the four membranes that constitute the drag sail will be completed using tape spring booms, each coiled around a spool when stowed.

Finally, the deployment of the drag sail will be actuated by a HDRM, which for ASTRAEUS-01 has been selected to be a nichrome-burn wire. This inexpensive and versatile mechanism will be used to sever the cords that prevent the tape springs and protective drag sail cover doors from deploying. The design will be further optimised for the available volume of the drag sail structure and rigorous testing will be used to validate this HDRM for ASTRAEUS-01's mission.

Acknowledgements

The authors would like to express their gratitude to Dr. Matteo Ceriotti from the James Watt School of Engineering at the University of Glasgow, for his precious guidance and support throughout the development of ASTRAEUS-01.

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Analysis of the Effectiveness of Sensors to Fulfil Scientific Cases in the Fly a Rocket! Campaign

Jasmine Brittan [1], *Ingrid Hjelle* [2]

Abstract

With space becoming a newly ubiquitous phenomenon, due to the evident popularisation of space travel, the European Space Agency Education has a mission to educate the future generations of engineers and scientists to accelerate new findings in the field. The Fly a Rocket campaign was curated to involve early undergraduates in the full launch of a sounding rocket, notably the Mongoose 98. In collaboration with Andøya Space Centre, the aim of the launch was to successfully meet the 4 predefined scientific cases. These were named Oliver Twist, The Cloud Atlas, 451 Degrees Fahrenheit and Rock & Roll and the cases were assigned to the three teams working on the campaign: sensors, payload, and telemetry. The week consisted of learning through the form of lectures and practical understanding via the instruction of the Andøya Space Team. The rocket launch culminated on the 4th day of the 5-day campaign, with a weather balloon also gathering atmospheric conditions.

Among the presenters of this report, both members had notable roles as the Principal Investigator and Range Control Officer, allowing us to provide both an overall analysis of the mission and in-depth insights, associated with the varying sensors. The Range Control Officer led the countdown procedure to launch alongside the Range Safety Officer, while simultaneously building the pressure sensor. Moreover, the Principal Investigator worked on the magnetometer.

Our team will present on behalf of the sensors team and evaluate the accuracy of the sensors to provide valid conclusions for the scientific cases. The team will present whether the accuracy of the data was reliable enough to answer our proposed questions. Additionally, thorough analysis was conducted using OpenRocket to determine its viability for future rocket launches.

Issues during the campaign launch included the mismanagement of payload integration being slowed and OpenRocket being inaccurate past a Mach number>2. Ultimately, this report verified some of our cases and provided important telemetry data to improve the use of future launches.

Keywords

Fly a Rocket, students, sensors

Acronyms/Abbreviations

ESA	European Space Agency
IMU	Inertial Measurement Unit
NAROM	Nasjonalt senter for romrelatert opplæring
OR	OpenRocket software
PI	Principal Investigator
PTU	Pressure, Temperature, and Humidity Sensor

RCO Range Control Officer

SSEA Symposium on Space Educational Activities

1. Introduction

Over the course of one week, 24 students from universities all over Europe gathered at Andøya Space Centre to participate in the Fly a Rocket! programme, a unique programme arranged by ESA Education Office, Norwegian Space Agency and Andøya Space education. During the programme, the students attended exciting lectures held by personnel from the space industry working at Andøya Space, worked together to build and launch a rocket, and last but not at least, made new friends who share an interest in science and technology.

2. Sensor Experiments

2.1 Deciding the Scientific Cases

The scientific goal of the rocket had to be decided by the students themselves. A PI-team was therefore chosen, consisting of a Principal Investigator and three Co-PIs, one from each team; sensor experiments, payload and telemetry. As the students had access to a wide range of sensors and a balloon, it was decided to focus on four scientific cases.

The first one is an analysis on different ways to decide the trajectory of the rocket. The objective was to determine which of the sensors would provide the most accurate location. The GPS was to be taken as the base measurement and each of the IMU, pressure sensor and Open Rocket simulation data was compared to the baseline. Hence, the error in each sensor could be found to determine which measurement was the most accurate one. The sensors used in this experiment were the GPS, IMU and pressure sensor.

The second one explored if it was possible for the rocket to detect when it entered and left clouds. The purpose of the case was to examine different methods for detecting clouds and to find out which of them would be the most efficient. The data from each sensor was examined and compared so that we were able to determine if the rocket was inside clouds and the atmosphere at the respective locations. Based on the video of the rocket flight, it was found that the rocket entered clouds around 6-7 seconds into the flight. It's expected that this event had an influence on the data obtained from the sensors, thus it should be examined first. The sensors used in this experiment were the optical, temperature and pressure sensor (rocket), humidity, temperature and pressure sensor (balloon).

The third one, which only used data from the balloon launches, analysed how temperature changes throughout the atmosphere. The main objective of this case was to collect atmospheric temperature data and pressure measurements at different altitudes from the balloon and from the rocket, and to confront these measurements with the 1993 ICAO standard atmosphere. The sensors used in this experiment were the Balloon PTU probe, external temperature sensor on rocket, pressure sensor on rocket.

The last one analysed the correlation between acceleration of the rocket and the spin, using three different sensors. The purpose of the experiment was to determine the spin of the rocket using the data received from three different sensors: the light brightness variation, the magnetic field strength variation and the y-axis acceleration. The sensors used in this experiment were the optical sensor, accelerometer, magnetic field sensor. These were choses as it provided us with three ways of measuring the spin of the rocket, and we could then compare the sensor accuracy.

Having to decide these scientific cases was an interesting challenge to the participants, as we all were students and used to being handed both procedures and goals before conducting research. Deciding on the cases required critical thinking, discussions of what was possible, and creativity.

2.2 Creation of the Sensors

For all of the aforementioned sensors, each component was soldered by the programme participants, using a lead based solder. and through-hole and surface-mount techniques. Under the instruction of the staff at Andøya Space Centre, the component arrangements were verified for each sensor. Hence, individual tests were performed on each of the sensors, mainly in order to know what values to expect and make sure they would not surpass 5 V, which was the sensors' upper operating range. For most sensors, this consisted of connecting the sensor board to the oscilloscope testing rig. [1] Telemetry proceeded to do a secondary test on each of our sensors. After validation from the testing, the sensor was delegated to the payload team for its integration into the sensor plate. [2]

3. What we did on the day

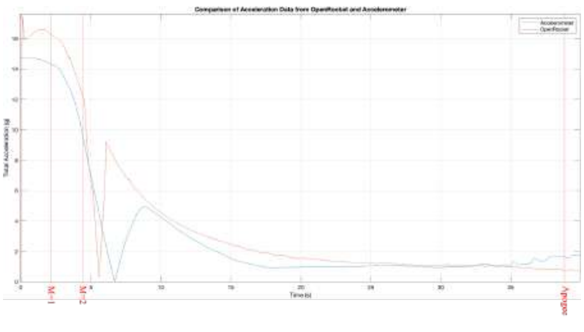
On the day of launch, a stringent countdown procedure was undertaken to ensure the safety of our mission and that each of our scientific cases criteria were met, as verified by our Principal Investigator (PI). The Range Control Officer (RC) was the main point of call who led the entire operation. This involved talking over the speaker system and ensuring smooth communication for a safe operation. The RC spoke to other notable personnel such as PAS, PM, PI and RSO as well as working directly with the RSO and resident range control at Andøya. One notable point was verifying clearance from air traffic control and removing vessels from our predicted splashdown area. [3]

The Principal Investigator however monitored if the atmospheric conditions were suitable for launch. Meanwhile, throughout the campaign, the PI was the student lead of the project so was thus also responsible for the feasibility of the scientific cases and the curation of the final report which was presented to ESA Education.

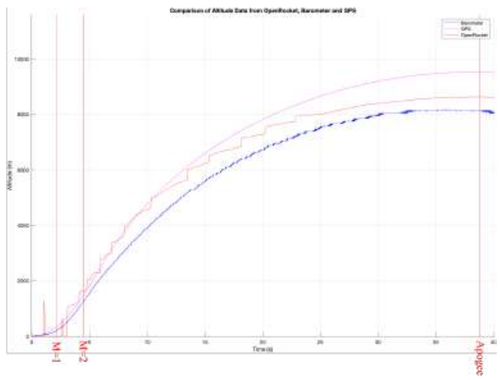
Subsequently, a significant delay occurred at T - 00-15-00 due to a first failed weather balloon and the subsequent launching of a second. As a result, the elevation and azimuth of our rocket had to be changed to the values of 301.3° and 73.7° to avoid a smaller fishing vessel. Our sounding rocket launch was later observed to have left the rocket launcher at around T+3 seconds. The telemetry team collected data as the rocket reached its apogee and our rocket ultimately was left in the ocean due to the lack of a recovery system.

4. Results & Discussions

4.1 Oliver Twist



(a)



(b)

Figure 4.1.1: Graphs showing the difference in (a) acceleration and (b) altitude between OpenRocket and the onboard accelerometer.

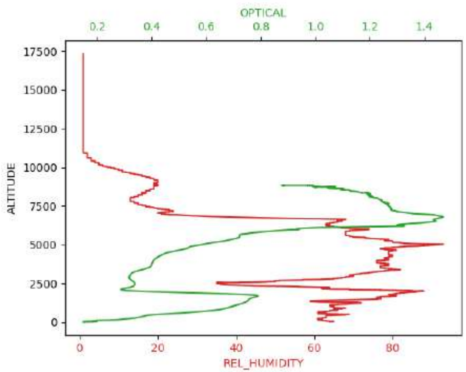
Interestingly, OpenRocket overestimates the acceleration right away, from ignition, by about 2g's. Over time, from about t = 10 s onwards, the two curves converge as can be seen in Figure 4.1.1a. There is no significant divergence after M = 1, in fact the simulation appears to be more accurate for the period 1 < M < 2 than for M < 1.

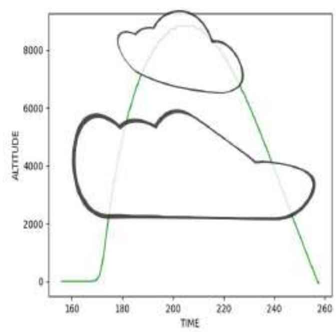
OpenRocket overestimates the apogee by about 896 m. This is likely due to the software neglecting the effect of wave drag. On the other hand, there is very little divergence between the OR and GPS curves during supersonic flight (approximately 1<t<14s) and therefore there may be another cause.

The results from OpenRocket have surprised us, as this seemingly simple tool managed to predict most of the flightpath's characteristics up to a reasonable degree. We conclude that even though it does not have the features to calculate the forces acting on the rocket above M>1, it certainly is a very powerful tool for quick rocket sizing and design that takes significantly less time to implement than creating a full analytical model and running a higher fidelity simulation.

4.2 The Cloud Atlas

The rocket launch provided a large amount of data which was analysed and compared with the dataset from the launch of the professional grade weather balloon which was launched 30 minutes before the rocket launch. The relatively short time interval between measurements allowed us to reliably compare these two datasets. Unfortunately the temperature sensors on the rocket were not accurate enough to calculate the temperature gradient which should change 0.6 °C/100 m inside clouds and 3 °C/100 m outside clouds [4]. The measured gradient could indicate the presence of clouds.The focus for analysis was shifted to the more promising method, using the voltage amplitude of the optical sensor. The dip in amplitude could indicate the atmosphere with more water particles eg. clouds. Next graph shows the correlation between the amplitude of the optical sensor and the increase of the humidity measured with a weather balloon.





(a) (b)

Figure 4.2.1: Combined graph of balloon humidity and amplitude of optical sensor (a) and the clouds detected (b).

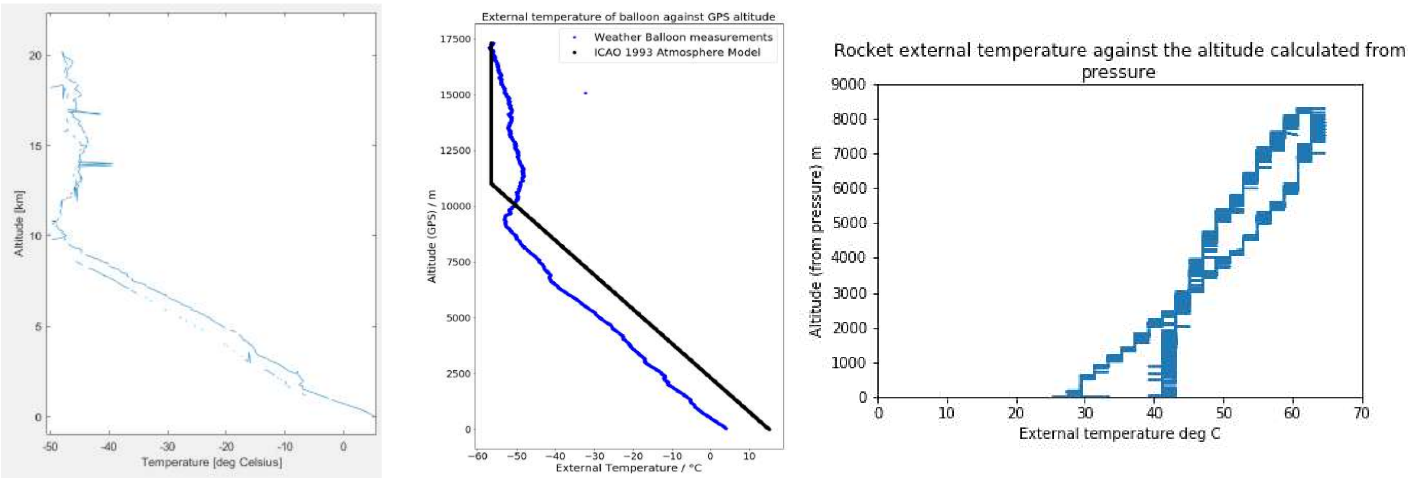
From Figure 4.2.1a it can be assumed the rocket achieved the apogee inside a cloud with the cloud base at around 6200 m MSL(Mean Sea Level). After exiting the highest cloud it was then in the clear region from 6200 m to around 4300 m MSL and then it entered a big cloud that had a cloud base at around 2200 m MSL. After exiting this cloud we can see the rocket coasted in almost clear skies until splash down. Comparing the second graph to the first it can be seen that the clouds were quite big in the area, especially the lowest one with the cloudbase at 2200 m. There is some difference in the highest clouds. It looks like the rocket entered it later(7500 m) probably on the sides of the cloud. See Figure 4.1.2b for better understanding.

The first hypothesis is definitely correct, because the dips are obvious at the altitudes the rocket entered clouds that were previously detected using a weather balloon. For the second hypothesis it was discovered that humidity is not exactly 100% in the clouds but there was a significant change in humidity when entering and exiting them, even in the cirrus clouds which are made from ice. The third hypothesis couldn't be properly tested because the temperature change was not reliable enough.

4.3 451 Degrees Fahrenheit

Comparing figures 4.3.1(a) and (b) the balloon measurements followed similar gradients as they ascended. These measurements are similar because they were launched with one day difference at the same location. As hypothesised the atmosphere model did not match the measurements well as it is an average for the surface of the Earth and the temperature gradients at northern latitudes differ from other regions.

For figure 4.3.1(c) the temperature increased as the rocket ascended which does not match what was expected. One of the main factors for the increase in external temperature is the drag experienced by the rocket. This drag includes skin friction and wave drag which was very significant during the powered ascent phase and during the coasting until apogee. An important note is that the initial temperature was around 25°C before lift-off whereas the actual external temperature was around 10°C. This discrepancy suggests that the sensor was being heated by the other electronic elements, this heat transfer probably happened through the antenna mounts the sensor was attached to as these were made of aluminium and connected to the aluminium plate.



(a) (b) (c)

Figure 4.3.1: (a)- altitude from pressure data against temperature for the 2nd balloon release. (b)- altitude from GPS data against external temperature for the professional balloon.

4.4 Rock & Roll

Figure 4.4.1 summarises the roll frequencies for 3 sensors - optical, magnetometer and accelerometer in centripetal direction. The optical data was cleared up from noise as the amplification unit on the circuit and data transfer caused a few peaks at 300 Hz, which could clearly be deemed as noise.

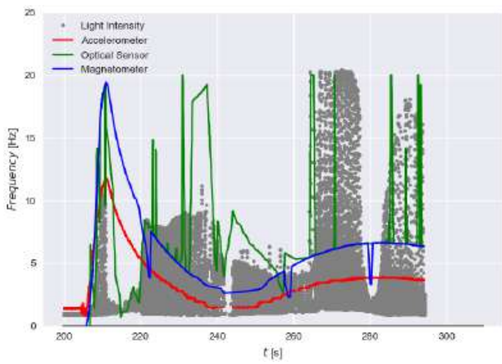


Figure 4.4.1: Roll frequency sensors comparison with light intensity

The representation of the frequency showed trend correlation for magnetometer and accelerometer in Figure 4.4.1. The optical sensor showed unexpected jumps in values, however, this could be explained by the rocket going through the clouds and the data being corrupted by this. The main time points where the clouds or noise had an effect are the points where the optical sensor data diverges from the trend which would be similar to the magnetometer and accelerometer. This happens mainly between 220-240, 260-270 and 280-285 seconds of the flight. The magnitude divergence is closely correlated with the higher average light intensity which signifies the rocket going through the clouds and the light intensity source being omnipresent around it.

Another important point to make from the data is that both the optical sensor and magnetometer recorded a much higher peak frequency than the accelerometer. This could be explained by the construction of the sensors. The accelerometer uses the principle of the strain gauge to measure the acceleration, which measures the change in resistivity of the material as it stretches due to acceleration. However, the optical sensor and magnetometer both use the principles of electromagnetism and light interaction. Processes including light and the magnetic field have much higher response rates and the values these two sensors have therefore a much better representation value.

5. Conclusions

The main goal of the Fly a Rocket! Campaign was for it to be a learning experience for the participants. By using creativity to decide on the scientific cases, learning new skills by soldering the sensors, building the payload and being in charge of the telemetry, and by being able to be a part of the countdown procedure on launch day, this goal was definitely met. In addition to all these learning factors the participants got to extend their network and experience how it is to work in the space industry.

On the contrary, our sensors provided data which can be extrapolated to verify the questions posed in our scientific cases, negating data which was lost during our rocket's trajectory. Moreover, OpenRocket provided a surprisingly accurate trajectory for our rocket up to Mach 2 and the pressure sensor provided a valid approximation for the GPS data. It was overall concluded that the campaign was successful, giving students from across Europe the opportunity to collaborate in a diverse team.

Acknowledgements

This report would not have been possible without the European Space Agency and Andøya Space Centre who arranged the Fly a Rocket! Campaign. It was a valuable experience that none of the participants will ever forget. We would also like to thank the entire Fly a Rocket! Team who conducted all the research that is discussed in this report.

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OSCAR-QUBE: Student made diamond based quantum magnetic field sensor for space applications

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Abstract

Project OSCAR-QUBE (Optical Sensors Based on CARbon materials - QUantum BElgium) is a project from Hasselt University and research institute IMO-IMOMEC that brings together the fields of quantum physics and space exploration. To reach this goal, an interdisciplinary team of physics, electronics engineering and software engineering students created a quantum magnetometer based on nitrogen-vacancy (NV) centers in diamond in the framework of the Orbit-Your-Thesis! programme from ESA Education. In a single year, our team experienced the full lifecycle of a real space experiment from concept and design, to development and testing, to the launch and commissioning onboard the ISS. The resulting sensor is fully functional, with a resolution of < 300 nT/ sqrt(Hz), and has been gathering data in Low Earth Orbit for over six months at this point. From this data, maps of Earth's magnetic field have been generated and show resemblance to onboard reference data. Currently, both the NV and reference sensor measure a different magnetic field than the one predicted by the International Geomagnetic Reference Field. The reason for this discrepancy is still under investigation. Besides the technological goal of developing a quantum sensor for space magnetometry with a high sensitivity and a wide dynamic range, and the scientific goal of characterizing the magnetic field of the Earth, OSCAR-QUBE also drives student growth. Several of our team members are now (aspiring) ESA Young Graduate Trainees or PhD students in quantum research, and all of us took part in the team competition of the International Astronautical Congress in October 2021, where we won the Hans Von Muldau award. Being an interdisciplinary team, we brought many different skills and viewpoints together, inspiring innovative ideas. However, this could only be done because of our efforts to keep up a good communication and team spirit. We believe that if motivated people work hard to improve the technology, we can change the way magnetometry is done in space.

Keywords

Quantum Magnetometer, Interdisciplinarity, International Space Station

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1. Introduction

Quantum sensing is a quickly expanding branch of quantum science, in which basic research concepts rapidly evolve towards practical applications, drawing attention in terms of high sensitivity and precision. Currently quantum technology and its utilization in the space environment is still in its infancy, but it has the potential to become the next standard with possible applications for space magnetometry, and for terrestrial applications such as geology and mining, navigation, and biomedical technologies (MRI, NMR, etc.). The project OSCAR-QUBE (Optical Sensors based on CARbon materials - QUantum BElgium) is tackling this topic by giving undergraduate students of different disciplines (physics, electrical and software engineering) the chance to work hands-on in the field of quantum and space technology, and providing them with experience in R&D early on in their career.

The aim of project OSCAR-QUBE is the development of a diamond based quantum magnetometer, using opto-magnetic defects, called nitrogen-vacancy (NV) centers, found inside the crystalline lattice of the diamond material. The NV centers can be exploited as magnetic field probes with a theoretical sensitivity down to 10 fT/sqrt(Hz), a fast response time of < 200 ns and a very wide dynamic range (from fT to 0.1T) [1]. Diamond is a very robust and radiation hard material, which makes the sensor perfectly suited for the harsh space conditions. Due to the tetrahedral structure of the its lattice, there are four different crystallographic axes along which the NV centers can be located, enabling vector magnetometry.

The working principle [2] of the sensor is entirely quantum mechanical and relies on the optical excitation of the NV centers (see fig. 1a) using green laser light, and the subsequent relaxation (fig. 1b). The method of relaxation can be either dark or fluorescent (emitting red light, fig. 1c) and depends on the spin of the NV center, which can be addressed by a resonant microwave field, creating a dip in the red light spectrum at the resonance frequency (fig. 1d). External magnetic fields affect this spectrum, splitting the dips. The distance between the dips is proportional to the applied field (fig. 1e). This method of determining the ambient magnetic field is called the Optical Detection of Magnetic Resonance (ODMR) [1]. In fact, two of these dips will occur in the signal for each one of the four crystallographic axes, generating in total eight dips. Each pair of dips gives the magnetic field component in one direction and the 3D vector field can be determined by making the vector sum of all these components.

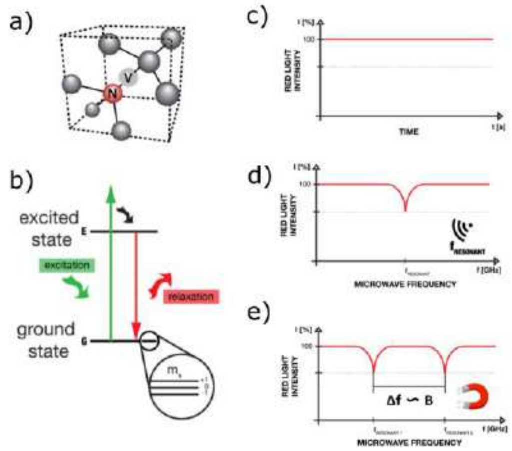

Figure 1. Principle of ODMR. (a) NV center in diamond lattice. (b) Simplified energy level scheme (with spin dependency) and transitions. (c) Radiative relaxation gives a stable red light signal. (d) Applying a resonant microwave field increases the probability of relaxation via a dark state. (e) Applying an external magnetic field changes the energetic spectrum of the NV center, giving rise to two resonances at a distance proportional to the magnetic field strength.

The OSCAR-QUBE was selected in the framework of the 'Orbit Your Thesis!' (OYT) program organized by European Space Agency (ESA) in April 2020 [3], with the aim to develop an experiment capable of mapping the Earth's magnetic field within a single year. The benefit of the OYT program is the close connection with the space sector and expert guidance throughout the review process. This way our team got to experience the full lifecycle of a space project, acquiring knowledge of design standards, requirements, and test campaigns, generating a successful result and launch of our device to the International Space Station (ISS).

In the following sections, the paper will describe the project journey, experiment principle and findings, and also the team formation and team dynamics with focus on interdisciplinarity and diversity. It will underline the importance of communication and planning of a student project, and it will highlight the educational return of an R&D space project.

2. Experimental part

2.1. Selection

The journey of the OSCAR-QUBE team begins with the team and idea formation phase,

DOI: 10.5821/conference-9788419184405.136

initiated end 2019 (when ESA Education opened the call for submissions for the 2nd OYT program). This was a suitable candidate platform for the experiment as the ISS provides global coverage and allows us to focus on the development of the device without taking into account power generation, orbital control, space debris, etc.

To enter the OYT program our team leader wrote a letter of intent, after which we all wrote a project proposal. We focused on the scientific concepts, and on the fit between the program and our experiment. We were shortlisted for the Selection Workshop on the 25th of February. At this workshop, we gave a presentation about our project, after which we got contacted by ESA , asking us to clarify some aspects of the QUBE. In mid-April, we were selected [3].

2.2. System design

First, we defined the four main parts of our experiment: laser, microwave generator, optical detector, and the control and power system to operate the other components. One team member was responsible for each subsystem and we set up a testbench where we slowly replaced commercial components with our own subsystems, allowing us to optimize each single subsystem without needing to touch the others.

The first review we had was the Preliminary Design Review (PDR). We had to provide the experts with our complete design and a detailed description of hardware and software. The ESA experts gave us feedback in the form of RIDs, which varied from functional concerns to grammatical errors. After corrected all the RIDS, the PDR data package was accepted [4].

2.3. Integration and manufacture

After optimization of the subsystems on the testbench, we went for integration. The general mechanical design of the structure was constrained by the OYT program and had to be a cube with size 10 x 10 x 10 cm³. The electronics team then designed the individual boards. The main challenge was the compatibility of the different designs, which was checked in several meetings

After creating our design, we had to pass the Critical Design Review (CDR). The goal of the CDR is to freeze the design and to make sure there are no last minute changes implemented, compromising the experiment or the safety of the astronauts. Therefore, we had to provide again every detail of our design. By this time we already had a functional cube, so we were confident in our design. After correcting our RIDs, we received ESA's blessing to continue and start building the flight model [5], of which figure 2 shows a schematic.

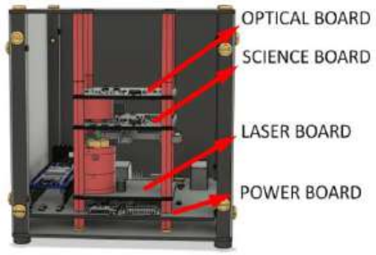

Figure 2: Schematic drawing of the QUBE. Standoffs are used to separate the four boards.

Software was created to store and transmit the measured data in packets (NV and reference data). If the QUBE is not connected to the ground, the packets are stored on an SD card, otherwise it transmits all data via Ethernet. This data is entered in a self-made User Home Base (UHB), developed to monitor the status and data of the sensor. Space Applications Services (SAS) has its own open-source mission control software package called Yamcs that is designed to receive telemetry and send telecommands while storing the incoming packets and formatting the raw values. The downside of Yamcs was that it only offered a basic web interface so we chose Javascript and Python to develop a GUI to interact with the sensor and display the real-time data.

2.4. Testing

The operation of the QUBE and associated software was tested during the development of the sensor. First, we characterized the NV axes of the diamond sample, using an in-house created 3D Helmholtz Coil. To make sure that the QUBE would survive the launch and space environment, we did several environmental tests: vibrational testing, thermal/ vacuum testing and EMI/ EMC testing. Interface tests were used at SAS to ensure correct functioning of the QUBE. All tests were passed [5].

2.5. Shipping and launch

After testing, the QUBE was put in a vibration minimizing package and shipped to ESA. Then we prepared ourselves for the launch, which happened on the 29th of August [6]. We set up a launch event at our university, where we invited the rectorate, our endorsing professor, our sponsors, and previous OSCAR iterations.

This event was also featured in newspaper articles and on Belgian television [7], helping us share our journey with the public.

2.6. Commissioning and operations

After the launch, we were invited to the ICE Cubes Mission Control Center in Zaventem, Belgium to see how Thomas Pesquet unpacked and installed the QUBE in the ISS [8] (location in fig. 3), after which the first data came in.

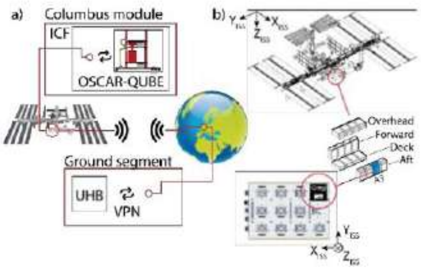

Figure 3: a) Global system overview. b) Reference frames of the QUBE's respective location onboard the ISS.

Once the data is stored on the server, we use Python to process it because of its versatility and the large amount of installable packages. Once a day, the data processing is triggered automatically. First, the packets are sorted by their timestamps to make sure they are in chronological order. Secondly, the positions of the individual peaks are determined by fitting the data with a Lorentzian curve [9] to extract the center frequency of the dip. In the third step, the GPS data and location of the ISS at each measurement point is added. Lastly, the data is made accessible in an understandable way, using an Elasticsearch database together with Kibana [10]. This allows us to make graphs and export specific sections of data for calculations.

To extract information from the ODMR data, equation 1 [11] is solved for the components of magnetic field B along the NV axes (X, Y, Z) and the frequency difference Δf between the corresponding minima in the spectrum. Here, ɣ is the NV gyromagnetic ratio, equal to 28.024 GHz/T. The B and NV axes components are evaluated in the same reference frame. Equation 1 has physical meaning when the components are transformed to the body fixed ISS frame LVLH [12] (local vertical local horizontal). Because the ISS rotates, an attitude correction has to be done by using its Roll, Pitch and Yaw. Another frame used to evaluate the data is the NED [13] (North East Down) frame which is heading invariant. With the data expressed in these coordinates, the magnetic field map of the earth can be created as a function of latitude, longitude and altitude.

$$2\gamma \begin{bmatrix} X_{NV1} & Y_{NV1} & Z_{NV1} \\ X_{NV2} & Y_{NV2} & Z_{NV2} \\ X_{NV3} & Y_{NV3} & Z_{NV3} \\ X_{NV4} & Y_{NV4} & Z_{NV4} \end{bmatrix} \cdot \begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} = \begin{bmatrix} \Delta f_1 \\ \Delta f_2 \\ \Delta f_3 \\ \Delta f_4 \end{bmatrix} \tag{1}$$

2.7. Outreach and team

Team OSCAR wants to inspire as much students as possible to choose a technical, scientific or engineering direction. To do so, we pay a lot of attention to outreach on social media such as Facebook, Instagram and Linked-in. On Facebook, we have 555 followers and our posts have reached at most 2 325 people. We've been featured in Czech [14] and Belgian newspapers and tv on multiple occasions. We also reach out to students directly, in lectures, presentations and in informal ways such as an art competition [7].

To quantify our experience, we held an online survey within the team. The results of this survey will be discussed in the following section.

3. Results and discussion

The OSCAR mission has three important parts: technology, science and student growth. The technological goal was to develop a quantum magnetic field sensor for space magnetometry with a high sensitivity and a wide dynamic range. We did this by creating a diamond-based quantum magnetometer (see fig. 4) that fits inside a cube with a side of 10 cm, weighing only 420 g, with a power consumption of 5 W. The measured resolution of this device is < 300 nT/ sqrt(Hz) and the bandwidth is 1.3 kHz [2].

Figure 4: left) Finished QUBE without side panels. right) the QUBE onboard the ISS during installation by Thomas Pesquet.

Using the QUBE, the scientific goal of gathering a magnetic field mapping of the world by measuring in Low Earth Orbit was addressed. Figure 5 shows a comparison between NV and reference data measured on the 27th of December. There is a clear resemblance

DOI: 10.5821/conference-9788419184405.136

between the two signals for all magnetic field components, which vary on different timescales. This is single orbit data but is representative for multiple orbits.

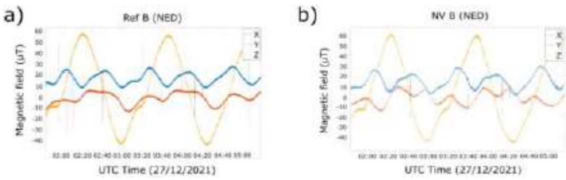

Figure 5: Magnetic field measurements with reference (a) and NV (b) sensor of 90 minutes.

Figure 6 shows the total magnetic field maps of the NV sensor and IGRF simulations created during the orbit in LEO. The NV magnetometer signal is similar to both the reference signal (not shown here) and the IGRF map, indicating that our sensor is capable of determining Earth's magnetic field.

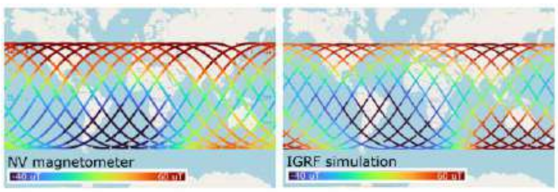

Figure 6: Total magnetic field map of NV sensor for 24h (left) and IGRF simulation (right).

The project opened up new possibilities for the students in terms of personal and professional growth. After finishing their master, two team members became Young Graduate Trainees at ESA (one applied this year) and another one became a PhD student in the Photonics and Quantum Technology group (three applied this year). In October 2021, we presented the experiment in Dubai at the International Astronautical Congress and won the Hans Von Muldau prize for best team project [18].

Many team meetings were held to exploit the advantage of an interdisciplinary team, with the aim of helping members gain insight on different disciplines, both the complex physics and its practical application. The previously mentioned survey checked the validity of this hypothesis and provided some lessons for the future:

- Communication in an interdisciplinary team is not easy (very specific knowledge, misunderstandings, etc.) but important. Done right, the different disciplines bring versatility and many insights.
- Do not provide too much work to individuals with specific skill sets, while others have time to learn this skill as well.
- Let team members get to know each other informally at the start, even more so during COVID restrictions. It makes the threshold to ask for help smaller.
- Do not underestimate the amount of documentation in the space industry. Let experts guide you in this.

The most unexpected thing we learned was different for everyone, but one thing we all have in common is that the reality of where we are today surpassed our initial expectations. Lastly, everyone's favorite moment was asked, which varied from the selection, creating the QUBE, the launch and installation, to the IAC. Other team members expressed how they liked all moments where the team was together and we could talk about topics of shared interest.

4. Conclusion and outlook

In a single year (April 2020 to April 2021), we created a quantum magnetometer based on NV centers in diamond, fit for a real space mission. After passing all required tests, we shipped the device and watched its launch to the ISS. In September 2021 the QUBE was installed and the first data came through to our user home base on ground, proving that our experiment had survived the launch and was fully functional. Now, we have been collecting data for six months and could generate preliminary magnetic field maps that correspond partly to reference measurements. The difference with IGRF predictions is still under investigation.

It has proven to be of utmost importance for us to invest in communication, both formally and informally, especially since we formed our team during the COVID-19 pandemic. The advantage of interdisciplinarity is that we bring different knowledge and perspectives to the table, but on the other hand it's not always easy for us to understand each other. By putting in this effort, we managed to create our sensor, necessary documentation, and content for our followers on social media and other outreach platforms.

Thanks to our sponsors, the QUBE will be brought back from space onboard the SpaceX CRS-25. This allows us to investigate the effect of space conditions on the QUBE and assess more precisely the technological readiness level and possible improvements. Thanks to the OYT programme, we gained visibility in the space industry and received new opportunities. For example, we got selected in the first round of the myEUspace competition from EUSPA, where we presented a spin-off mobile app Aurora Catcher that allows tourists to detect northern lights with quantum magnetometers.

We are also reiterating our sensor to create compatibility another platform in the YPSat project, where a group of ESA Young Graduate Trainees fly their experiment on board the Ariane 6 rocket's maiden flight. The goal is to technically improve the sensor by reducing its size, weight and power consumption, and to push the science by sensitivity improvement and determining the attitude of the launcher.

Acknowledgements

Our sincere gratitude to our endorsing professor Milos Nesladek and the Quantum Photonics and Technology lab for supporting our journey, and to ESA's OYT project and Space Application Services, for the opportunity. Many thanks also to our sponsors, Melexis, pom Limburg, Element Six and Select System for allowing us to retrieve the QUBE and continue the research.

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DOI: 10.5821/conference-9788419184405.136

ASCenSIon Innovative Training Network: mid-term overview and lessons learned

Alessia Gloder[1], Martin Tajmar[2], Christian Bach[2]

Abstract

The field of access to space is wide and complex, and it involves several disciplines and areas of expertise such as propulsion physics, software development, experimental studies, numerical simulations, thermodynamics, missionisation, etc. A gap in the training of young European researchers at doctoral level has been identified in this field, as no high-level education programme exists with the ability to range across such a large range of research topics. With the aim to fill this gap, 24 European entities from academia, industry and research centers have partnered in the framework of "ASCenSIon", an Innovative Training Network funded by the European Commission within the Horizon 2020 Marie Skłodowska Curie Action. The objective of the project is to contribute to the establishment of a both ecologically and economically sustainable space access for Europe, therefore advancing its State of the Art. This is achieved by training 15 Early Stage Researchers of different background, nationality, gender and age, to become experts in their fields and to have a deep understanding of the access to space domain as a whole. Within ASCenSIon, the Early Stage Researchers, who are enrolled in a PhD programme, acquire both technical and transferable skills thanks to an inclusive and diverse training programme held at local and project level. Unlike more ordinary PhDs, the training offered by ASCenSIon does not only focus on narrow scopes of research fields, one domain (e.g. industry or academia) and one country. It features instead an interdisciplinary, intersectoral and multicultural approach. The offer includes training events in different forms, such as workshops, lectures, experimental weeks and summer schools, which are complemented by the participation in conferences and similar events. Given that the project started in January 2020 and will end in December 2023, this paper provides a midterm overview of the project and the lessons learned so far, with a particular focus on the remote vs in-person training experience forced by the Covid-19 pandemic outbreak.

Keywords

Access to Space, Innovative Training Network, Interdisciplinarity, PhD, Training

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Acronyms/Abbreviations

ESR	*Early Stage Researcher*
GNC	*Guidance, Navigation and Control*
ITN	*Innovative Training Network*
IRP	*Individual Research Project*
RLV	*Reusable Launch Vehicle*
SOTA	*State Of The Art*

1. Introduction

Innovative Training Networks (ITNs) are high-quality, highly-demanding projects funded by the European Commission which aim at raising excellence and structure research and doctoral training in Europe. This is achieved by training a new generation of creative, entrepreneurial and innovative early-stage researchers, able to face current and future challenges and to convert knowledge and ideas into product and services for economic and social benefit [1]. ITNs are expected to have a certain level of impact at researcher, organisation and system level and are characterised by some common aspects, such as: enabling join research training and/or doctoral programmes, enhancing exposure to different participating organisations, addressing both technical and transferable skills, fostering Open Science, increasing the international, interdisciplinary and intersectoral mobility of researchers in Europe [1].
ASCenSIon is an ITN that has received funding from the European Commission within the Horizon 2020’s Marie Slodowska-Curie action; it started in January 2020 and ends in December 2023, for a total duration of 48 months. Following ITNs’ core objectives, it introduces a research and training programme aimed at developing a generation of researchers who are expected to bring technical, economical and ecological improvements to the State Of The Art (SOTA) of access to space in Europe.
The need for such a training programme at doctoral level becomes evident when analysing in detail the current space market trends: with companies such as SpaceX and Blue Origin leading the change towards Reusable Launch Vehicles (RLVs), the access to space field is clearly undergoing a transformation. In addition, the participation of other ambitious nations like United States, India, New Zealand and China is increasing the pressure and competition on Europe, which risks to fall behind. To keep up with this change, Europe surely needs short-term innovations, but also young professionals able to understand the complexity of field of launcher development as a whole. The changing access to space field raises a series of challenges that the new generation of engineers needs to be able to tackle in its wider context and not only as launch vehicles and operations [2]. With its research and training programme, ASCenSIon addresses exactly this gap, and presents itself as the only doctoral training programme at European level aiming to address the access to space field as a whole.

2. ASCenSIon

ASCenSIon acronym stands for "Advancing Space Access Capabilities - Reusability and Multiple Payload Injection", and it describes the project objective to contribute to the establishment of an economically and ecologically sustainable access to space for Europe. ASCenSIon aims to fulfil it by forming a new generation of researchers with both scientific and soft skills through a dedicated network-wide research and training programme which empowers and prepares them to become leaders in the space transportation sector in Europe. The Early Stage Researchers (ESRs) employed within the project are 15 in total and are enrolled in a PhD programme in different European partners. Within their research they focus on launcher systems that are (partially) reusable and able to inject multiple payloads into multiple orbits. This, while keeping in mind the commercial applications and the needs of the users and the fast-evolving space market. The scope of the project is not to focus on one unique RLV design, but to identify and enhance technologies and solutions which are critical for the space access domain and prove their feasibility.
The approach is highly interdisciplinary and intersectoral, and it relies on the active participation of the entire project consortium. With such an approach, ASCenSIon aims to set the baseline for future collaborations in Europe and bring together professionals who are experts in their fields, underlying the importance for European entities to work together.

2.1. *The Consortium*

ASCenSIon consortium is a synergetic group of 25 European partners, which have been selected based on their expertise and prestige to well cover all the aspects of the access to space domain and its market, from fundamental research to commercial applications. These entities include universities, small to mid-size enterprises, big companies and governmental research institutes, and they are further divided into: a) beneficiary partners, who are the host institutions of the ESRs, and into b) associated partners, who contribute to the project bringing knowledge and expertise and hosting the ESRs during their research stays (secondments). A full and updated list of the involved partners is available in the ASCenSIon website [3].

The core of the consortium are 15 Early Stage Researchers, who are talented young professionals that have been selected among 276 applicants from all over the world and that are employed within ASCenSIon for a total of 36 months. These 15 PhD students have different genres, backgrounds and nationalities, and have been selected based not only on their technical, but also on their soft skills and motivation to participate in such a highly-demanding project. Last but not least, the consortium also relies on the experience and knowledge of an Advisory Board, constituted by renowned world-wide experts. The Coordinator of ASCenSIon is Technische Universität Dresden (TUD), which is one of the German universities of excellence [4].

2.2. The research programme

ASCenSIon research programme focuses on the main research areas of launch vehicle design: 1) Propulsion technologies and their reusability; 2) Guidance, Navigation and Control (GNC); 3) Aerothermo-dynamics of re-entry and safe disposal. Sustainability is an underpinning factor, and it is considered, for example, in the study of green, environment-friendly propellants or in the safe disposal of space objects, as well as taking into consideration the space situational awareness. The three research areas identified above correspond also to the three technical work packages of the project, and each researcher addresses at least one of them. During the three years of involvement, each of the 15 researchers works on a specific Individual Research Project (IRP) which is highly interconnected with the other IRPs, with a synergetic and interdisciplinary approach. Following the project vision, the IRPs have been shaped to cover all the aspects of the access to space domain.

This synergetic approach exists not only between the PhD students, but also between the partners, and it is well depicted in Figure 1. The idea behind such a synergetic approach is to create a strong network within and outside the project, aimed to last longer after the project end. Within ASCenSIon this is facilitated by the intensive programme of training courses and network wide training events. The full list of the employed ESRs and their IRPs can be found in the paper "Advancing Space Access Capabilities For and By Early Stage Researchers" by Gloder et al. [5], as well as in the project website [3].

2.3. The training programme

Previous analyses of the access to space domain showed that a training programme for young researchers covering the whole field of space transportation, i.e. including fundamental aspects of propulsion physics, system design,

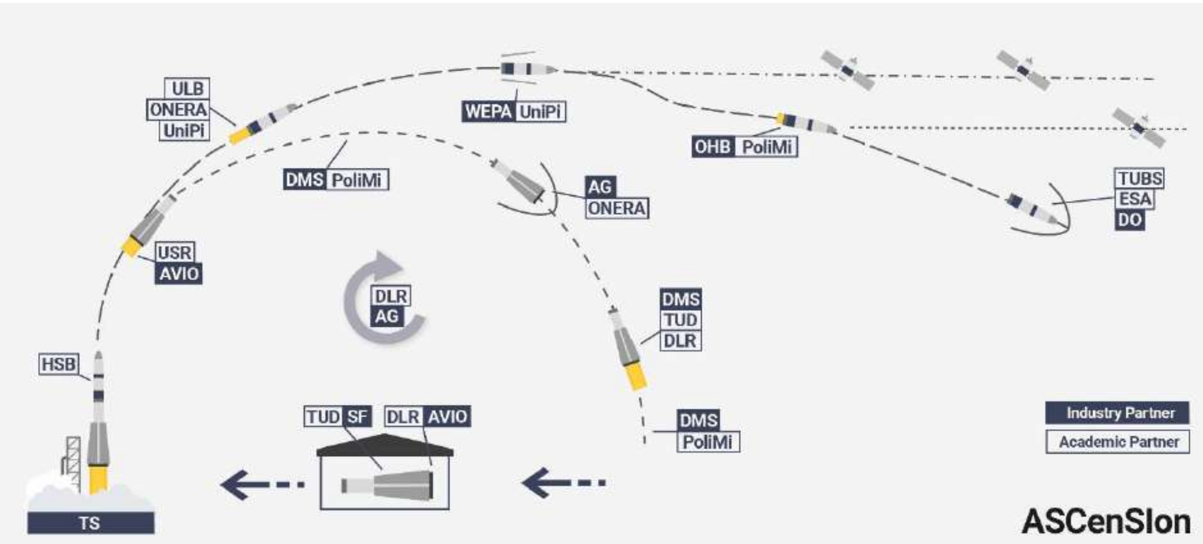

Figure 1: Synergies of the ASCenSIon consortium.

DOI: 10.5821/conference-9788419184405.137

GNC, sustainability and reusability, is currently missing in Europe. Three other research training programmes for launcher systems have been identified in three countries addressed by ASCenSIon: the master in Space Transportation Systems (STS) at Sapienza University of Rome in Italy, the French "Project etudiant de recherché spatiale Européen universitaire et scientifique (PERSEUS), and the German programme "Studentische Experimental-Raketen" (STERN). Despite this, these three programmes address students at bachelor and master level, leaving ASCenSIon as the only doctoral programme in Europe that focuses and advances the field of space transportation.

The training of ASCenSIon goes beyond the more traditional PhD programmes that normally focus on one discipline, one domain and one country. It develops on two levels: a local programme, carried on by the institutions that host the PhD students and include the usual offers, and a network-wide training programme which aims at expanding the training of the ESRs with a structured, multicultural and multisectoral approach and introduces them to the whole launcher development field. These network-wide trainings are offered quarterly in the form of experimentation weeks, summer schools, workshops and conferences.

Moreover, the young researchers are expected to gain not only technical, but also transferable skills (for example on scientific communication and entrepreneurship). To complement the training, they experience at least two periods of secondments during their employment, one at an academic and one at an industrial partner. They are trained by experts from industry and academia and gain not only theorical, but also practical knowledge. A structured approach is maintained to ensure that all the ESRs get equal benefits during their training, as well as multi-partner supervision and access to unique research environments.

3. Mid-term overview on the training programme

Despite the structured approach of the training programme, the original plan for ASCenSIon had to be re-discussed and partially changed due to the outbreak of the worldwide Covid-19 pandemic. The real training programme of ASCenSIon started in January 2021 after the selection and employment of all the ESRs, so still in the middle of the crisis. Being ASCenSIon highly reliant on the mobility of both its researchers and supervisors within Europe, as all other ITNs, it was almost impossible to organise in-person events for the majority of 2021, due to the different safety and travel rules in place in the different countries and institutions involved. Consequently, the proposed network-wide events had to be switched online, and this required a quite different approach in terms of organisation, commitment and offer with respect to what was initially foreseen. Of course this partially affected the content and quality of the training and, in particular, some of the hands-on experiences had to be cancelled, as well as visits to partner institutions. Being highly reliant on the synergies between the involved people, starting such a complex and dynamic project without meeting in person indeed represented an additional challenge.

The main training events organised within ASCenSIon from its beginning until the date of delivery of this paper are: a kick-off event (January 2021), during which the ESRs and supervisors met each other virtually for the first time, were introduced to the project and received lectures on both technical and entrepreneurial aspects; a technical conference (June 2021), during which the main technical aspects of the research were discussed and presented to both associated partners and external experts; a training week (November 2021), which was the first in-person event of the project and took place in Politecnico di Milano (Italy), during which the ESRs experienced partner and lab visits, received lectures on both technical and soft skills, had the chance to directly interact with the project partners and work package leaders and receive feedbacks and suggestions on their research, and, last but not least, had the chance to gather together and get to know each other better. These major network-wide events were also integrated with other opportunities, such as the attendance of the lectures of the Master in Space Transportation Systems organised by Sapienza University, a dedicated special session at the AIDAA XXVI International Congress, the attendance of the DLR Summer School on space propulsion, as well as the participation in other conferences and events, such as the International Astronautical Congress (IAC) in Dubai in October 2021, or the dedicated workshop on Human Spaceflight Mission with astronaut Gerhard Thiele.

As a mid-term consideration, the authors of this paper, who are the Coordinator of the consortium, can say that overall it was possible to maintain quite satisfactory standards for the training, including a varied offer in terms of partner and expert participation, content, and format. Thanks to the softening of the safety rules in place during 2021, secondments could be organised almost in the initially foreseen

DOI: 10.5821/conference-9788419184405.137

times, and only a few suffered delays, without having major impacts on the overall research programme. Despite this the authors are convinced that, for such a training programme, online events are a good alternative, but they certainly cannot fully substitute in-person events. Meeting in person is fundamental to keep up the quality of the proposed training, the motivation of the participants, their involvement and a fluent and efficient communication among the participants, which are all fundamental aspects for the well-being of a project and its synergy.

4. Lessons learned

Given that the project started in January 2020, this paper is written approximately in the middle of the project length, therefore allowing already the sharing of some lessons learned and some considerations.

First of all, while on one side a rigorous approach is needed for the fulfilment of the requested deliverables and tasks in such a large project with so many partners, it is important that all the involved people maintain an understanding and flexible attitude. This is fundamental to avoid discontent, the arising of misunderstandings and for the people to be able to work in a productive and stimulating environment. This does not apply only to interpersonal relationships, but also with respect to the planning and management of the project itself. The training offered by ASCenSIon is highly demanding for both the people who organise it and receive it, as it adds to all the tasks that the researchers carry on locally, and the matching of the two does not happen easily. The participation in conferences and events, the planned secondments and the availability of the involved partners also contribute to the need for a flexible approach with respect to the initial technical and training schedule, which therefore needs constant revision and adaptation. Overall, ASCenSIon requests quite an effort from all the involved people that needs to be taken into careful consideration.

A fundamental lesson learned by the authors is that a good planning of the risks and mitigation strategies can save a lot of problems in case one (or more) of these risks materializes; to the list of potential risks also high-impact, low-probability events such as worldwide pandemics, wars, etc should be included since the beginning, especially if a project lasts some years. A paper previously published by the authors [5] addressed for example the impact of the Covid-19 pandemic on the project, which in the case of ASCenSIon happened right at the beginning. Being the pandemic an unforeseen risk, its impact on the project was quite high, even though the implementation of timely mitigation strategies allowed to greatly reduce the collateral damages. Such an apparently afar risk, as well as others (e.g. a war), should therefore not be underestimated. A part from this, other foreseen risks materialized during the period of interested addressed by this paper (January 2020 – March 2022), such as the unexpected loss of key expertise/staff (due to the withdrawal of a beneficiary partner, for reasons not linked to the project), the withdrawal of an ESR (again, for external reasons), technical problems to achieve the research objectives, and delays in the recruitment of the ESRs (due to the outbreak of the pandemic). In these cases, proper mitigation strategies and timely interventions were fundamental to avoid the rise of bigger problems and allowed to tackle the issues before they escalated.

Another aspect of outmost importance is the careful selection of the partners and of motivated ESRs. For the project to achieve its final objectives, especially in the case of a synergetic project such as ASCenSIon, not only their prestige and good curricula are essential, but also their involvement, proactiveness and motivation for the entire duration of the project, as well as an open and efficient communication at all levels. The training programme relies in fact on the availability of the project partners to host and organise the events, while the research programme relies on the sharing of information, knowledge and best practises, as well as on the production of high-quality work and supervision. Unmotivated, unavailable and uncommunicative persons highly affect the whole structure of the project, and put at risk the achievement of its goal.

Conclusions

ASCenSIon is the only doctoral training programme in Europe that addresses the access to space field as a whole, setting a new standard. It addresses the field of space transportation with an interdisciplinary, multicultural and intersectoral approach, which highly relies on the synergy of the whole consortium.

It is a highly demanding project, in which factors such as risk mitigation strategies, partners' collaboration and involvement, timely communication and proactivity are essential for the project development and tracking, as well as for ensuring visibility and delivery of reports, deliverables and milestones.

Acknowledgement

The authors acknowledge the contribution of all the people involved in the project, whose trust and daily involvement are fundamental for its development and completion. The authors also acknowledge the funding Agency of the project, the European Commission: the project leading to this application has received funding from the European Union' s Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 860956.

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STAR-XL: Student Transponder for Satellite Ranging on X & L-band

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Abstract

The ESA ESEO Mission [1] included an amateur radio payload [2]. The results of which included the development of radio technologies that utilised final year student projects over a 5 year period. Many lessons regarding compliance and process enabled a new payload to follow: the Student Ranging Transponder Radio for X-band and L-band (or STAR-XL). The STAR-XL design leverages key aspects of the ESEO payload design for a generic CubeSat platform; including TT&C voltage and current sense circuitry, receiver circuitry, and flight software. But instead of a maximum 4800 bps telemetry and transponder system - the STAR-XL targets a 100 kHz bandwidth system that will allow faster downlink rates that are forward error correction, link margin and modulation order dependent. With 100 kHz bandwidth, the linear receiver is designed to also operate as a transponder - enabling ranging and navigation applications such as orbit determination and further experiments from amateur radio groundstations. This paper details the recent student project efforts in three key areas: a new STM32-based on-board computer, an X-band up-converter board and dual X/L band patch (as shown in Fig. 1). The new OBC includes an IQ modulator for transmitting complex waveforms and an optimised flight software suite that takes advantage of dual DMA hardware on-chip to reduce overheads. The X-band upconverter board required the development of new safety interlock and RF chain circuitry on a Rogers (RO4350B) PCB material. A new dual X/L-band patch antenna and filter circuit is also built and measured. Each of these projects has led to new lessons and increased the real-world case studies used to teach spacecraft avionics.

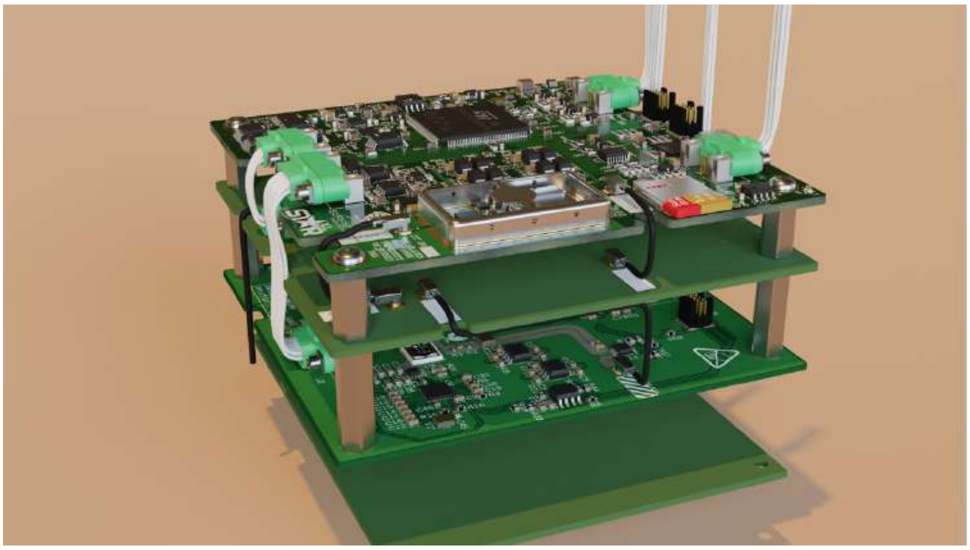

Figure 1. STAR-XL CAD Blender Model

Keywords

Transponder, Satellite, Ranging, Radio

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1. Background

A 1U CubeSat payload, known initially as FUNcube-NEXT and later STAR-XL, is being developed based on AMSAT-UK's FUNcube-4 payload, which is on the European Student Earth Orbiter (ESEO) satellite that was launched in December 2018 by ESA. FUNcube-NEXT will comprise a flight computer board that will be an improved version of the one in FUNcube-4. It will support downlink modulation and bandwidth experiments with the aim of increasing the downlink data rate. It will also have a new microcontroller both to support the higher downlink data rates and because the part used in FUNcube-4 has reached end-of-life status.

2. Flight Computer Development

When developing this flight computer board, a standalone Elegant Bread Board (EBB) flight computer was developed. It has all the functionality of the final flight computer board, including an RF oscillator and RF IQ modulator for the experimental downlink improvements, and in addition includes facilities to enable two distinct candidate microcontrollers (a low power low performance one (STM32L4P5) and a high-power high performance one (STM32H725)) to be evaluated in reality. These facilities include the ability to switch between the candidate microcontrollers, instrumentation to enable the power consumption of key parts of the design to be analysed, and USB communication between the microcontrollers and a PC.

The RF results include PSK constellation diagrams resulting from configuring the development board to produce a variety of PSK modulations. New dynamic MCU clocking results show that the MCU can change its clock frequency dynamically, how the MCU utilisation, current consumption and power consumption depend on the clock frequency, and also how these are affected by enabling the MCU caches.

Power consumption analysis results show that the STM32H725 easily meets the MCU power budget requirements when clocked at 256 MHz despite being a high power MCU and that higher clock speeds are possible provided certain precautions are taken. At 256 MHz, its performance is approximately 12 times that of the processor used in the FUNcube-4.

In the expected orbit for FUNcube-NEXT, the radiation exposure should not be significantly greater than on the surface of Earth, except when over the SAA. As a result, using radiation-hardened components is deemed unnecessary. However, SEUs must be tolerated, so hardware ECC availability will be a criterion for choosing MCUs. Should an MCU without ECC be chosen, memory scrubbing techniques will be employed. Ultimately, should the STM32H7 be used as the flight computer MCU, the risk of memory corruption due to SEUs would likely be decreased to an acceptable operating level, even without additional firmware to perform memory scrubbing.

Several design aspects from the ESEO CCT [2] are to be carried forward to the flight computer development board. The existing current sensing approach, including chosen current sensor, input filter and ADC will be incorporated into the new design. The CAN bus architecture and transceivers will also be kept.

The Analog Devices design to couple a single-ended DAC to the IQ modulator is adapted to fit the project objectives and includes a 5th order Bessel filter to remove DAC quantization noise.

Finally, established PCB layout techniques will be employed whilst designing the PCB for manufacture. A single ground plane will be used to avoid unintentional ground loops, and the analogue and digital domain will have separate power planes.

Figure 2. STAR-XL Flight Computer EBB PCB

2.1. Dynamic MCU Clocking

To test the STM32H7 dynamic MCU clocking, firmware was written that gave the MCU a fixed amount of work to do per second, while the MCU core clock was cycled through a series of frequencies and the MCU utilization, current and power were measured. The firmware used the FreeRTOS real-time operating system, with the work task running at the highest priority.

Percepio Tracealyzer [3], a commercial instrumentation tool for FreeRTOS firmware, was used to monitor the MCU utilization and display it on the PC. Tracealyzer has two modes of operation. In one mode, known as snapshot, the instrumentation data is stored on the MCU during logging, and then downloaded at the end. In the other mode, the instrumentation data is streamed continuously to the PC in real-time. The real-time streaming was found to work with the STM32F767 on an STM32 Nucleo board, and later on an STM32H743 on an STM32 Nucleo board after working with Percepio and receiving an update to the software. The dynamic clocking experiments were conducted using the non-real-time instrumentation (snapshot) mode.

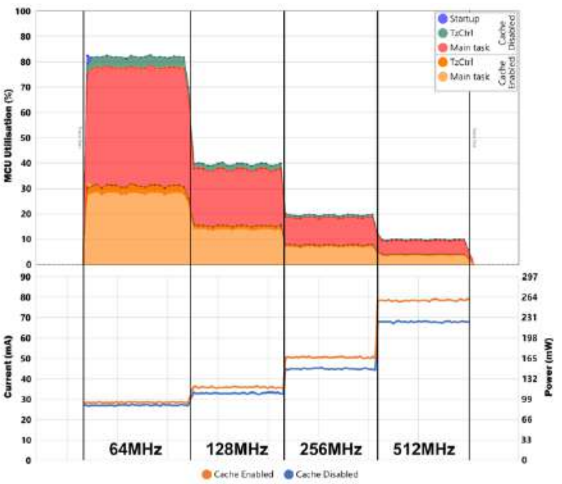

Figure 3. Percepio Tracealyzer showing Frequency vs Current Consumption.

Note that enabling the caches leads to a performance increase of approximately 167% for only a small increase in power consumption.

For use in Space, it is often preferential to disable caches as they are particularly vulnerable to SEUs. However, in this case, the increase in performance is significant enough to consider alternative approaches to handling SEUs vulnerability.

The new flight computer can reliably generate BPSK signals up to 19200Baud, a considerable improvement over ESEO, and has been tested up to 115200Baud, of which the hardware is fully capable but limited by single-buffered-DMAs. AFSK signals can be decoded in the same manner as ESEO, however optimisations have been performed to reduce the CPU usage from the 50% on ESEO, to 37% as a baseline with the microcontroller, and finally further optimisations were made to optimise the entire system down to 13% CPU usage. This gives a lot of room for future expansion.

The new flight computer also operates at a much lower power consumption than ESEO, operating at 94.1 mW with all systems including the redundant CAN interfaces running at full capacity, all while maintaining redundant oscillators and backup power supplies for adverse situation recovery.

3. Flight Software

During the development of the STAR-XL hardware, a new fork of flight software was being written. The functionality encompassed by this software includes the sampling and decoding of the AFSK uplink baseband, the gathering & encoding of data from the payload and the generation of the BPSK downlink baseband. This was all handled by the new STM32H7 series CPU. A key feature of the software is the requirement for multiple functional areas of the program to be executed in a pseudo- parallel way; this necessitated the use of a scheduler to separate the execution time of the processor into threads.

FreeRTOS was reselected for this purpose due to its low memory impact, high performance and free use license. FreeRTOS also has excellent existing integration with the STM32 series microcontrollers, having been rigorously tested as part of the STM32CubeMX/IDE development tools provided by STMicroelectronics.

The decision to treat the flight software as a completely thread-parallel system has introduced the requirement for resource-locking, however this extra performance overhead is offset by the improvements in single core performance of the CPU and the inherent capability of porting to a dual (or greater, in the future) core CPU with minimal extra software effort required.

3.1. Software Architecture Improvements

As seen in thread execution time in the ESEO flight software, collisions can be seen between the uplink and downlink ISRs. While this has been partially resolved by reducing the processing time spent in each ISR and ensuring that nested vector interrupts are enabled, this has never solved the issue.

ESEO literature defines a “sampling jitter of only 1.8% of the sampling frequency in 1.2kbps mode and 7.8% in 4.8kbps [is observed]”. Due to the low sampling frequency and the comparatively high clock speed of the

DOI: 10.5821/conference-9788419184405.138

microcontroller this jitter should be a lot lower. It is obvious that the interrupts are still colliding, just in a considerably less noticeable and catastrophic way. Having 2 interrupts which are both highly time critical, and where there is a high probability of both firing at the same time, or while the other ISR is still running is a significant processor time contention issue. This is a perfect situation to leverage the high flexibility DMAs available on the new STM32 platform for both ADC and DAC sampling, in order to move the sampling load from the CPU to hardware and remove the reliance on hard-real-time interrupts.

In the new solution for STAR-XL, the DAC and ADC are configured to trigger on the rising edge of their respective hardware timer (internal to the CPU), the ADC will then convert a sample and trigger the DMA once it is complete. The DMA engine will then move the sample to a ring buffer in memory ready for the CPU to process. Likewise for the DAC, a hardware timer will trigger the DMA to move a sample from a memory buffer to the DAC, the DAC will then trigger and the sample will be converted to the output.

This approach has the benefit of eliminating the jitter caused by ISR collision, as the peripherals and DMA operate entirely independently of the CPU. From the perspective of the CPU core, a ring buffer is asynchronously filled with samples at a regular interval. The buffers are sized appropriately such that they will never be fully filled nor emptied by the DMA and peripherals; it is then the responsibility of the CPU to ensure that these buffers are adequately serviced. During this entire process there are minimal system interrupts, the scheduler is free to allocate CPU time as it sees fit.

The Uplink and Downlink are now entirely decoupled from the processes which generate their samples; the buffers now are able to be generated in an environment requiring considerably less hard-real-time performance. This also has the advantage that the CPU cycles that would otherwise have been used to trigger (and wait for) the ADC and DAC can now be used to prepare or process samples. This allows for a much higher sample rate to be used, which contributes to improving the probability of receiving accurate symbols from the uplink and can reduce the filtering requirements of the downlink. A higher temporal resolution can be developed at the DAC output. This allows an in-situ raised-root-cosine filter to be implemented which in turn allows a higher data rate to be achieved on the downlink without introducing harmonics.

The processor chosen should has a fully featured DMA engine along with 2+ independent ADC peripherals. Therefore, one ADC can be dedicated to reading the AFSK uplink using the DMA. To expedite these transfers and reduce bus contention the processor chosen should have a suitable inter-peripheral crossbar matrix (or manufacturer equivalent) to allow the DMAs to access RAM at high speed without impacting the speed or latency at which the CPU can access that same RAM. If there is a section of RAM that can be accessed using a different bus that would be ideal to allow for multiple simultaneous RAM operations to take place.

3.2. Profiling, Logging and Debug

Critical to debugging, testing and validating the software is a versatile and well-structured logging system. The ability to output logs to a debug UART or ITM is critical to debugging running software without interrupting it with breakpoints; even a log as simple as a heartbeat can be useful for determining if a processor is still running. Logs are also useful when performing tests to determine the number of packets transmitted and received from various communications interfaces, this is useful when performing statistical analysis of communications reliability.

The logging system is designed to be as low-impact as possible, while also maintaining high levels of functionality. A “Logger” is created for each file with source code that will be instrumented for logging, likewise the various “Loggables” for said Logger are also defined using macros of a similar structure. These Loggables include:

- Events – Log the hit of a particular line of code, such as a conditional or state.
- Function – Log the entry and return from a function, along with its execution time and other parameters
- Housekeeping Result – Special event type for the housekeeping thread to log a failure or success of a housekeeping activity.

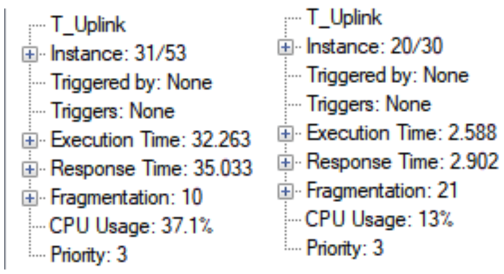

Figure 4. AFSK Uplink: Optimised Implementation CPU Usage Breakdown

DOI: 10.5821/conference-9788419184405.138

3.3. Thermal Chamber Testing

The chamber was programmed with a thermal profile depicted in Fig. 5, in which the chamber and board was heated to +55C as fast as the chamber can safely allow, dwelled for a period then cooled as rapidly as the chamber will safely allow to -25C, another dwell and the cycle was repeated 4 times for a total of 4 hot dwells and 4 cold dwells. At the first hot and cold cycle a set of instantaneous state and statistical analysis tests were performed to obtain a baseline of the boards performance at the extremes of temperature expected during spaceflight. The cycles were left running overnight with the board depowered. As seen in the thermal data figure, there was a gap in the thermal measurement data caused by the university IT department restarting all networked computers at 3AM. Suitable provision should be made to not allow this to happen in future tests.

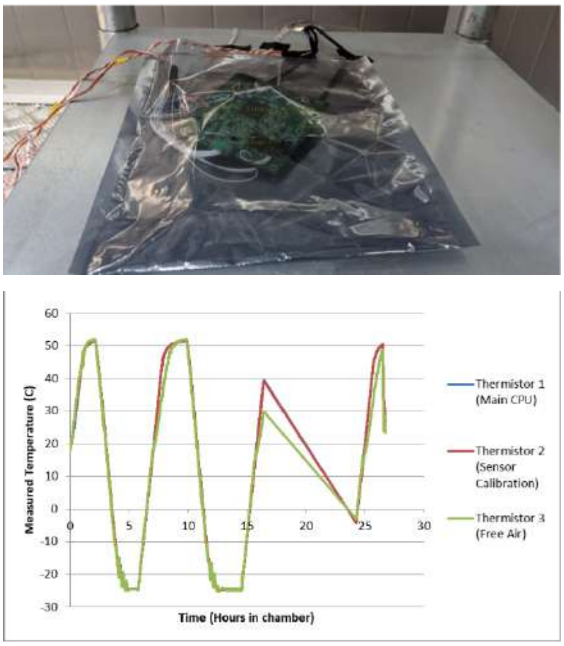

Figure 5. Thermal Chamber Internal Setup & Testing Recorded Thermistor Data

4. RF X-band Tx Board & Antenna

Iterative designs of the proposed RF chain for the STAR XL payload are shown below.

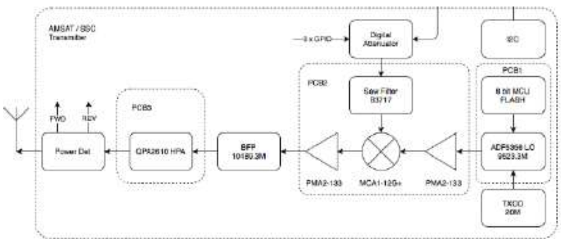

Figure 6. transmitter chain from the STAR XL system diagram

The received 1264 MHz signal arrives at the L-Band receiver developed and is mixed down to an intermediate frequency of 45 MHz. From here, the signals are separated, with the AFSK modulated commands being forwarded on to the On- Board Computer (OBC). The RF switch allows the transmitter to select whether to broadcast a response to the AFSK commands, or forward on the other signals that were not sent to the OBC. The signal then continues through the chain, where it is mixed up to another intermediate frequency of 866 MHz.

The intermediate 866 MHz signals are passed from the L-Band receiver section to the X- Band transmitter section. The intermediate frequency is mixed with a local oscillator set at 9623.3 MHz, producing a desired RF output at 10489.3 MHz, and the other modulation product at 8757.3 MHz. The transmitter chain then filters out the unwanted product and any of the local oscillator that has made it through to the output, where it is boosted by a high-power amplifier (PA) and then transmitted back to Earth.

A number of EBBs were developed including a high power amplifier and mixer / filter circuits in the following figures.

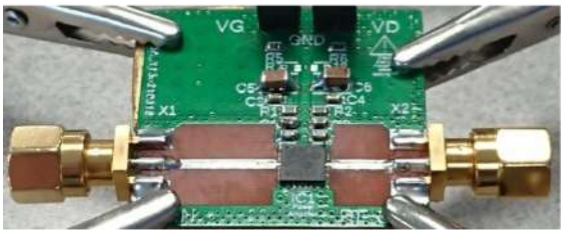

Figure 7. The modified HPA PCB, showing the new SMA connectors (with 50-ohm terminators attached)

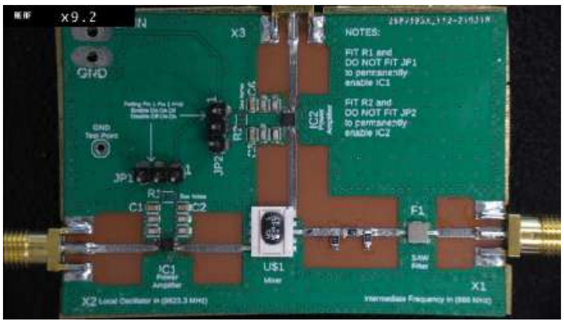

Figure 8. The completed circuit board for the RF Mixer, with modified SMA connectors and added Pi attenuator

We have verified that the DC response of the PMA2-133LN+ amplifiers matches that described in the datasheet. The MCA1-12G+ mixer performed as expected, generating a stable, low-noise signal at 10489.3 MHz as desired. The S-Parameters of the system were measured and found to be acceptable for the

DOI: 10.5821/conference-9788419184405.138

performance of the system. Overall, the mixer EBB design performed as desired, and the parts selected for use in the block diagram are satisfactory for use in the final transmitter design. It may be necessary to add matching components at the outputs of the PMA2-133LN+ amplifiers, and the Pi attenuator values may be amended to provide different attenuation and better matching at 50Ω.

The High-Power Amplifier board had the most issues, with PCB design flaws, transmission line errors and supply rail anomalies. More than 60% of the power in the system was being wasted as heat. Despite this, the transfer response of the device followed the expected performance indicating a capable device if all these problems are rectified. After correcting the design, a final board design is developed.

Figure 9. STAR-XL X-band Transmitter

Given the new X-band transmitter, a new antenna is needed for dual L-band receive and X-band transmit.

Table 1. Dual-band Antenna Design Parameters

Mechanical Properties	**Dimension**	
Overall dimensions	100.5x82.6x2.2mm	
Radius of Void in L-band patch R_{Void}	8.5mm	
Width L-band patch W_{Patch}	61mm	
Diagonals L-band patch L_{DLong}, L_{DShort}	92.5mm, 89.5mm	
Width of tuners in L-band W_{Tuner}	5mm	
Feed inset L-band x_{feed}	21.5mm	
Substrates & height h	1.524mm RO3003, Patch PCB	0.508mm RO4350B, Feed PCB
Aperture feeding dimensions X-band	See Table 12	
Tuner Dimensions X-band	See Table 13	
RF Properties	**L-band**	**X-band**
Centre frequency f_r	1.264GHz	10.4893GHz
Bandwidth	18.2MHz (S11 ≤ -10dB)	919MHz (S11 ≤ -15dB)
Axial Ratio at f_r and in direction of propagation (z-Axis)	1dB, AR BW 3.6MHz	2.2dB, 3dB AR BW 297MHz
Half Power Beamwidth (HPBW)	95°	106°
10dB Beamwidth	180°	160°
Power reduction at 120° beamwidth	4.8dB	4.3dB
Antenna Peak Gain	5dBic	4.9dBic
Polarisation	RHCP	LHCP
Cross coupling X-band to L-band	< -40dB	

Figure 10. X-band Antenna

Here, the measurement results of the manufactured combined antenna are presented. First, the L- band measurements are investigated and then the X-band measurements are also shown. Figure 10 shows images of the assembled combined antenna as seen from the top side (a) with the L- and X- band patches.

Although the bandwidth is reduced in the aperture integrated antenna, the design can still be used well given the possibility of tuning. Despite this limitation, the simulated design fulfils all design requirements of this work can thus be manufactured.

Acknowledgements

This work is possible with the support of AMSAT-UK and the Uni. of Surrey UG/PG dissertation project students, staff and support services.

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SGAC Global Satellite Tracking Initiative

Daniel Sors Raurell [1], *Laura González Llamazares* [1], *Sergio Tabasco Vargas* [1], *Lucille Baudet* [1]

Abstract

The Global Satellite Tracking Initiative aims to support international students and young professionals to set up ground stations to download real-time data and images from satellites orbiting above their regions. The objective is to empower and build capabilities among space enthusiasts around the world and to promote the space sector through hands-on activities and real space technologies related to satellite communications.

The Space Generation Advisory Council, together with SatNOGS as an integral part of the Libre Space Foundation, have been supporting the initiative to enhance the development of a global open source network of satellite ground stations. The initiative will be providing all the resources, hardware, and know-how that is needed to set up ground stations. A competition was launched by the end of 2021 to select teams of space enthusiasts and supply them with a kit and step-by-step instructions on how to build their own ground stations.

By setting up ground stations in backyards, local universities, or maker clubs, teams are not only self-learning about telecommunications and satellite technologies, but they are creating a meaningful impact in their local communities by bringing the broad society closer to science, technology, engineering, mathematics and, in particular, space. The initiative also intends to support space missions while engaging local communities from different regions around the world in the space sector through appealing imagery and tools.

After closing the Call for Applications in this pilot initiative, 10 winning teams were selected upon receiving almost 200 applications from more than 60 countries. The selected winners are based in the following emerging space faring nations: Benin, Bolivia, Egypt, Ethiopia, Nepal, Peru, Philippines, Rwanda, Vietnam, and Zimbabwe. They are being supplied with a basic Ground Station Kit and instructions on how to receive live images and data from different space missions, starting with the following frequency bands:

- 137 megahertz: To receive images from National Oceanic & Atmospheric Administration satellites.

- 144-146 megahertz: To receive images and data from the International Space Station.

- 440 megahertz: To receive data from numerous scientific and educational small satellites.

Those teams that manage to set up the basic ground station kits and conduct some outreach and educational activities will receive a more advanced system. This paper captures the process to be followed by the selected teams, from the unboxing of the hardware to the reception and processing of data from operational space missions.

Keywords

Education, Satellite tracking, Ground station

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Acronyms/Abbreviations

SGAC	*Space Generation Advisory Council*
GSTI	*Global Satellite Tracking Initiative*
NOAA	*National Oceanic & Atmospheric Administration*
ISS	*International Space Station*
SDR	*Software Defined Radio*

1. Introduction

The Space Generation Advisory Council (SGAC) is the global network for students and young professionals interested in the space industry, with more than 15000 members globally from more than 150 countries. SGAC supports the United Nations Programme on Space Applications, with the vision of employing the creativity and vigour of youth in advancing humanity through the peaceful uses of space. SGAC organises events worldwide, on a local, regional and international level, as well as several space related projects within specific working groups.

As members of SGAC, the authors determined that the organisation could enhance its impact by engaging in hands-on activities for the benefit of young space enthusiast around the globe. A proposal was submitted and the SGAC Global Satellite Tracking Initiative was selected to join the first cohort of the SGAC Incubator Programme [1].

The Global Satellite Tracking Initiative (GSTI) [2] aims to facilitate students and young professionals to set up ground stations and download real-time data and images from satellites flying above their regions. Due to the nature of the activities, the GSTI team got in touch with SatNOGS [3], an initiative by the Libre Space Foundation that operates an Open Source global network of satellite ground stations. The objective is that, once the GSTI teams have become familiar with the operation of the basic ground station kit provided by the GSTI, they keep developing their skills and capabilities while interacting with other space enthusiasts by joining SatNOGS operational collaborative network.

2. Selection Process

The funding secured through the SGAC Incubator Programme, together with in kind contributions from partner organisations, allowed for the procurement and delivery of ten basic ground station kits. In order to choose ten teams from around the globe, a two-step selection process was launched in October 2021. The selection criteria used were:

a) Motivation: the responses ranged from university students trying to get involved in hands-on projects to local communities involved in scientific outreach interested in widening their portfolio of activities.
b) Feasibility: the answers received included individuals trying to set-up a ground station in their own backyard, as well as teams that had secured access to dedicated facilities already hosting telescopes and other receivers.
c) World Location: the teams were asked to explain why their geographical location was adequate for the project while being invited to check the existing coverage in the SatNOGS network. Applications from more than 60 different countries were received.
d) Outreach and impact: the responses went from university professors interested in offering their students a chance for practical training, to individuals in remote locations planning to help their local communities to be more engaged in science and technology.

The first step was an online application form, which allowed for a pre-selection of 20 teams among the close to 200 applications received. During December 2021, the GSTI team interviewed these 20 teams to come up with the 10 awardees. The selected team names and nationalities are listed in Table 1 and their approximate geographical locations are shown in Figure 1.

Team Name	Country
Chasqui 2	Peru
Fly by encounters	Egypt
GST Benin	Benin
Hanos Orbit	Ethiopia
Ludibrium	Vietnam
Pacha	Bolivia
Rwanda Space Agency Team	Rwanda
SEDS-MSU	Zimbabwe
Team Deep Space	Philippines
Team Everest	Nepal

Table 1. Selected teams

Figure 1. Selected teams map

3. Ground Station Kit

The Ground Station Kit was designed with the objective of minimizing cost, size and complexity. This was intended to maximize the number of kits that could be delivered within the available financial envelope while allowing for a rewarding experience from the participating teams in receiving their first space data.

3.1. Kit Size and Content

The kit was designed to fit in a plastic container box of 30 x 20 x 10 centimeters. When assembled, the size of the system is enlarged primarily by the deployment of a V-dipole antenna, composed of two rods of around 50 centimeters each at an angle of 120 degrees.

The components of the kit are listed below:

- Raspberry Pi 4 model B
- SANDISK Extreme class 10 microSDHC memory card of 32 Gigabytes
- RTL-SDR V3 dongle
- Dipole antenna base with 60 centimeters of RG174 coaxial cable
- Two telescopic antennas of 23 to 100 centimeters
- 3 meter RG174 extension coaxial cable
- Flexible tripod mount
- Suction cup mount
- 3-D printed dipole antenna support at an angle of 120 degrees

Figure 2. RTL-SDR dongle and antenna set

3.2. Power Requirements

The kit uses power output from a standard USB port. Most USB ports supply 5 Volts of electricity with a maximum current of 0.5 Amperes. This leads to an overall power output of 2.5 Watts.

3.3. Targeted Satellites and Applications

The main objective of this initiative is to acquire signals from orbiting spacecraft for educational, inspirational and capacity building purposes. For this reason, the targets for signal acquisition will be spacecraft emitting openly, including:

- National Oceanic and Atmospheric Administration (NOAA) satellites, which provide timely access to global environmental data. Frequency band of 137 megahertz.
- International Space Station (ISS), since it is deemed that in listening to a spacecraft that permanently hosts humans in space will be very motivational. Frequency band of 144-146 megahertz.
- Educational and scientific satellites (especially CubeSats) in Low-Earth orbit. There is the potential of contributing to the Launch and Early Operations Phase through collaborative networks such as SatNOGS. Frequency band of typically 440 megahertz.

4. Receiving and Processing Satellite Data

The process of assembling and setting up an operational ground station can be challenging for people with no previous experience in using similar technologies. In order to flatten the learning curve and make the encouraging experience of receiving and processing data from orbiting satellites more accessible, the GSTI includes a set of instructions and exercises that enable a gradual approach.

The instructions of the SGAC Global Satellite Tracking Initiative Kit are divided in two procedures:

- Procedure-1 (basic): focused on receiving weather data from NOAA satellites using a personal computer.
- Procedure-2 (advanced): focused on setting-up a Raspberry Pi with SatNOGS software, leading to an autonomous online ground station.

GSTI is currently working with the selected teams to implement Procedure-1, which is summarized in this section.

DOI: 10.5821/conference-9788419184405.139

4.1. Antenna setup

Procedure-1 starts with the assembly of the kit components and the deployment of the V-dipole antenna. The two telescopic antennas need to be extended to 52 centimeters of length [5] and inserted through the dipole antenna support to secure the 120-degree angle before connection to the dipole antenna base. Figure 3 shows the system assembled on the flexible tripod mount.

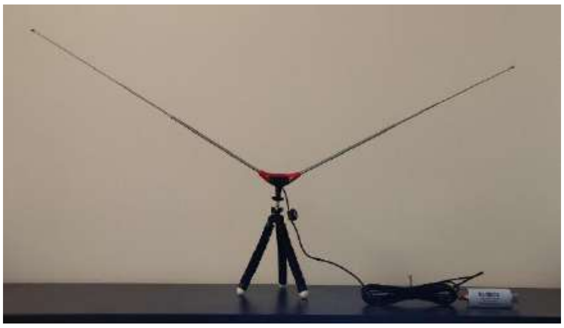

Figure 3. Antenna assembly

4.2. Downloading and installing the software

GSTI relies on the use of free-to-use software. The main software products required to complete Procedure-1 are:

- SDR# [4]: Software Defined Radio (SDR) software to tune into different frequencies.
- WXtoImg [5]: Fully automated weather satellite decoder.
- Satellite Tracking Software: Such as Orbitron (personal computer) [6] and Heavens Above (smartphone) [7], which facilitate the visualization of satellite orbit geometries and make it easier to understand where to point the antennas.

4.3. Hands-on exercises

Procedure-1 considers three main exercises to help users to gradually become familiar with the kit and exploit its capabilities.

4.3.1. Exercise 1

The first exercise invites users to connect the RTL-SDR V3 dongle to their personal computer and configure it as the source within SDR# to listen to a local radio station. This helps the users to become familiar with the SDR# software, its configuration options and user interface.

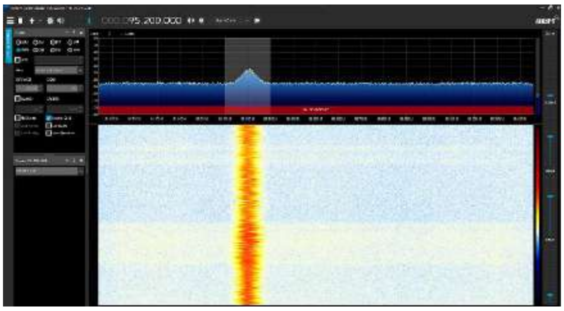

Figure 4. Local radio station signal in SDR#

4.3.2. Exercise 2

The second exercise focuses on decoding an image from the audio recording of a satellite signal [8]. This allows users to verify that they have understood how to carry out the record and image decoding functions in WXtoImg before attempting to capture a satellite pass.

4.3.3. Exercise 3

The last exercise of Procedure-1 consists on downloading an image from an operational NOAA satellite. The main steps are:

1. Plan a pass based on your geographical location and local time, making use of one of the suggested satellite tracking software products.
2. Configure SDR# to tune into the right frequency depending on the target satellite [9]:
   a. NOAA 15: 137.6200.
   b. NOAA 18: 137.9125.
   c. NOAA 19: 137.1000.
3. Record the pass and decode the images using WXtoImg.

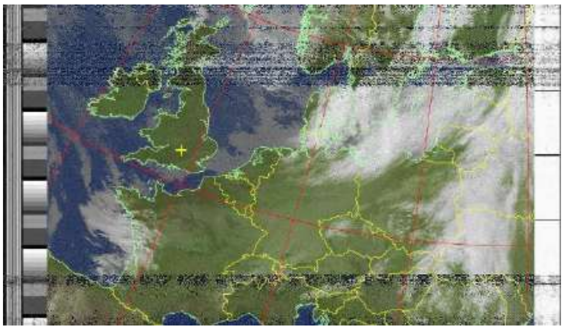

Figure 5. Decoded NOAA image using WXtoImg

5. Results and discussion

The SGAC Global Satellite Tracking Initiative received applications of close to 200 teams of space enthusiasts from more than 60 different countries. Due to funding constraints, only 10 of those teams are receiving a ground station kit.

However, GSTI aims to become a platform open to all the applicants in which the ground station kit and instructions will be made available. The intention is to allow anyone to join the community, replicate the kit and benefit from the resources developed during the initiative.

The selected teams are starting to receive the funded ground station kits and complete the exercises proposed in Procedure-1. Once completed, they will have the chance to further develop their skills and start contributing to the SatNOGS network through Procedure-2, which is currently under development.

6. Conclusions

The success rate of the selection process suggests that there is an untapped interest among university students and young professionals to engage in hands-on space activities.

At the same time, this initiative provides an example of how the widespread availability of affordable consumer electronics and open software can be leveraged to interact with existing space infrastructure. This has the potential of making space more accessible to all, helping to promote and support education in science and technology and contributing to the creation and expansion of collaborative projects of tangible benefit to the space community, such as SatNOGS.

Acknowledgements

The SGAC Global Satellite Tracking Initiative would not have been possible without the support of our partners, who have facilitated access to hardware, knowledge and resources:

- SatNOGS, an integral part of the Libre Space Foundation, is designed as an open source participatory project based on the users operating a ground station that is accessed via a web page.
- RTL-SDR.COM is a blog all about low cost software defined radios and their applications. They also manufacture and sell the RTL-SDR V3 and various low cost SDR accessories.
- SDR-Technologies is a French company specialised in Software Defined Radio based ground stations for satellite communications.
- GPIO Labs builds high performance, user-friendly RF modules. Application areas include radio astronomy, satellite communication, airplane tracking, agriculture, test & measurement and more.
- Pimoroni Ltd is a hobbyist electronics company based in Sheffield, Yorkshire, UK.

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Here you have some examples of references.

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[6] Stoff Website: www.stoff.pl, last visited: 20th March 2022.

[7] Heavens Above Website: www.heavens-above.com, last visited: 20th March 2022.

[8] Youtube Website: www.youtube.com/watch?v=tHDFHc3JgpY, last visited: 20th March 2022

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Abstracts

Towards an automation of contingency mission products generation for Mission recovery

Francesca Covella[1], *Stefano De Padova*[2], *Richard Southworth,*[3]

Abstract

As part of my year-long traineeship in the flight control team of the Integral Mission, in the first six months I worked on a couple of projects belonging to the general framework of automation of operation products, that is an ongoing trend. Integral is not only a spacecraft, but a gamma-ray observatory in space launched nineteen years ago. Even if it has experienced different anomalies, due to the successful major re-engineering of the mission operations, the Space Programme Committee has approved a mission extension.

The aim of the first application I wrote is to reload and uplink TCs in case of communication system problems or similar. The application saves a backup instance(s) of a sequence extracted from the science mission planning files, with the assigned values of the commands' parameters, to load said sequence onto the manual stack and uplink it to the spacecraft if it was not correctly uplinked, for instance due to interruption of the telecommand link. The application can be used to retrieve any instance of a sequence from past or future revolution, appearing in a certain so-called augmented parameter file for other purposes. The application produces Task Parameter Files which can be loaded on the manual stack, by the spacecraft engineers.

The second application can be used to generate a specific telecommand sequence that contains information about the so-called polling sequence table, used to regulate the flow of information on the data bus between the peripheral units and the central on-board computer. Manipulation of this table is normally done using an offline task as part of the mission planning process. The tool developed gives the opportunity to allocate the number of programmable slots of the PST as the user wishes to each payload instrument individually. The tool takes care that the values chosen follow the constraints. This tool is intended to be used in case of problems on board Integral when a fast and safe re-programmation is necessary. A new type of anomaly developed due to the physical degradation of some hardware components on-board. It was found that to regain control of the spacecraft one had to redistribute the processor load throughout the software cycle this was done by adjusting the bandwidth allocation defined by the PST. Doing this operation manually has two major drawbacks, which are undesirable during an anomaly: long time for completing the task and likelihood of errors.

The applications were tested, validated, and installed on the Integral Mission Control Software. They have been used operationally and contribute towards maintaining mission operations performance.

Keywords

Automation, Operation, Anomalies

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Implementation of interactive digital tools for astronomy education

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Abstract

In order to overcome the challenge of explaining complex topics on a STEM curriculum, many have proposed digital simulation-based learning as a strategy. In recent years, several virtual experiences have been tested to make the learning process easier for students, however a minority of them have focused on astronomy. We used and tested some of the technologies available for creating such simulations and games, and based on the PhET research guidelines by the University of Colorado Boulder, we produced a bundle of astronomy related digital experiences for various levels of education and complexity. We studied how individuals interact with these types of experiences to learn astronomy concepts. The preliminary results of this study also give insight into what are some of the key features an educational astronomy simulation should have, and how teachers and educators can get into making their own simulations with easy-to-use tools and very basic technical skills, which also improves their knowledge of astronomy concepts.

Keywords

Astronomy, Interactivity, Simulation-based learning.

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Development of aerospace activities in Malta: Aerospace Program and new MSc in Aerospace Engineering at MCAST

Leonardo Barilaro[1], *Roberto Tiscio*[2]

Abstract

In recent years Malta started to establish its role as one of the emerging nations in the Space Sector, supporting sustainable development and economic growth. The Malta Government's aim is to create a regulatory framework and incentives which improves the nation's attractiveness and capability to capitalise upon commercial activities related to outer space. Malta is developing synergies with European-level regulations concerning space policy development and space research support through the promotion of Research and Innovation and of science, technology, engineering and mathematics subjects which are vital for the operation of space activities.

In this framework, the Malta College of Arts, Science and Technology started its Aerospace Program in October 2020 and in October 2021 kicked off the related Master of Science in Aerospace Engineering. The vision of the Institution promoting it aims to create a center of excellence in the sector of Technology and Measurements for Aerospace with the target of boosting the local academic research and industry, increasing international collaborations and enhancing the brand of the Institution.

The Master is developed to be part-time, flexible in terms of blended learning and with different available exit points for the Learner. The course aims at attracting undergraduates and professional in aerospace from Europe, Asia and Africa, providing the skills required by national and international aerospace companies. The aerospace pathway will produce engineers highly skilled in designing and implementing aerospace projects, focusing on more productive and environmentally friendly technologies. This course responds to today's challenges and the need for a cleaner sky and environment as well as to provide safer, faster and cheaper transportation for a growing society.

The student can choose to specialize in one of the following fields: Structures and Measurements for Aerospace, Aerodynamics and Space Technologies.

This paper describes the first milestones of the research activity carried out and the development of the aerospace engineering curriculum for master students. A business analysis evaluation of the research and business opportunities in the rapidly growing aviation market and the emerging space sector in Malta has been performed as groundwork. The main program and the collaborations with international partners are presented; in particular, the paper will introduce the collaboration with the University of Padova (Italy) to develop the first hypervelocity impact facility to study space debris in Malta and to exchange students and professionals between the institutions.

Keywords

Malta Aerospace Program, MCAST MSc Aerospace Engineering, Space Debris Research

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Analysis of Impulsive and Low-Thrust Transfer Orbits for ESA's LISA Mission under Third-Body Perturbations

Juan Palomares[1], Josep O. Lizandra[2], Blanca Tejedor[2]

Abstract

LISA (Laser Interferometer Space Antenna) is a European Space Agency's L3 (third large-class) mission which will send three spacecrafts into a 20º Earth-trailing orbit. These spacecrafts will have the objective of detecting gravitational waves, which could provide answers to great mysteries of the Universe. Hence, the aim of this research was to assess the possible impulsive and low-thrust transfer scenarios for the LISA mission, under a restricted three-body environment. This analysis comprised the computation of feasible impulsive and low-thrust transfers by means of different approaches and the comparison of results. For the validation process, details of the design of LISA were extracted from a European Space Agency's declassified file.

Within this context, the fundamentals of the circular restricted three-body problem were studied analytically. Hence, the system of equations that governs the motion of an object affected by two external gravitational pulls from two massive bodies was deduced. Subsequently, LISA operational orbits were evaluated through a set of hypotheses, to know the specific position and velocity of the spacecrafts at the end of their transfer. Furthermore, the analytical solutions allowed to confirm whether the requirements from the European Space Agency could be achieved. The findings demonstrated that third-body perturbations prevent the acquirement of fully periodic operational orbits for LISA. Therefore, station-keeping could be necessary.

Finally, results of potential impulsive transfer orbits for LISA by means of a Multiple Shooting procedure were obtained. Likewise, by slightly modifying this Multiple Shooting Method and taking advantage of MATLAB's optimization capabilities, a prospective low-thrust scenario for the mission was procured. From the comparative analysis between scenarios, it can be concluded that the most feasible solution for LISA is the low-thrust one. This option could reduce the cost of the mission (and, indirectly, future missions) without reducing its performance considerably. In addition, it was demonstrated that the methodology implemented in this research could be generalized for various kinds of missions with relative ease.

Keywords

Formation Flying, Low-Thrust, Mission Analysis, Three-Body Problem, Trajectory Optimization

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SUN and The Space Industry Webinar Series

C Leach[1], L Berthoud[2], I Raper[3], K L Smith[4]

Abstract

The Space Universities Network (SUN) is a UK organisation which aims to enhance the quality of learning and teaching of space subjects by providing support and resources to the higher education space science and engineering community. Our members include 93 teaching staff spanning 37 universities across the UK. SUN enables the developing, sharing and promotion of effective practice and innovation in the delivery of university-level space science and engineering curricula. In this work, we outline the ways that this practice is disseminated through the network. The use of academic workshops, case studies, and network-wide communication streams are described. The development of the SUN resource bank from which staff can draw material to enhance their space teaching experience for students is also discussed.

During the 2020/21 academic year, with the COVID-19 pandemic forcing the UK academia and industry into lock down, SUN organised and delivered a series of virtual seminars. The motivations, organisation methods and content of this series are outlined. Each webinar was comprised of a 30-minute technical talk by an industry specialist, a 20-minute interview with them, and live Q&A from the audience. Each session had a strong emphasis on education, aiming to help bridge the gap between students and industry, and to mitigate the current skill shortage in the space sector in the UK. Throughout the series a range of topics from government-led space missions, through GNSS, to the refurbishment of water-landed payload fairings was covered. Each event was recorded (if allowed) to be made available for students for access via our YouTube channel. Attendance has increased as the series has progressed, and the webinars will continue with the 2021/22 SUN Space Industry Webinar Series. Finally, we discuss possible improvements to our offerings and lay out our plans for the 2021/22 academic year.

Keywords

Higher Education, Space Network, Webinars

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The GIS4Schools project

Edoardo Fabbri[1], *Elisa Filippi*[2], *Marco Scarselli*[3], *Maria Antonia Brovell*[4], *Marco Gianinetto*[5], *Daniela Carrion*[6]

Abstract

The GIS4Schools project is a strategic transnational and multi-stakeholder partnership (including 10 Partners from 5 EU Countries) in the field of School Education funded by the Erasmus plus programme with the aim to introduce new methodologies based on the use of GIS technologies applied to the impact of Climate Change to improve pupils' STEAM's learning. The project aims at addressing the need for improving STEAM education by providing pupils with proper analytical skills to understand better the world in which they live and to tackle environmental and societal challenges. Indeed, to improve STEAM's learning, it's fundamental to find better ways to nurture the curiosity of children linking science with other subjects and disciplines. To this purpose, the project fosters a new approach for the involvement of pupils in STEAM disciplines' learning by introducing the teaching of GIS and satellite technologies for Earth Observation, which is not yet adopted in a "structured way" in Secondary Schools in the EU, and by applying it to the thematic area of Climate Change, receiving increasing attention by young people.

The project started in September 2020 and it will last until 2023. Secondary Schools from 4 different EU Countries (Spain, Italy, Portugal, Romania) are involved for a total of more than 200 pupils and 24 teachers as direct beneficiaries. From a methodological perspective, pupils will combine Inquiry-Based Science Education (IBSE) with Problem Based Learning (PBL) approaches to an interdisciplinary contextualization of the science topic.

During the first year of activities a Training package focused on GIS and Remote Sensing for Secondary Schools has been developed by the Polytechnic University of Milan and tested among teachers and pupils. From October 2021 pupils will be engaged in the co-creation of GIS outputs focused on specific climate challenges by exploiting information and data provided by Copernicus, Sentinels' satellite, and other sources. In detail, the Romanian school will focus on air pollution, the Portuguese school will investigate soil erosion and the risk of floods, while the Spanish and Italian schools will investigate respectively the marine biodiversity and the forestry biodiversity in the mountains. As players of this co-creation process pupils are expected to keep high their level of engagement, to improve their familiarity with Earth Observation and GIS, as well as to increase their general level of interest of STEAM disciplines, which could encourage them to choose STEAM in the continuation of their future academic studies.

Keywords

STEAM, Climate Change, GIS, Earth Observation, Secondary Schools

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Casanova: a solid rocket engine for CanSat suborbital missions

Aleix Coma[1]

Abstract

CanSats -small satellites the size of a soft drink can- have been extensively used in student competitions and other educational events to teach and train the future scientists and engineers. In this project, with the purpose of extending the possibilities of CanSats, a small suborbital launcher has been devised. The launcher would consist of a single-stage rocket that would be attached to a high-altitude balloon, and launched from a height of 30 km. The rocket would take the payload -consisting on a single CanSat- to an apogee of at least 100 km, providing a few minutes of microgravity and exposure to a space relevant environment. The main customers for this launch system would be education centers and students willing to conduct educational and academic research projects.

The focus of the project has been to define the technical requirements, to design and to develop the solid rocket engine that would power the envisioned rocket. The technical requirements, constraints and design parameters -including different propellant formulations, solid grain shapes and material and shape of the engine case- were defined. Numerical simulations of the engine's internal ballistics, rocket trajectory and transient heat transfer were performed to obtain a preliminary design of the engine.

Afterwards, an experiment to test the effectiveness of different ablative materials for protecting the rocket engine case was conducted, which showed satisfactory and consistent results with those of the simulations. Finally, CAD models and blueprints of the rocket engine pieces were produced, and a real-scale prototype of the rocket engine was assembled.

Thanks to the simulations, the experiment and the prototype, the feasibility of such a launcher was proved. Future work shall complete the design and continue towards the development and testing phases.

This project was developed by an undergraduate student on his own initiative and with the help of his academic tutor. It represents a year of work and was presented as his Bachelor Thesis.

Keywords

CanSat, rocket, suborbital

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Suspension of Carbon Nanotubes under Dielectrophoretic Influence

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Abstract

The field of application of Carbon NanoTubes (CNTs) is very versatile due to their special thermal, electrical and mechanical properties [1, 2, 3]. They can be used, to develop materials for ElectroStatic Discharge (ESD) and ElectroMagnetic Influence (EMI) protection, sensor technology and mechanical reinforcement [4, 5, 6], which opens up a wide range of applications in industry and research [7, 8]. Therefore, it is necessary to understand the basic properties and thus make them accessible for manufacturing processes. Since the properties are largely dependent on the alignment of the CNTs [9], it is essential to understand the alignment process in detail. “S Cephei” will therefore observe and document this process while using the REXUS platform [10] to exclude gravitational influences during the microgravity phase of the flight. The alignment is achieved in the experiment by dielectrophoresis as a result of an electric field, whereby the electric field is caused by applying an alternating voltage to a capacitor. This process is influenced by temperature, viscosity of the suspension, frequency and amplitude of the alternating voltage, and the type and quantity of CNTs [11]. Several cameras are used for documentation, which allows a threedimensional model to be generated by software, thus improving the understanding of the process.

Keywords

REXUS, SED, STAR Dresden, Carbon Nanotubes, CNTs, ESD protection, EMI protection, Alignment of CNTs, Dielectrophoresis

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Affordable rocket design with interchangeable rocket engine mount for different mission objectives, equipped with payload bay for amateur CubeSats and CanSats.

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Abstract

Amateur rocketry has been offering opportunities to students and enthusiasts to earn a spot in the field of space engineering and project development. Our goal is not only to design a reliable and affordable rocket, but to provide a platform to launch additional experiments, such as amateur CanSats and CubeSats, with different flight profiles. We will achieve this milestone by designing and developing an adaptable engine mount according to the given solid propellant motor characteristics. Our purpose is to attain the greatest results during the flight. Furthermore, different materials are going to be employed. It will be possible to modify the rocket fins design seeking to optimise the stability and the apogee. The principal advantage of our design is that changing the engine mount on the same rocket will be possible, making it reusable. This will, also, reduce the cost per launch.

Moreover, the rocket will be able to achieve periods of hypergravity and microgravity, which can be attractive conditions to study how systems work under their effects. Initially, it will provide 3L of payload volume with anti-vibration walls to protect the electronic devices and it will incorporate batteries and sensors to support the experiments onboard. It will feature telemetry modules to transmit data such as pressure, acceleration, orientation or speed. In addition, we will add protected SD card modules and EEPROM devices to save the flight and experimental data in case of radio interference or recovery system failure and crash of the vehicle. Video Cameras will also be included. In conclusion, this project aims to provide an economical rocket to launch amateur experiments with several alluring fight profiles and motivate people to experiment and launch their ideas in the aerospace engineering field.

Keywords

Rocket, affordable, accessible, payload, versatility, telemetry.

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Description of the Flexible Microwave Payload-1 (FMPL-1) onboard the ^{3}CAT-4 Mission

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Abstract

FMPL-1 is the first of a suite of passive microwave payloads based on Software Defined Radios developed at the NanoSat Lab. It is the main payload of the ^{3}CAT-4 mission, a 1U CubeSat, which was selected in the 2nd edition of the ESA Fly Your Satellite! (FYS) program, and will be launched in Q3 2022.

FMPL-1 integrates 3 experiments in a single platform: an L1+L2 Global Navigation Satellite System - Reflectometer (GNSS-R), an L-band Total Power Radiometer (TPR), and an Automatic Identification System (AIS) receiver.

- GNSS-Reflectomerty is a passive technique which involves measuring the reflected signals over the Earth's surface emitted by GNSS satellites, and by comparing them with the direct GNSS signals, it is possible to obtain reflectivity maps from which the soil moisture content, the wind speed, the sea-ice extent and thickness can be measured, or even altimetry observations can be performed.

- Microwave radiometry relies on the fact that all bodies at a non-zero absolute temperature emit electromagnetic radiation. FMPL-1 implements a Total Power Radiometer with frequent internal calibrators: a hot load and an active cold load.

- Finally, the AIS receiver is in charge to receive the telemetry signals sent at VHF by ships, vessels, base stations or satellites, for its geo-localization.

FMPL-1 is composed of four different modules: Payload Antennas, Radio Frequency module, SDR platform, and the Computer On-Module:

- The Payload Antennas are a group of antennas with different features (i.e. frequency band, polarization, etc.) connected to the corresponding RF chains: there is a L1-L2 and 1.4 GHz band deployable helix antenna, which is explained in a companion paper, and a VHF monopole for the AIS experiment.

- The Radio Frequency module includes an LNA chain for each experiment.

- The SDR platform is the digital back-end of the RF receiver which performs further amplification, filtering, demodulation, and ADC conversion.

- Lastly, the Computer On-Module is the microcontroller in charge of executing the FMPL-1 control software.

Keywords

Remote Sensing, Earth Observation, GNSS-R, Radiometry, AIS.

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Design and assembly of an affordable amateur rocket engine test bench using linear guides to reduce energy lost to structural deformation.

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Ángel Martín[2], Antoni M. Barredo[2], *Raúl Cruces*[2] , *Rodrigo Martín-Cuevas*[2]

Abstract

Solid propellant rocket engines are the most accessible alternative for amateur rockets enthusiasts. Users can acquire reliable solid propellant rocket engines from a professional manufacturer, which can be costly, or decide to develop their own engines to save on expenses. Nonetheless, these DIY-rockets are commonly used with the ignorance and uncertainty of its performance data. Said data is indispensable in order to properly design and optimize the rocket. Therefore, our team set out to design and develop an affordable test bench which will allow to characterize a rocket engine.

The main goal of this test bench is to obtain high precision measurements of thrust. However, there are a lot of factors that play against our behalf; out of them, we consider that energy lost by friction and structural deformation are the most important issues to tackle. These problems are tried to be solved, or at least minimized, with the use of a linear guide (rail/track) that guarantees frictionless linear movement along the track; as well as ensuring that loads are applied perpendicularly to the load cell which will output real-time thrust data during the experiments. Vibrations are measured with accelerometers placed on the load cell and on the blocks, and these are greatly reduced by mounting the rocket on top of the blocks that run over the linear guide. This linear rail is made of stainless steel that can withstand high temperatures. Nevertheless, several thermal sensors were scattered along the rail to check the temperatures reached on the guide. In addition, ambient pressure and humidity are measured. The test bench is designed to operate with a wide range of rocket diameters and lengths, allowing the user the freedom to experiment with different parameters during the manufacturing of their engines. Finally, a high strength steel case was added for user safety, since unexpected explosions during rocket engine tests are not uncommon.

The test bench design will ensure high precision thrust measurements while being accessible to the amateur rocketry niche; thus, helping further democratize access to space.

Keywords
Thrust, rocket engine, bench test, precision.

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HABCAT

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Abstract

HABCAT is a secondary education centers STEAM program with the main goal of facilitating the execution of near space projects in these centers. Today, the main project is advice, support for the design, construction, launch, monitoring and recovery of High Altitude Balloons for scientific purposes. For this, the program has available to the centers, procedures documentation and theory of all the technical aspects of the flight of a High Altitude Balloons in addition to all the software necessary to make the stratospheric probes hardware ready to work. The aspects of this hardware and software cover the Energy Power System, On Board Computer and Data handling, Payload, Communication System, Recovery System, Thermal Control System and tracking in Real Time of the probes.

In addition, all the scientific material recollected is made available to all centers, thus providing teachers with a large amount of data with which to carry out teaching activities.

From an educational point of view, HABCAT intends to create a network that allows professionals from the aerospace sector, external collaborators and teachers to be in contact in order to bring this kind of initiative closer to the new generations of students and thus foster interest in the study of the STEAMs.

Keywords
Educational, HAB, Near Space, STEAM, Stratosphere

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Optical and spectral characterization of a COTS multispectral camera for Earth Observation

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Abstract

A Commercial-Off-The-Shelf multispectral camera included in the RITA payload, belonging to Alainsat-1, has been characterized and subsequently validated for the purpose of retrieving vegetation indices from several areas of interest and to detect other features as algal blooms and oil spills. Several properties of the camera, consisting of a Complementary Metal-Oxide Semiconductor sensor with 25 channels from visible light (600 nm) to near-infrared (975 nm) spatially distributed in a 5x5 snapshot mosaic filter layout and 16 mm lenses, have been evaluated. Firstly, the sensor response linearity and the optical vignetting effect have been assessed with both the Qualification Model, a sensor replica of the actual model that will be put into orbit but with Red-Green-Blue filters, and the Proto-Flight Model, made up by the multispectral sensor. These characteristics have been accordingly validated with the manufacturer's specifications. Then, an image processing algorithm to detect defective pixels, that makes them stand out among their neighbours, has been applied to several uniformly illuminated images. To conclude the characterization, the Qualification Model camera has been subjected to an Environmental Test Campaign to analyse the dark current behaviour and the blur effect of the camera lens under thermal and pressure transitions to simulate space conditions by using a Thermal Vacuum Chamber. Finally, the camera has undergone a calibration process using a monochromator set-up to remove undesired contributions present in the physical channels and spectrally correct the overall sensor response. The results of the characterization and the spectral correction conclude that the instrumentation selected is valid to perform Earth Observation.

Keywords

blur, CMOS sensor, Earth Observation, Environmental Test Campaign, multispectral

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CubeSat Integrated Deployment System for 1P and 2P PocketQubes

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Abstract

In the recent years, the miniaturization of electronics and the use of commercially available components has enabled the access to space to smaller organizations and universities, thanks to a reduction in costs and the appearance of dedicated small satellite launchers. The definition of the CubeSat standard fostered the development of commercial-of-the-shelf (COTS) components that helped bring the production down, as well as increasing their reliability thanks to the gained flight heritage.

CubeSats, despite their low cost when compared to traditional space missions, can still have significantly high development and launch costs, which foretold the use of smaller systems, leading to the appearance of PocketQubes, providing an affordable solution as educational activities and technology demonstration test beds.

As one of its payloads, the ³Cat-8 mission from NanoSat Lab (at the Universitat Politècnica de Catalunya) will host onboard two 1P PocketQubes that are being designed for IEEE (Institute of Electrical and Electronics Engineers) as part of a suite of educational materials, carrying a series of Internet of Things (IoT) and scientific payloads onboard. The picosatellites will be deployed by the inhouse developed deployer to be integrated in the 6U CubeSat.

This work plans to assess the feasibility and design the system, compliant with the current PocketQube Standard, ensuring a low-profile solution occupying only 1.5U of a CubeSat for a two 1P PocketQube deployer, provide ease of manufacturing and integration through its modular design and allow support for internally and externally mounted subsystems and platform components.

Keywords

CubeSat, PocketQube, Technology demonstration, Access to space

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Enhancing the students involvement in hands-on aerospace research: lessons learned and perspectives at Sapienza S5Lab

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Abstract
In the recent years, the S5Lab (Sapienza Space Systems and Space Surveillance Laboratory) research group at Sapienza University of Rome has participated in several hands-on aerospace research projects, with the aim of developing space systems with University students. The research topics focus on space systems development (mainly CubeSats and stratospheric experiments) and on space debris optical observation (with a deployed network of optical observatories in Italy).

S5Lab have launched four CubeSats from 2017 to end of 2021, namely URSA MAIOR (participating in the QB50 programme), 1KUNS-PF (in collaboration with University of Nairobi, participating in the UNOOSA-JAXA KiboCube Programme), LEDSAT (participating in the ESA Fly Your Satellite! Programme and conceived with the University of Michigan), WildTrackCube-SIMBA (winner of a launch opportunity by the International Astronautical Federation and GK Launch Services and developed in collaboration with Machakos University and University of Nairobi). All these projects have been supported by ASI and have seen a significant involvement of students at all levels in the development stages of the satellite, from concept to operations.

S5Lab have also developed two BEXUS stratospheric experiments (STRATONAV in 2016 and TARDIS in 2019), whose core teams have participated in the HEMERA H2020 Balloon Launch Infrastructure between 2020 and 2021 for the development and launch of the STRAINS stratospheric project, supported by ASI.

Other hands-on project opportunities have been offered to the students through the participation in the IGLUNA initiative between 2019 and 2021 (managed by the Swiss Space Centre and ESA_lab@CHF) and by forming design teams for international contests, such as the Mission Idea Contest organized by UNISEC-Global.

This poster will describe the past, present and future project at S5Lab and with the main lessons learned concerning the involvement of students at all levels in international students and research programmes for space systems development.

Keywords
Hands-on; Educational; Students projects; CubeSat; Stratosphere

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Student Aerospace Challenge: an opportunity for undergraduate engineering growth

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Abstract

The Student Aerospace Challenge is an international annual competition bringing together undergraduate, masters and PhD students for the design of a suborbital commercial mission, from the conceptual design of the vehicle to its legal or medical consequences. Sponsored by several principal stakeholders of the European Space Industry (including the Education Office of ESA, ArianeGroup, and Dassault Aviation) it provides a remarkable opportunity for engineering growth, both from the technical and personal standpoints. Having participated in both the 2018 and 2020 runs of the challenge, to great success, we have taken away invaluable lessons and experiences.

Participating in the SAC was a challenge—both technically, since most of the engineering applied in the analysis was beyond what was studied in the degree, and logistically, since all team members worked together remotely and participated in parallel to their studies and work. This was worth the effort—the experience of working in a real and applied project, combining disciplines in an ambitious design, is invaluable for any aspiring engineer.

On both occasions we faced a similar challenge: the global design of a suborbital, long-range, high-speed vehicle. We proposed the aerodynamic, propulsive, thermal, structure, GNC and trajectory conceptual design for the mission, from a Systems Engineering perspective. Such a global vision on the mission, highly encouraged and supported by our professors, really helped us strengthen the acquired knowledge from our studies, which inevitably lacks the big-picture approach this design challenge involves.

The 2018 edition was a turning-point in our university studies. Together with our professors, we quickly gained a set of teamwork and management skills and knowledge inaccessible in any other manner, which has become invaluable throughout the rest of the degree, and to this day. Our 2020 participation, coinciding with our last year as undergraduates, became the perfect finale to a four-year learning cycle, and we were able to reach much further. Applying the lessons learned in the 2018 edition, we were awarded ArianeGroup prize in our proposal for the Mission Profile and Concept work package.

Keywords
International Challenge, Student Aerospace Challenge, Undergraduate Projects

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Key success factors of EO New Space companies and their evolution

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Abstract
The utilisation of the Component-Off-The-Shelf (COTS) technology as well as the development of the small satellites which weigh less than 500 kg, have meant a manufacturing cost reduction of satellites at Very Low Earth Orbit (VLEO). This has meant a change in the Space Industry during the last decade by opening new opportunities and market segments to provide real-time updating, live geo-information and democratization of space. According to statista, the market of small satellites has a clear increasing tendency as from the 52 satellites launched in 2012, more than 300 were launched in 2017 and 1,202 in 2020. For this reason, three different companies of EO market operating at VLEO were investigated in 2018, UrtheCast, Black Sky Global and Satellogic, to analyse their Business Model in order to find the success factors of these companies and identify the elements that define their outperformance. A criterion was defined to evaluate the three companies, precisely Market Survival, Productive evolution and Cost-efficiency. These criteria would help researchers understand the performance of these companies, determine the most successful, and identify the characteristics that are key for their success. As a result, some key success factors have been found like having innovation as the core value, the utilisation of the Lean manufacturing philosophy to reduce costs during the satellite manufacturing process, and making strategic alliances with other stakeholders of the sector like ground segment to be competitive in the industry. In 2021, three years later, these same companies have been tracked and analysed again to verify if the conclusions are still valid. It has been observed that during this time, each of them has found their own way on the market, but the most successful ones still share these key success factors, and yet another one has been identified, Vertical Integration.

Keywords
Earth Observation; small satellites; VLEO; success factors; business model; New Space

Investigation of Microorganisms in the Stratosphere

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Abstract

The stratospheric microbiome has been investigated several times using the methods of classical microbiology. In this experiment, we have combined them with some novel approaches including whole-metagenome amplification and NGS sequencing. The analysis of metagenome has helped determine the content of various species of bacteria in the sample collected in the stratosphere. Diversification of methods has helped distinguish culturable microorganisms from non-culturable ones. The experiment supplies information about the possibilities of spreading bacteria around the world which is important from the point of view of epidemiological threats and environmental biodiversity. It also may provide the scientists with knowledge about the mechanisms of survivability of microorganisms in stratospheric conditions such as high doses of UV and cosmic radiation, low temperature, and low humidity.

The microorganisms have been collected in the stratosphere by a filtering system equipped with six filters. Three filters were placed between ever-closed valves as control filters. The biological material was collected in the remaining three filters, one of which was used for metagenome isolation. Two of them provided the microorganisms for setting up cultures on agar media. One of the control filters was treated like the one for metagenome isolation and the other ones were treated similarly to the ones used for setting up the cultures. The stratospheric microbiome has been compared to the microbiome of the air collected from the place of the balloon's start, using an identical, on-ground filtering system. All the parameters of the stratospheric balloon flight and the sample collection have been recorded.

The experiment was launched onboard the BEXUS30 balloon sent within REXUS/BEXUS program. The microbiological part is continued in laboratories of the Gdansk University of Technology.

Keywords

Metagenomics, Microbiology, Phi29 Polymerase, REXUS/BEXUS, Stratosphere

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Structural Analysis of a 2U CubeSat, 3D vs. 1D model

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Abstract

CubeSats in the last years become highly versatile platforms. They are cost reduced, has a simple development process and are very accessible. Because of this, different universities and projects have shown interest in small satellites and their educational purpose.

The main goal of this article is to share with the academic community and those who are interested in the concerning fields, the methodology used and the results obtained in the mechanical analysis using FEM of a 2U CubeSat structure. This work involves the design and modelling of a 2U CubeSat using a 3D and 1D model for the structure and meeting all the requirements of the Cubesat Design Specification (rev 13). To build the numerical model, we studied the mechanical behaviour of the structure under launch conditions following the NASA General Environmental Verification Standard. The model consists of the structure along with the different subsystems required for its operation, as well as a payload volume, with masses representative of the final assembled satellite.

The expected outcome of this study is the methodology and a comparison between the two different models.

Keywords
CubeSat, FEM, Structural Analysis

Direct Satellite Trajectory Control Using Flywheels

Meet Joshi[1]

Abstract

The students at the WinSAT team have proposed a novel system that can enable immediate flight path control for deep space missions. One of the biggest limitations of deep space satellite missions is the ability to undergo rapid and substantial directional changes under the circumstances where the mission objective changes or the system needs to be repurposed for a different study. The significance of this problem was identified upon considering the developments in flywheel technology among other potential candidates for research, it was determined that a reevaluation and subsequently proposed enhancements to the capabilities of Flywheel-systems was a technical contribution that should be prioritized. As of now, the mission parameters for any given long-duration (+2 years) scientific mission must be devised with keeping the means of flight control limited to gravitational maneuvering and single-use cold gas propulsion. The proposed system is intended to resolve issues that have traditionally hindered long-duration satellite missions, providing a cost-effective and "reusable" means of rapid flight path control for deep-space satellites. The system utilizes controlled interactions between a flywheel operating at high angular velocities and a stationary clutch plate which receives energy from the flywheel and exits the spacecraft in a controlled trajectory (the clutch plate is reloaded for each use). The kinetic energy is transferred to the spacecraft by the conservation of angular momentum, and as the plate exits the system, the satellite is propelled in the desired direction. Seeing how the flywheel system can slowly re-gain momentum through an electric motor and the on-board solar panels, the operational period is only limited by the number of sacrificial clutch plates allotted under the mission parameters. To achieve the desired performance, the flywheel itself is kept suspended in a magnetic field, in the micro-gravity of space, which allows reaction wheels of this type to maintain high angular velocities for extended periods of time. Seeing how most of the apparatus can only reach the desired speeds of ~50,000 rpm in a microgravity environment, most of the team's efforts went into using mathematical models and simulations to determine proof of function. It was determined that the system is most optimal in cases where the mission objective changes over time, as even with the added feature of the flywheel acting as a reaction wheel for single-axis rotation, the added weight of ~60kgs is only ideal for large scale studies that require deep space travel.

Keywords
Cold Gas Alternatives, Education, Deep Space Satellites

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Volunteer-led space education with rovers, CanSat and programming for brighter future space explorations.

Erzse Daniel-Zoltan[1], *Nilgesz Arnold*[2]

Abstract

CoderDojo Oradea was founded in 2014 to offer interested children the context in which they can learn programming in an informal and fun environment. Four years later, in 2018, a group of astronomy enthusiasts, who had participated in ESA's AstroPi competition a year earlier, organized a weekly space robotics session to take part in the national ExoRo competition organized by ROSA (the Romanian Space Agency). Over 40 students took part in the last three years in industrial and space robotics competitions, achieving the performance of being twice in the CanSat European Finals held by ESA.

In a world where children are often discouraged from exploring their curiosity, we have seen the value of helping them discover the vast potential of their cosmic interests. Our small ambitions aroused the curiosity of dozens of children from different high schools, who were eager to participate in robotics competitions and other activities. Volunteering has given them access to hands-on projects related to engineering, programming, and climate change. CDOSR has been trying to offer our students the opportunity to work on space-related activities, participate in various competitions, and participate in high school and student projects. In the future, we hope to organize more events of this nature both locally and nationally.

CDOSR's goals are to provide high school students with space engineering skills, prepare them for more advanced studies in the field, and create a group of qualified workers who can meet the challenges of future scientific explorations and commercial exploitation of space. Our activities also include promoting science and engineering among high school students and children and reducing the disparity between the involvement of men and women in STEM.

Our participation in the last three years in the CanSat and ExoRo competitions has divided the activities of the CDOSR into several specialized groups: competition documentation, programming, structural engineering, hardware design, aerodynamics and satellite recovery systems, flight control, reception ground data, marketing (sponsorship financing), all these groups being run by the students and supervised by our volunteer mentors. These interdisciplinary projects make collaboration among all groups crucial. In this paper, we will outline the successes of our team in two competitions: the rover we made for the ExoRo competition and the final CanSat design. We will also share with you the methods used by students and what they gained from these competitions, and any lessons learned.

Keywords

Space mission design, Space education, CanSat, ExoRo, Project-based learning

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An Augmented Reality App teaches volcano monitoring from Space in Schools with Sentinel-1 data

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Abstract
Ground movement can be observed from space using radar interferometry. This works essentially by measuring the distance and angle between a satellite and a spot on the ground twice and subtracting them. This uses the transit time of radar waves, sent from the satellite to the ground and reflected back. Very precise measurements and calculations using geometry, orbital mechanics, and properties of electromagnetic radiation are performed to measure changes in ground position between the two chosen overflights of the satellite, which can span anything from a few days (e.g. before and after an earthquake) to several years (e.g. volcanic activity underground).

Radar interferometry thus includes the practical application of many theoretical scientific principles that school students learn in their regular classes. This approach teaches interdisciplinary thinking and many more soft skills, but is also quite complex for them to grasp. For this purpose, an augmented reality (AR) app was developed to be used in combination with a printable, static work sheet using active and collaborative learning approaches. This allows the use of digital elements like 3D models, animations, and gaming in a Bring-Your-Own-Device approach. This can be used almost independently of socioeconomic status of the students or the school as it works even on old and cheap devices.

The students start with preparatory homework, two videos conveying the required prior knowledge. Copernicus satellite Sentinel-1 and its relevant parameters are then introduced in the worksheet: Orbit position, attitude, and signal. Several math tasks further help students familiarize themselves with the functionality of radar satellites. These exist in two difficulties: “simplified” and “real data”. The subsequent geography tasks use the AR app, at first to familiarize themselves with the example area, the Campi Flegrei in the Naples region, as a 3D model with elevation and visual information, then to “take images” with a little game. An idealized, animated 3D model is used to explain interferograms. Finally, the students can overlay the real interferogram from Sentinel-1 radar data, and the elevation change calculated from it, on the 3D model of the region in the AR app. The students then have tasks to discuss what this means for the region and put it in a context with the local history and future.

The poster presentation will focus on the demonstration of the functionality of the app and discuss the educational and technological concept.

Keywords
Secondary Education, Radar, Interferometry

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CalliopEO – Teaching Coding To Primary Students From Space

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Abstract

The star-shaped microcontroller Calliope mini enables playful access to computer science, even at primary school age. The microcontroller contains a number of sensors (e.g. light sensor), LEDs and buttons that pupils can programme via a graphical interface. In this interface, pupils can create programming in the form of blocks, whereby the programme sequences are conveyed without complicated syntax. The wide range of tasks, existing teaching materials and the additional use of JavaScript as a programming language allow for individual integration into lessons. Due to the different levels of difficulty and good documentation, pupils can learn individually. So far, over 100,000 of these small computers are in use in German schools.

The Calliope mini microcontroller on board of the ISS functions as demonstrator for an educational call to Schools for pupils in the age of 10. Many pupils lack programming skills after completing their school education, even though, in the course of digitalization, skills in the fields of engineering and information technology are becoming increasingly important. Since these subjects do not necessarily have to be offered in schools, great differences can arise in this area of education. The school activity "CalliopEO" aims to make these subjects more attractive. Primary students are asked to submit software coded by pupils parallel to a high-profile space mission, in favour of ESA's astronaut Matthias Maurer's mission, in which the Calliope mini microcontroller is equipped with sensors and thus transform it into a multi-measuring instrument and Earth observation device. Calliope mini is connected to ESA's Astro Pi IR hardware in order to 1) increase autonomous functionality and thereby reduce crew time requirements, and 2) capitalize on the Astro Pi programme window deployment and 3) help promote the ESA competitions also in German schools. The deployment will happen according to the experiment schedule of Astro Pi IR in Spring 2022. While similar in nature to ESA's Astro Pi Mission Space Lab Challenge, the rationale for the CalliopEO activity was twofold: 1) The Calliope mini computer is much more widely used in German schools than the Raspberry Pi, and 2) the Calliope mini coding language is targeted to a more primary age group. The poster presents the hard- and software implementation in the Columbus laboratory and during window deployment as well as first impressions of the student code submissions.

Keywords

Calliope mini, microcontroller, block coding, Astro Pi

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NAASCube program, an innovative aerospace program for students, driven by the Nouvelle Aquitaine Academic Space Center

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Abstract

In 2019, the Nouvelle-Aquitaine Academic Space Center (NAASC) was created to foster innovation by involving students from various higher education institutions in collaborative aerospace projects. Different programs concerning Access to Outer Space were identified that drive them in a dynamic and intergenerational way, with the support of aerospace companies and institutions.

One of these programs, named NAASCube, is related to the development of a nanosatellite with students. It is innovative for several reasons.

First, it is a collaborative program between institutions from geographically remote areas, providing different trainings with different timings and duration. In this context, more than 30 students are involved each year in the CubeSat program, all focussing on the same topic. Some of them are designing the scientific and technological payloads of the nanosatellite, while others are working on the platform, dealing with system aspects and software. Others are designing ground-based testing equipment for vibratory and thermal analysis, for instance, before launching the nanosatellite. The remaining ones are preparing the operational phase, working on the ground segment and telecommunications. Coordination of the program is secured by regular teleconferences, face-to-face meetings and a shared digital working environment for communication and documentation.

Furthermore, the NAASCube program focuses on project management. Students must organize their teams with project managers, subsystem leaders, tasks monitoring… It is supported by the CNES Nanolab-Academy project, which provides collaborative tools for orbits and attitude simulations. Students are compelled to follow CNES CubeSats Standards, and to prepare each end of phase review in a professional manner. Very enlightening!

Concerning the payloads of the nanosatellite, students are encouraged to find collaborations with research laboratories or companies. Two payloads are presently based on lab research: one for IoT (Internet of Things) demonstration and the other one for physics purposes. The two

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other payloads result from collaborations with companies, either major industrial groups or startup created by students. All these initiatives are real opportunities for students to gain valuable work experiences in the aerospace field.

In conclusion, the NAASCube program is an example of the way an Academic Space Center can develop aerospace skills, know-how and innovation through the training of students from very different backgrounds. The final aim of the NAASC is to bring together the Nouvelle Aquitaine Region, academics, CNES and companies with a common objective of launching a first nanosatellite in 2025. And, in longer-term, the goal is to build an aerospace competence center for new industrial, societal, and environmental applications.

Keywords
NAASC, nanosatellite, education, CNES, NanoLab-Academy

Peer 2 Peer up to Space

Steffen Jauch[1], Stefanie Jaeger[2]

Abstract

The fascination for the infinite, the unknown and the big question of humanity "Are we alone?" is particularly strong among children and young people. The STEAM subjects can benefit enormously from this, as they are able to provide pupils with knowledge and skills to find their own answers to their questions.

Since 2018, (almost) everything in the Realschule Calberlah has revolved around the exploration of space, with all the related sciences and their anchoring in the curriculum. The core of the project is our version of MissionX - Train like an Astronaut workshop. Every week, 24 primary school pupils (12 girls, 12 boys) experience facets of space exploration, ESA and NASA astronaut training, space technology, science, healthy eating and sport. Of course, the fun factor plays an important role in the ongoing child-friendly approach to science. They are guided by six 8th grade students, a school social worker and a teacher.

Within one school year, we follow the schedule of a real space mission: At the beginning, we dive into the history of space exploration and go into the current missions of our ESA astronauts. Afterwards, the mission training on Earth begins for the students. We practice to become fit like an astronaut, strength, endurance, dexterity, fine motor skills, coordination and balance, train an EVA (extra-vehicular activity = space walk), programme (Lego) robots on a mars like training field , investigate the sun and the other planets, and familiarise ourselves with basic physical principles such as the recoil principle, gravity, speed and acceleration. Alongside this, we prepare the experiments for our space sojourn. Often these are biological tests and experiments on plant growth, the effect of micro-gravity on the body or dangers for astronauts during space travel. We also investigate materials such as copper, steel, wood, brass, polystyrene, aluminium, polyamide, to prepare with the students for the construction of their rocket. Their acquired knowledge and skills flow into the development, construction and design of their rocket. The project ends with the rocket flying day in our village!

Building on this, many projects have become established in our school: Once a year we organize our SpaceDay in cooperation with the DLR_School_Lab Brunswick, we take part in the AstroPi Challenge of the ESA, construct a Moon Camp or take care of the monitoring and control in the smart school garden to prepare the foundation of a settlement on Mars.

Keywords

STEAM SpaceistheContext Inspire

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Effective student team infrastructure towards CubeSat mission design in pandemic times

Ida Gwozdz, Marco Giugliarelli, Simone Poppi, Elia Fregonese, Paolo Minacapilli, Massimiliano Bussolino, Andrea Zanetti, Lorcan Kelleher, Fabio Porcari, Vahid Nateghi, Andrea Pizzetti, Mateusz Garbacz,

Abstract

Provide a concise Abstract of your poster, with a maximum of 400 words. It should include the goal(s) of the research, and summarize the results and conclusions. Do not use any abbreviations or references for the Abstract! Abstract text shall be in Arial, size 11. Note that the first page of the paper only includes the Title of your Paper, the authors list, the Abstract, and the Keywords. This page will be available online during the congress to give the attendees an idea of the content of your oral presentation. The Abstract can be updated from the original submission, and does not have to respect the 'blind review' criteria anymore. No figure can be included in this last version.

Keywords

CubeSat, organisation, Covid-19

The space industry, along with the engineering industry in general, has seen tremendous changes during the last two years in the organization and communication of engineering teams internally and externally with third parties, due to the COVID-19 pandemic. The Cubesat team faced the same situation, while focusing at developing the very first satellite conceived by students of Politecnico di Milano and still striving to ensure a good balance between quality of the product, experience for students, simplicity of the project and budget management. With these key goals in mind and in the middle of a pandemic, a new way of development and collaboration inside the team had to be found. The paper documents how the Cubesat team has tackled a variety of problems during this particular situation, not only overcoming the penalizing pandemic situation but also exploiting different benefits deriving from it in order to boost the efficiency of the Cubesat team and multiply opportunities to contact companies, attend virtual seminars and receive funds or free components, given the restricted budget. This work will present sequentially the steps the team has completed so far, leading them in a few months to the preliminary design of the satellite. These steps include: recruitment of the first 9 members of the team, review of different payload providers, call for funds, selection of payloads, mentorship calls with professors, expansion of the team to 35 members, etc. All of this while structuring the work of a multicultural team by holding weekly remote meetings and assigning tasks managed with the use of online platforms.

A student-made approach for CubeSat design: the 6S roadmap

Ida Gwozdz, Marco Giugliarelli, Simone Poppi, Elia Fregonese, Paolo Minacapilli, Massimiliano Bussolino, Andrea Zanetti, Lorcan Kelleher, Fabio Porcari, Vahid Nateghi, Andrea Pizzetti, Mateusz Garbacz, Veronica Viera, Angelo Boceda, Luigi Marchese, Andrea Manganiello, Maurizio Vetere, Paolo Secci, Simone Alfano, Federico Migliosi, Nadia Lamera, Davide Perico, Nicola Pavia, Maurice Pepellin, Davide Martire, Finn Vehlhaber, Davide Zampa, Aldo Fejzo, Marcello Morini, Annalisa Ottaviani, Enrico Chemello, Ciro Salvi, Pedro Silva, Davide Scalettari, Gianfranco Salih, Luca Daidone, Leonardo Delleani, Abdalla Reda, Pietro Califano, Vincenzo Paolella, Emanuele Tomassi, Elisa Garbagnati, Gabriele Marra

Abstract

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Keywords

CubeSat, student design, roadmap

The space sector is under continuous expansion and so are the educational activities around it. The here proposed paper has the scope of showing the processes that led the 6S CubeSat team from PoliSpace, Politecnico di Milano students' led space association, with a few ideas in their minds to a robust hierarchical organization which, in a few months, has concluded the preliminary design of the first CubeSat prepared by students of one of italian technical universities. Firstly, the origin of the project is presented, with a focus on the methodology and criteria for the payloads selection and the mission definition. A water-based thruster, a structural battery and a perovskite solar cell have been identified for the 1U sattelite. A review of the system design follows, with a zoom on the different subsystems, their novelty, and their educational aspects. Such analysis is contoured by three mission drivers: novelty, to have a consistent scientific return; simplicity, to cope with the non-experienced team; reduced costs, due to limited funds availability. This paper gives a complete overview of the 6S roadmap extending the discussion to technical issues encountered during the path, with a particular emphasis on the experience gained by students and their approach while following ECSS standards.

Space educational hybrid activities during the pandemic: Visualising & Constructing a life on Mars

Alina-Mihaela Vizireanu[1], *Mark Waters*[2]

Abstract

In the context of the COVID-19 pandemic in 2020, education experienced the direct transition to digitalisation at the international level, and academic studies migrated to the virtual environment. According to official UNESCO data presented by Statistics, September 2020, more than 1.5 billion students globally have been affected by partial or total closure of educational institutions. With the closure of schools, both students and teachers started the journey to the New Education - the Online School. However, the main problem was yet to be assessed as "children are not the face of the pandemic".

Addressing the significant need to empower young people of all backgrounds to be inspired and feel connected with the educational system and progress their future careers, 4wardfutures, a careers' charity, developed two initiatives to address both STEM and Arts curricula through the impact of innovation and technology. The VALOM (Visualising a life on Mars) programme draws together people's creative heritage and endeavours throughout the ages with humankind's interest in travelling to and setting up settlements on a planet like Mars. The CALOM (Constructing a life on Mars) project is a careers education programme developed to give young people the opportunity to work individually or as part of a team, plan and design a settlement on Mars, explore how they will get to Mars, and subsequently survive.

Through the online programmes, young people are able to participate in interactive webinars with professionals from the space, creative, science, and engineering sectors to explore the challenges that humans will face travelling to and living on Mars. They were introduced to how we have used cartoons, comic books, painting, drawings, and music to visualise space travel and life on a planet like Mars through the ages. Also, they could explore the technology that would enable humans to construct a Life on Mars, technology that has a dramatic impact here on Earth and the future workplaces these young people will be progressing into.

The authors would like to acknowledge the considerable assistance of our many collaborative partners, and especially the teachers at Ellesmere Port Catholic High School and Bridgewater High School, Cheshire, United Kingdom.

Keywords
Space, education, STEAM, Mars, pandemic, online, career

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