LEOniDAS Drag Sail Experiment on the 2021 ESA Fly Your Thesis! Parabolic Flight Campaign

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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].

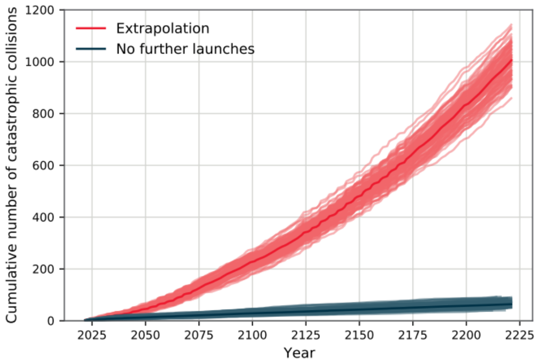

Figure 1: Long-term evolution of cumulative collisions in LEO in simulated scenarios [1]

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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.

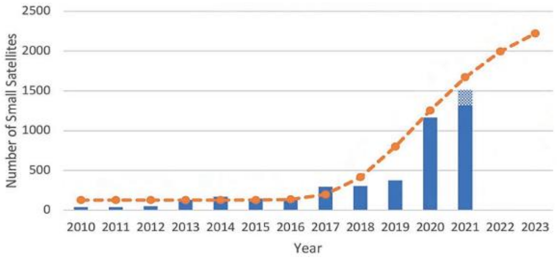

Figure 2: Trend in the number of small satellites launched (2010-2021) [3]

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.

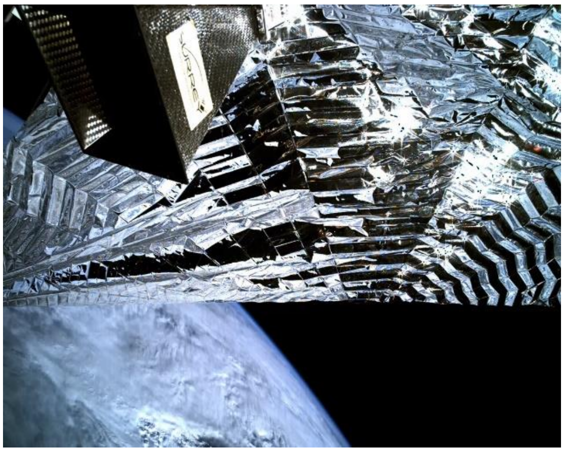

Figure 3: Image captured by TechDemoSat-1 post sail deployment (image courtesy of SSTL)

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, 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

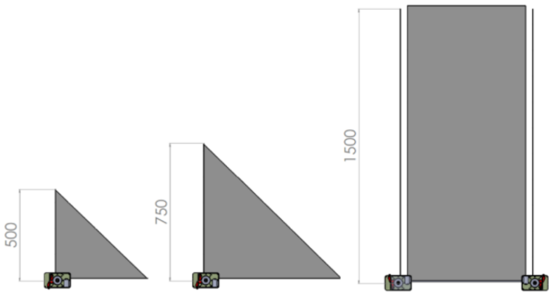

Figure 5: In order of appearance, Sail1, Sail2 and Sail3 (dimensions in mm)

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[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).

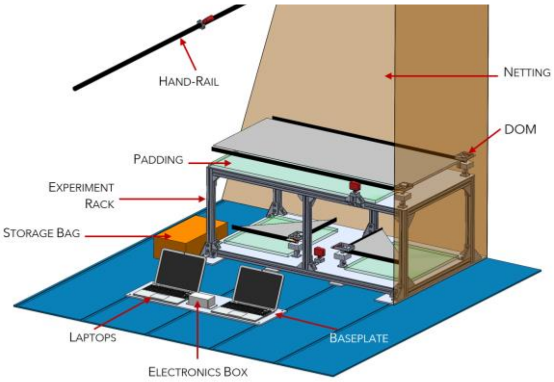

Figure 6: Overall experiment set-up with all the sail modules deployed

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^{TM} 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 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.

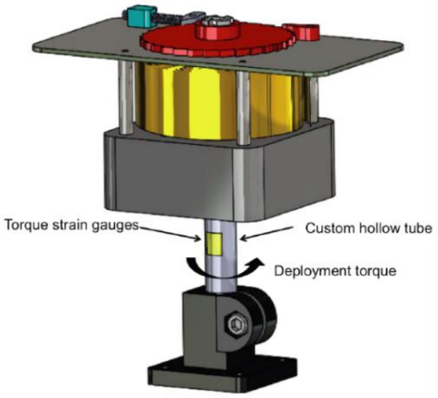

Figure 8: Strain gauge measurement setup

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 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.

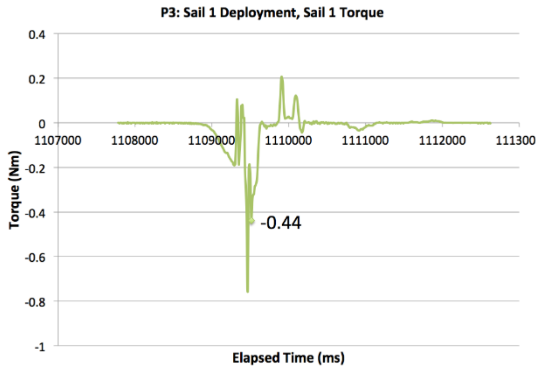

Figure 9: Deployment torque profile of Sail2

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.

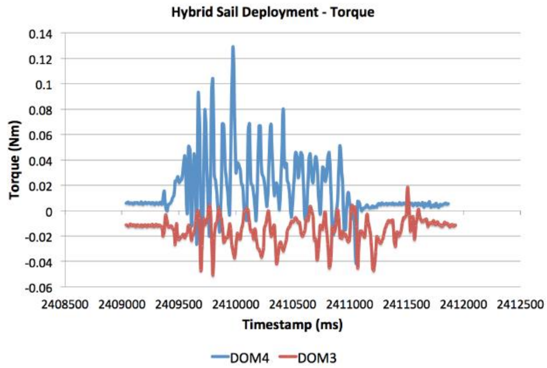

Figure 10: Deployment torque profile of Sail3

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.

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