Journal Pre-proof

Drag augmentation systems for space debris mitigation

Zaria Serfontein, Jennifer Kingston, Stephen Hobbs, Ian E. Holbrough, James C. Beck

PII: S0094-5765(21)00275-7

DOI: https://doi.org/10.1016/j.actaastro.2021.05.038

Reference: AA 8683

To appear in: *Acta Astronautica*

Received Date: 30 March 2021

Revised Date: 21 May 2021

Accepted Date: 26 May 2021

Please cite this article as: Z. Serfontein, J. Kingston, S. Hobbs, I.E. Holbrough, J.C. Beck, Drag augmentation systems for space debris mitigation, *Acta Astronautica* (2021), doi: https://doi.org/10.1016/j.actaastro.2021.05.038.

Acta Astronautica, Volume 118, November 2021, pp. 278-288
DOI: 10.1016/j.actaastro.2021.05.038

IAC-20-A6.6.9 (x60184)

Drag Augmentation Systems for Space Debris Mitigation

Zaria Serfontein[a], Jennifer Kingston[b], Stephen Hobbs[c], Ian E. Holbrough[d], James C. Beck[e]

[a] *School of Aerospace, Transport & Manufacturing, Cranfield University, Cranfield, Bedford, MK43 0AL, United Kingdom*, z.serfontein@cranfield.ac.uk, ORCID https://orcid.org/0000-0002-5704-1677
[b] *School of Aerospace, Transport & Manufacturing, Cranfield University, Cranfield, Bedford, MK43 0AL, United Kingdom,* j.kingston@cranfield.ac.uk, ORCID https://orcid.org/0000-0002-3605-5842
[c] *School of Aerospace, Transport & Manufacturing, Cranfield University, Cranfield, Bedford, MK43 0AL, United Kingdom,* S.E.Hobbs@cranfield.ac.uk, ORCID https://orcid.org/0000-0002-1464-5382
[d] *Belstead Research Ltd., 387 Sandyhurst Lane, Ashford, TN25 4PF, United Kingdom,* ian.holbrough@belstead.com
[e] *Belstead Research Ltd., 387 Sandyhurst Lane, Ashford, TN25 4PF, United Kingdom,* james.beck@belstead.com

Abstract

Space debris is a critical threat to future and on-going missions. The commercialisation of the space sector has led to a rapid growth in the number of small satellites in recent years, which are adding to the already high number of objects currently in low-Earth orbit (LEO). Low-cost small satellites operators are under increasing pressure to comply with debris mitigation guidelines as part of the application process for a launch licence. Drag augmentation systems are a potential low-cost and low-impact solution for small satellites. By increasing the effective area of a satellite, and therefore its drag, these sails reduce the de-orbit period of a satellite, subsequently reducing the probability of significant collisions and supporting the sustainable use of space. Cranfield University are developing a family of drag augmentation systems (DAS) to assist in the long-term conservation of the space environment. The DAS are lightweight, cost-effective, reliable sails deployed at end of mission. Currently three of the drag sails designed, manufactured, and tested at Cranfield University are in orbit and two of the devices have successfully deployed their sails. This paper will discuss these sails and will highlight results from recent studies; examining the scalability of the system, the vehicle dynamics after sail deployment, the medium-term impact of the sail on the host satellite's ability to continue operations, and the long-term effect of the sail on the demisability of the satellite. The DAS technology has a strong enabling potential for future space activities, allowing satellites to operate responsibly and sustainably.

Keywords: Space Debris, Drag Sails, De-Orbit Systems, Sustainable Space, Small Satellites, Low Earth Orbit

1. Introduction

Two major themes for the space sector in recent years have been the rapid growth in the number of small satellite (<500 kg) missions, and the recognition of space debris as a critical threat to future and on-going missions. Although advances in small satellite technologies have made space more affordable and accessible to all, enabling new users to enter the space sector, the increase in launches of this class of satellites continues to add to the already high number of objects in low-Earth orbit (LEO).

In 2019, approximately 80% of total satellites launched were small satellites [1]. That last decade has seen a shift in the dynamic of the space industry, with commercialisation fuelling the proliferation of low-cost small satellites and subsequently substantially reducing the costs associated with entering the space sector. The growth can be attributed to a number of factors, including increased private funding, increased public interest and advances in satellite technologies. Looking to the future, this increase in the number of satellites, as highlighted in Fig. 1, is expected to continue, especially with the rising popularity of satellite constellations [2] [3], [4]. This presents a serious challenge for space debris mitigation and has encouraged the development of technologies to enable small satellites to operate in a more sustainable environment without creating further debris.

ESA's Annual Space Environment Report [5] captures the concerning evolution of the space debris environment. As of the end of 2019, approximately 14,000 trackable objects (objects with a diameter ≥10 cm [6]) were orbiting Earth in LEO, with many more smaller objects. The number of objects and their collective mass have been rising steadily since the beginning of the space age, occasionally leading to involuntary collisions between operational payloads and space debris. The number of objects is of particular concern due to their orbital velocity. Objects orbit Earth at ~7.8 km/s; with that much energy, even a relatively small piece of debris can cause substantial damage to a spacecraft. With these collisions, the threat of the Kessler syndrome [7] is ever increasing. This describes a theoretical scenario in LEO where the debris from one collision continues to impact other satellites, increasing the likelihood of subsequent collisions and causing a ripple effect until nothing is left unscathed and spaceflight is rendered too hazardous to conduct.

Equally problematic is the spatial density distribution of spacecraft in LEO [8]. Increasing the number of satellites at certain altitudes will have more severe consequences than others. Natural post-mission re-entry within the required 25 years [9] is generally assumed for altitudes below 650 km [10], making them attractive orbits for low-cost small satellite missions with limited de-orbit options. For future mission, this could potentially result in a cluster of spacecraft between 600 km and 650 km. Therefore, in this *New Space* era, it is imperative not only to focus on the technological and scientific advancements, but also to consider the sustainability of spacecraft and the impact the spacecraft will have on its environment.

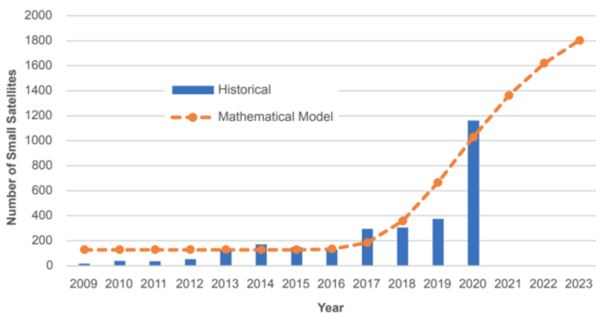

Fig. 1. Small Satellites Launched Since 2010 [2]

In 2002, the Inter-Agency Space Debris Coordination Committee (IADC) created a set of internationally accepted space debris mitigation measures. The IADC Space Debris Mitigation Guidelines was presented to the United Nations Committee on Peaceful Uses of Outer Space (COPUOS), who have prioritised standardising debris mitigation measures and creating guidelines to ensure the long-term sustainability of outer space activities. These guidelines have been codified as international standards [11][12] which state that spacecraft shall limit their post-mission presence in the LEO protected region to a maximum of 25 years from the end of mission. Since the number of spacecraft launched is rapidly increasing, these post-mission disposal guidelines will be an important mechanism to minimise the future population growth of objects in space. Low-cost satellites operators are under mounting pressure to meet these debris mitigation guidelines since proving compliance is necessary to obtain a launch licence. Although compliance trends are increasing, ESA's Annual Space Environment Report emphasised that, for spacecraft with an end-of-life (EOL) after 2010, 60% of satellites between 10 and 100 kg and 48% of satellites between 100 and 1,000 kg are still not compliant with the guidelines and made no attempt to be compliant.

There are a number of approaches to removing a satellite from orbit at EOL, including active de-orbit using propulsion, but amongst de-orbit 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 de-orbit process.

Cranfield University is developing a family of scalable drag-augmentation systems (DAS) for de-orbiting small satellites in LEO at end of mission, allowing them to comply with space debris mitigation guidelines and assisting in the conservation of the space environment [13]. To date, two systems have been developed and qualified: Icarus and De-Orbit Mechanism (DOM). These are simple, low-cost, reliable solutions, intended to have a minimal impact on the host satellite, allowing them to be fitted at a late stage in the design, assembly or integration phases. Two models of Icarus are currently in orbit (see Table 1) and both models have successfully deployed their sails. The DOM, on-board the ESA ESEO satellite, was launched in 2018 and has yet to deploy its sail.

Table 1. Cranfield University Drag Sails

DAS	Host Satellite	Date Launched
Icarus-1	TechDemoSat-1 (TDS-1)	8th July 2014
Icarus-3	Carbonite-1 (CBNT-1)	10th July 2015
DOM	European Student Earth Orbiter (ESEO)	3rd December 2018

This paper will highlight the recent advances made towards further developing and commercialising the Cranfield University DAS family. The follow sections will detail two studies carried out to assess the scalability and adaptability of the sails and to assess deployment dynamics post sail deployment. These studies resulted in new design recommendations for future iterations, quantified the effects of sail deployment on the host vehicle and ensured the sail will not impede the overall demisability of the satellite.

2. Cranfield University DAS Family

In 2015, Cranfield University carried out research to identify the number of small satellite LEO missions, between 2015 and 2020, that would not comply with debris mitigation guidelines without implementing a de-orbit strategy, such as deploying a drag augmentation device [14]. The assessment relied on data from SpaceTrak™, a database of future launch schedules, and the CNES orbit propagation tool STELA. The study resulted in the identification of the target market for passive de-orbit devices: microsatellites (10 – 100 kg) and minisatellites (100 – 500 kg) in LEO, particularly spacecraft without propulsion subsystems.

Although a significant number of launches in recent years have been specifically for the launch of small satellite constellations, drag sails are not currently considered appropriate for satellite constellations. To avoid disruption to the rest of the constellation during the de-orbit process, these satellites will require controlled re-entry, achieved through active de-orbit. Medium and large satellites (>500 kg) are also out of scope for these devices, since they are often equipped with on-board propulsion, but a passive de-orbit system could still be integrated as a back-up device.

In order to understand the performance of subsystems, and in particular which subsystems are more likely to fail towards satellite EOL, Cranfield University carried out a failure analysis [15]. A sample of satellites from the SpaceTrak™ database* in the 100-1,000 kg class, launched between 2000 and 2014 and in LEO, Medium Earth orbit (MEO) and Elliptical orbits, was chosen for the study. The aim of this study was to investigate the effect of subsystem failure on the de-orbit disposal method. Elaborating on the SpaceTrak™ subsystem failure classifications, five failure typology groups were derived; TTC (telemetry, tracking, and command including control processor failures and on-board data handling issues), POW (electrical distribution, batteries, and solar arrays issues), ATT (gyro, reaction wheel, attitude control, thrusters, and fuel anomalies), MECH (mechanisms, structures, thermal, and antenna deployment failures) and PAY & UNK (payload and unknown problems).

Two requirements related to de-orbit disposal devices, highlighted during the CleanSat study (discussed later in this section), were an overall spacecraft system reliability of 90% at EOL according to and specified in the ESA Space Debris Mitigation Verification Handbook and the ability of the device to activate successfully after 10 years on-orbit. These criteria were applied to the SpaceTrak™ data and the study concluded that the combined reliability for the TTC, POW and ATT subsystems (required for a propulsive de-orbit) dips below 90% after only 2 years in orbit and was 77% at 10 years in orbit. For satellites relying on active de-orbit manoeuvres, a passive de-orbit method could be included in case of failure.

Cranfield University has developed and qualified two simple, low-mass drag augmentation systems: Icarus and De-Orbit Mechanism (DOM). They are intended to have a minimal impact on the host satellite, allowing them to be fitted at a late stage to a mature design. To deploy, these devices require a brief current pulse at satellite EOL. The sails enlarge the effective area of the satellite, increasing its drag and rate of orbital decay, and allowing it to re-enter and burn up in the Earth's atmosphere. The size of the sail required depends on several variables, including the mass of the satellite, its configuration and its orbital altitude. Two models of Icarus have deployed their sails and are in the de-orbit process; Icarus-3 deployed on 7th November 2018 and Icarus-1 deployed on 31st May 2019.

In 2017, Cranfield University took part in the technology assessment and concurrent engineering phase of ESA's Clean Space initiative CleanSat [16], focused on three key areas for future LEO spacecraft: design for demise, de-orbiting systems, and passivation. The study was integral to evaluating the DAS design drivers (reliability, low-mass, low-cost, simple design and interfaces, testability, safety, scalability, and no additional debris production) and aided in maturing the DAS customers' top-level requirements. Additionally, this highlighted several requirements which need verification to qualify the drag sails for commercialisation, including:

- *Deployment Dynamics:* Random tumbling of the spacecraft shall be assumed to estimate the effective area of the deployed device.
- *Demisability:* The device shall be fully demisable, with no debris reaching the surface with kinetic energy > 15 J.
- *Lifetime:* The device design shall be compatible with 10 years ground storage, without need for complementary re-acceptance testing at the end of the storage period.
- *Lifetime:* The device shall be able to deploy successfully after a host satellite operational period of up to 10 years in LEO.
- *Environment:* The device shall ensure the expected performance under the radiation conditions observed during the operational lifetime and the disposal phase.
- *Environment:* The device shall ensure the expected performance under the atomic oxygen environment of a worst-case de-orbit scenario from 600 km, within 25 years from end of mission to re-entry.
- *Environment:* The device shall ensure the expected performance under the debris/meteoroid environment of a worst-case de-orbit scenario from 800 km, within 25 years from end of mission to re-entry.

2.1 Icarus-1 and Icarus 3

Icarus-1 was the first drag sail developed by Cranfield University as a demonstrator payload on the TechDemoSat-1 mission (depicted in Figure 2 and Figure 5 [17]). During the design process, the primary design criteria was ensuring the sail would pose no additional risk to the host spacecraft. Commercial off-the-shelf (COTS) components were used to accommodate budget

* satellite database which collates data regarding satellites, including failure rates and reliability

and schedule restrictions. The device conformed to additional requirements, including:

- *Safety:* preventing premature deployment, triggering deployment with an arm/fire architecture, ensuring actuation was under the control of the host satellite
- *No additional debris production:* reducing the effect the satellite has on it surrounding environment
- *Reliability:* minimum of 95% device reliability, assuming overall spacecraft reliability of 90% (ensuring compatibility with ISO 24113 at the time of design)
- *Low-mass:* ensuring the mass of the device does not exceed mass of propellant needed to achieve de-orbit

The 0.65 m booms were rigid struts joined by tape spring hinges, stowed together with the sail in a rectangular frame around the edges of one satellite panel. The symmetry of the design improved its manufacturability and allowed for redundancy. Icarus-1 successfully deployed in May 2019.

Icarus-3 was a smaller, simplified version of Icarus-1, delivered to SSTL's microsatellite Carbonite-1 mission in three months and adapted to a mature satellite design. The Icarus sail size is limited to the length of the boom struts, which in turn are restricted by the size of the satellite panel. Since Carbonite-1 was smaller than TechDemoSat-1, Icarus-3 was smaller than Icarus-1. Several minor design changes were integrated to improve the reliability of sail deployment and to simplify the stowage and deployment process.

Icarus-3 successfully deployed in November 2018 after Carbonite-1 completed its mission. Preliminary analysis, completed by the Defence Science and Technology Laboratory (DSTL) as part of their Daedalus observation campaign, confirmed an approximate doubling of the change in mean motion, and therefore likely drag, of the satellite post sail deployment. Since the deployment of Icarus-3 would double Carbonite-1's projected area from 0.6 m^2 to 1.25

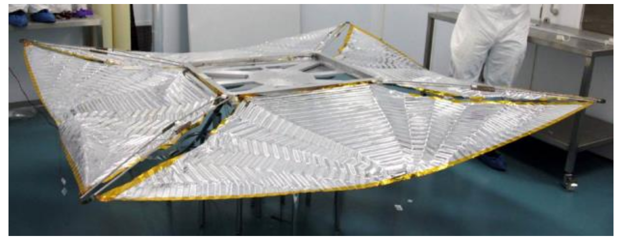

Figure 2: Icarus-1 in Cleanroom at Cranfield University

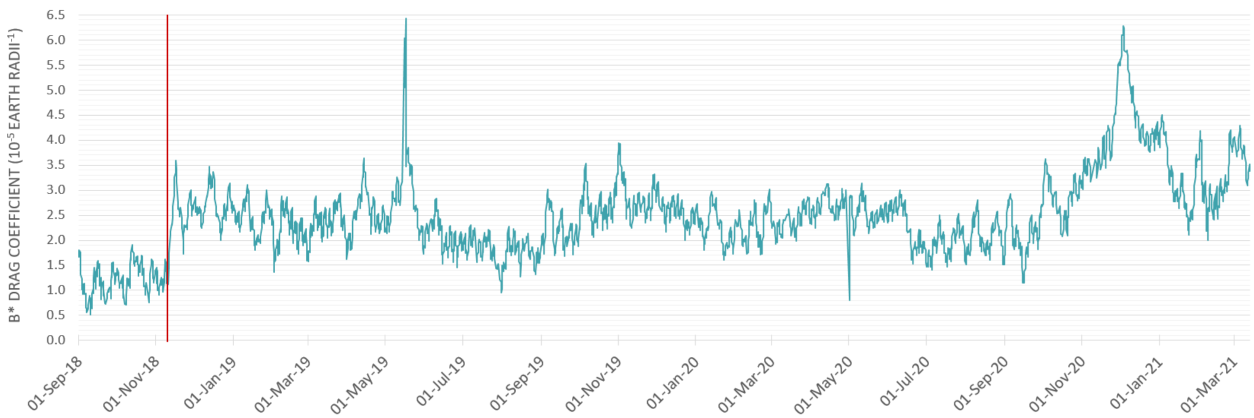

Figure 3: Change in Carbonite-1 B* Ballistic Coefficient, Data from Space-Track.org (Red Bar - Sail Deployment Date)

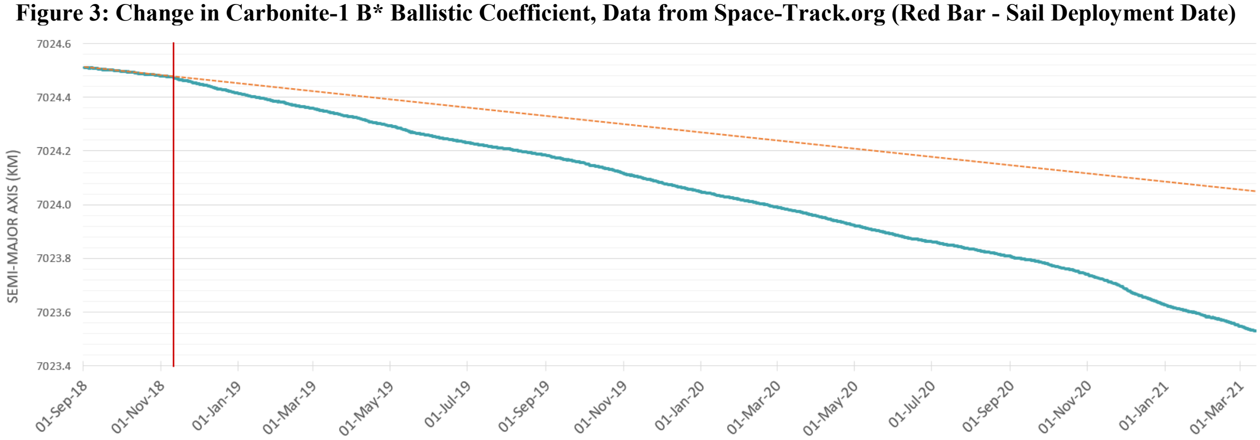

Figure 4: Change in Carbonite-1 Semi-Major Axis Decay, Data from Space-Track.org (Red Bar - Sail Deployment Date)

m^2, this was in line with expected results for a tumbling satellite. These results were further validated by Cranfield University's analysis of the publicly available two-line element set (TLE) data from Space-Track.org. Space-Track had several daily data points for Carbonite-1, including tracking its B* value, representing the satellite's susceptibility to drag, and the rate of semi-major axis decay.

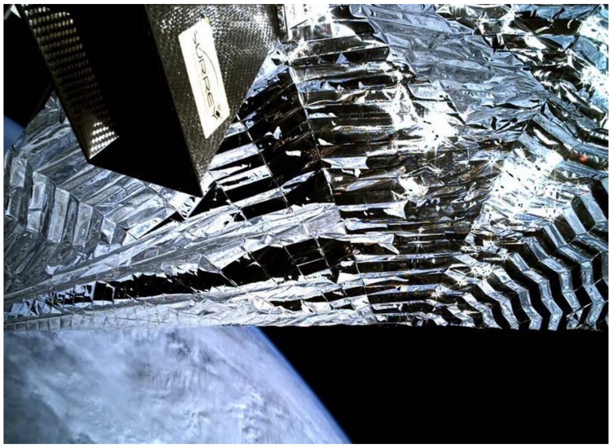

Figure 5: Image Captured by TechDemoSat-1 Post Sail Deployment (Image courtesy of SSTL)

Shortly after sail deployment, a rapid increase in B* is evident (see Figure 3 and Figure 4). The average B* value is doubled compared to nominal operations before sail deployment, reflecting the doubling of the satellite drag. Similarly, an assessment of the satellite's rate of change of semi-major axis showed an increase from -0.69 m/day pre- deployment to -1.18 m/day post-deployment. The dotted orange line in Figure 4 propagates the expected rate of semi-major axis decay if the sail had not been deployed. Since this trend has continued, it can be assumed that the sail has remained intact.

2.2 De-Orbit Mechanism

Cranfield University's DOM was integrated with the ESA microsatellite ESEO. The self-contained DOM module is significantly smaller than the Icarus models and can be mounted on one side panel of the host satellite. The copper beryllium booms and sail quadrants are coiled around a central spool, which is held in place by Kevlar cords. By co-reeling the sails and the booms, assembly and stowage times were significantly improved. In contrast to the Icarus models, the scalability of the DOM is not restricted by size of the host satellite and the encompassing frame, but rather by the booms themselves.

To actuate deployment, the Kevlar cords restraining the central spool are severed by activating two CYPRES™ cord cutters, allowing the stored strain energy in the booms to be released. The overall sail area is 0.5 m^2, consisting of four equally sized aluminised Kapton sail quadrants. This sail was a small-scale technology demonstrator and, as discussed in Section 3, the concept can provide much larger areas if needed.

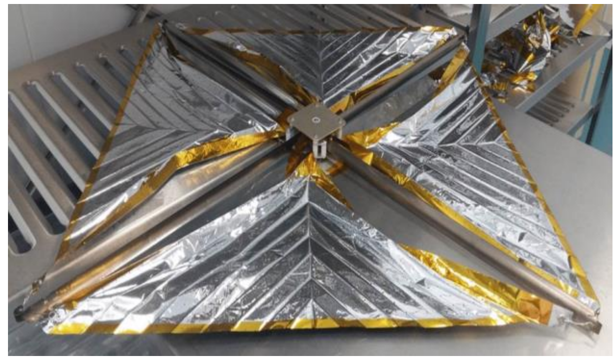

Fig. 6. DOM Flight Model at Cranfield University

2.3 Hybrid Design

The hybrid concept, depicted in Fig. 7, focuses on the scalability of the drag sail design and aims to further improve the adaptability of the device, allowing it to be tailored to a wider range of satellite configurations. The concept was derived from the strengths and weaknesses of the previous heritage designs. By creating a more modular design, and potentially separating the booms and sail modules, the design is no longer restricted to the size of the host satellite and the sail is no longer overlapping with the satellite body. Since the design does not require a full side panel of the host satellite to be free of protrusions, such as antennas, the resulting design is far more scalable than heritage designs.

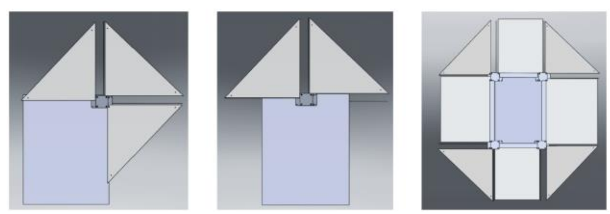

Fig. 7. Proposed Hybrid Concept Based on the Icarus and DOM Designs

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 EOL plan needs to be updated, hybrid sails could be rapidly procured as late-stage additions to ensure the satellite still complies with debris mitigation guidelines.

The following sections will discuss additional scalability, adaptability, and deployment dynamics analyses completed at Cranfield University, addressing some of the aforementioned design drivers.

3. Scalability: DOM Design Assessment

In order to assess the scalability of the new hybrid concept, the scalability of the DOM module needs to be investigated. The following section describes the experimental results which quantified the limits for the length of DOM booms in 1 g testing conditions. These results, combined with theoretical calculations based on the current DOM module volume, determine the scalability of the DOM module, with different boom and sail configurations, without adjusting the size of the DOM housing.

3.1 Scalability: Experimental Results

Copper beryllium is difficult to machine and handle. For these experiments, spring steel tape measures were used to simulate the c-shaped copper beryllium (CuBe) booms. The spring steel booms were similar in geometry and behaviour to CuBe, but were significantly easier to manipulate and do not have the added toxicity concerns associated with CuBe. Spring steel has a higher elastic modulus and is therefore stiffer than CuBe in the extended, deployed configuration, but CuBe has a significantly higher tensile yield strength, leading to better recovery characteristics and allowing the booms to ‘bounce-back’ after a snap-though failure. Since CuBe has optimal structural properties for the booms, the results obtained with the spring steel booms were considered the lower limits of the capabilities of CuBe booms.

Qualifying a product for microgravity conditions is expensive and intensive, and over-engineering a product for testing in 1 g conditions can be cost-effective. The first set of static experiments highlighted the maximum length of a single shell boom, which could support its own weight, was approximately 1 m. In order to increase this length, a different cross-section will be needed.

For the second set of experiments, a lenticular storable tubular extendable member (STEM) cross-section was utilised. These closed-section STEM booms were significantly stiffer compared to single shell booms, but at the cost of being more than twice the mass. Initially, the booms were fabricated by joining two opposite-facing spring steel shells together with Kapton tape, but this resulted in a concentration of stress during coiling and a phenomenon known as inner flange buckling. Due to a difference in length between inner and outer shells, the shells would deform during the stowage process. This phenomenon was amplified by the small initial coiling diameter. Increasing tension while coiling aided in preventing the inner shell from bifurcating, but this local stress concentration phenomenon was still present. The results confirmed that CuBe tape springs are too thick and the DOM spool diameter is too small to accommodate lenticular STEM booms.

To rectify this issue, rather than permanently bonding two shells with tape, two spring steel shells were held together in a polythene sheath. The friction between the tape spring edges in the sheath created a closed cross-section; leading to improvements in torsional stiffness and buckling loads but, by allowing the shells to slide past one another, the deformation due to stress concentrations was avoided. In this configuration no inner flange buckling was observed.

While the current DOM deploys four booms simultaneously and symmetrically, the hybrid design relies on greater configuration flexibility and the ability to deploy different numbers of booms and sail quadrants symmetrically or asymmetrically. To develop the hybrid concept, it is important to determine the effects of deploying only one or two booms and the effects of deploying those booms asymmetrically on the deployment process. The following tests were carried out:

1. Supported deployment
   a. Single lenticular sheathed boom
   b. Two parallel lenticular sheathed booms co-reeled
   c. Two perpendicular lenticular sheathed booms co-reeled
2. Unsupported deployment
   a. Single lenticular sheathed boom
   b. Two parallel lenticular sheathed booms co-reeled
   c. Two perpendicular lenticular sheathed booms co-reeled

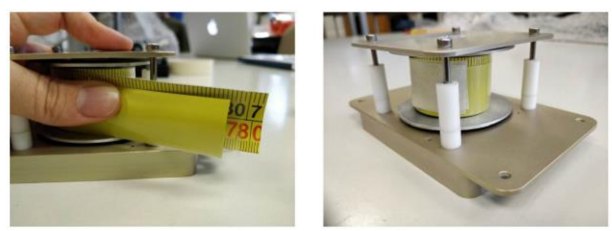

Fig. 8. Test Set-Up: Spring Steel Booms Held Together by Polythene Sheath in DOM Housing

Supported tests involved deploying the booms on a flat, smooth surface. Supported deployments of single, parallel and perpendicular booms were successful, repeatable and convincing. Unsupported tests highlighted two main challenges. Firstly, after a certain boom length, the booms would deploy fully before failing due to buckling. The rapid deployment followed by a sudden stop caused the booms to vibrate in their weakest axis, resulting in a bend-snap failure. Secondly, the booms would deploy optimally up to 75% of their total length before jamming inside the mechanism. The deployment process was dampened and boom guides were added to support the booms, but these were not successful. The mass of the booms had exceeded the limit at which they were able to deploy fully and remain extended without bend-snap failure, with the given deployment force in a 1 g environment. All three configuration tests resulted in the same approximate maximum boom lengths before failure: 1.5 m for supported booms and 1.1 m for unsupported booms. Therefore, 1.1 m represents the lower limit for the scalability of the sheathed CuBe booms, more than double the current DOM boom length. Since CuBe booms are more resistant to bend-snap failure, the most common failure mode in these tests, the actual booms are expected to perform better in future experiments.

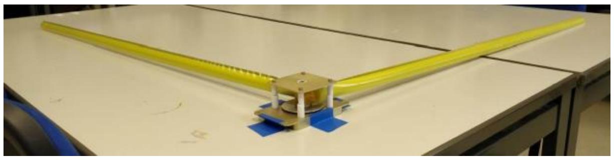

Fig. 9. Test Set-Up: Two Perpendicular Lenticular Sheathed Booms, Supported Deployment

3.2 Scalability: Theoretical Results

The maximum length of boom which could fit within the existing DOM housing was determined by calculating the total thickness of the co-reeled booms t_t, dependent on the number of thin-shell walls n, the thickness of each thin-shell wall t_{sh}, the thickness of the sheath t_s, and the packaging efficiency μ of the mechanism:

$$t_t = n(t_{sh} + t_s)(1 + \mu) \quad (1)$$

A sheathed lenticular boom is considered a two-walled structure where the number of shells is $n = 2$. Empirical data from literature suggested a packaging efficiency of 25% is acceptable as a first approximation [18]. To estimate the number of windings around the central spool ω, the shape was approximated to an Archimedean spiral and calculated based on the maximum co-reeled outer coiled radius r_f and the initial coiling radius r_i:

$$\omega = \frac{r_f - r_i}{t_t} \quad (2)$$

The initial coiling radius was equal to the radius of the central spool and therefore the transverse radius of curvature of the boom. Keeping the radii of the booms and spool the same aids in achieving a smooth stowed profile when the booms are wrapped around the central spool. Finally, to estimate the maximum length L of each boom for a given configuration and number of booms, the following equation was used:

$$L = \pi t_t \left[\left(\omega + \frac{r_i}{t_t} \right)^2 - \left(\frac{r_i}{t_t} \right)^2 \right] \quad (3)$$

To reflect the possible hybrid configurations, the maximum theoretical boom length to fit within the existing DOM housing was calculated for one to four booms. Currently, the maximum outer radius of the DOM housing is 38 mm. This exercise also highlighted the fact that the relationship between increasing the DOM overall housing size and increasing the boom length is not linear. Table 2 how increasing the radius by approximately 20% to 48 mm allows up to 70% longer booms to be stowed within the same housing.

Table 2. Maximum Theoretical Boom Lengths for Differing Number of Booms and Outer Radii

Number of Booms	Outer Radius r_f	Maximum Boom Length
1	38 mm	4.55 m
2	38 mm	2.27 m
3	38 mm	1.52 m
4	38 mm	1.14 m
1	48 mm	7.68 m
2	48 mm	3.84 m
3	48 mm	2.56 m
4	48 mm	1.92 m

Furthermore, the experiments showed that altering the configuration and distribution of the booms did not have any visible adverse effects on the deployment process. Independent of configuration, the maximum boom length limits remained the same and there was no observed excess blossoming, which can occur when the boom starts to uncoil within the DOM housing, causing the mechanism to jam. To overcome blossoming, layers need to be able to slide past one another by overcoming the friction between layers [19]. This is an important finding for the hybrid concept, where asymmetrical and uneven deployment are part of the design.

3.3 Light Boom Alternatives

The scalability assessment in the previous section found that the boom lengths could be increased from 0.5 m to 1.1 m for unsupported deployment in 1 g without changing the housing or the deployment process. Since the DOM housing and deployment actuators remain fixed, the primary driver for the mass of the overall system is the mass of the booms. Thus, the scalability of the system does not only depend on the physical limits of the mechanism, but also on the mass of the booms. Lightweight composites were investigated as a weight-saving measure to replace the copper beryllium booms. Composites have been proposed due to their mechanical properties, in particular, their high strength to stiffness ratios. An additional benefit of composites is the ability to tailor the directional properties of laminates to optimise the properties of the booms to meet the design requirements.

The DOM booms have conflicting mechanical property requirements for their stowed and deployed configurations. In the stowed configuration, the laminate needs to have a high strain to failure ration and a low axial Young's modulus to ensure compact storage, to reduce creep and to ensure the mechanism will have predictable deployment dynamics. Conversely, once deployed, the booms require a high axial modulus to maximise the boom's stiffness and help reduce the probability of the slender boom's most common failure mode; global column buckling. A boom's stiffness can be improved by increasing the percentage of fibres in the boom's axial direction.

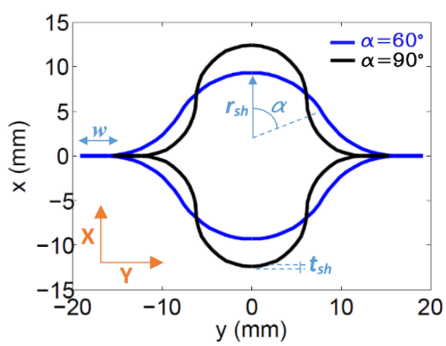

Fig. 10. Examples of Differing Subtended Angles and Web Widths

Geometrically, the moments of area about the principal axes need to be maximised while ensuring the flattening and rolling strains limits are not exceeded. The moments of area can be maximised by balancing having the largest possible subtended angle α with the smallest possible web width (depth of bonded edges) ω. Since the booms will be stowed for a long period, it is imperative to recognise the viscoelastic effect in composites as a high risk in the design. Creep and stress relaxation effects are significant over long-term storage periods and can result in a flatter cross-section, and smaller subtended angle, than originally fabricated. Past studies [20] have tested the limits of composite booms and shown that a subtended angle greater than 80° will result in unacceptable flattening strains and web widths smaller than 3 mm result in large shear stresses. Therefore, the optimal characteristics recommended for the DOM booms include a subtended angle of α = 80° and a web width of ω = 3 mm.

The optimal composite boom cross-section was determined to be a collapsible tubular mast (CTM), as depicted in Fig. 10, due to its strong mechanical properties and manufacturability. As seen in the DOM scalability section, inner flange buckling occurs when bonded lenticular boom is coiled about a spool with a small diameter. To combat this phenomenon, the CTM booms need to be fabricated with thin-ply materials and a toughened epoxy with a high glass transition temperature and low outgassing should be used.

The optimal layup for a compact coiled configuration is an asymmetric [-45/0/45] or [0-90PW/45PW] layup, depending on available materials. Unidirectional inner plies maximise the boom axial stiffness and improves the boom's resistance to creep, whereas outer surface ±45° plain weave (PW) plies provides torsional stiffness and ensures cross-sectional stability. Additionally, the ±45° PW ply reduces the chances of premature delamination under high strain, helping to suppress compressive micro-buckling failure modes, common in highly loaded axial plies. This has the added benefit of preventing surface cracking during packaging. One negative side-effect associated with an asymmetric layup is the introduction of thermal stresses in the boom, promoting axial curvature and potentially resulting in a twist in the boom. This is not a primary concern, but will need to be monitored. With this layup, the composite booms will be ~56% the mass of CuBe booms.

Cranfield University has the necessary facilities to manufacture the composite booms in-house. Ideally, a single-step cure process would be performed out-of-autoclave. Not being limited by the size of an autoclave will improve the scalability of the boom. To reduce tooling, and therefore cost, a flexible silicone plug, as discussed in Fernandez's paper [20], could be added to the process as an inner male mould for the laminates. It can be easily removed after the curing process and it eliminates the need for a second top tool. The bottom half of the omega-shaped laminate is placed on the female tool followed by the silicone plug, adhesive strips, the top half of the laminate, a top release film, breather ply and vacuum bag. Curing is completed with two temperature soakings. Vacuum pressure needs to be maintained until the final cool-down process to prevent the ends of the booms suffering from thermally-induced deformations. Cranfield University has extensive experience with bonding technologies within their composite department. Utilising these skills, it would be possible to have significantly smaller moulds and bond the booms together in a separate step. Although this fabrication process would take longer and the booms would be slightly thicker, it would reduce the cost of the tooling required significantly.

Further research into composite booms is being conducted at Cranfield University along with other advanced concepts, including inducing bi-stability into the booms [18]. Adding a second stable coiled configuration would ensure the mechanism would not need to be stowed in a high strain state. The bi-stable boom deployment process can be tailored to a specific deployment resulting in a more controllable system and potentially an easier system to simulate microgravity conditions.

The hybrid drag sail design will be tested on a series of parabolic flights in October 2021 as part of the European Space Agency's Fly Your Thesis! programme. New composite booms will be fabricated and tested as part of this campaign.

4. Assessment of Deployment Dynamics and Demisability

As part of a UKSA Pathfinder project, Cranfield University and Belstead Research Ltd. analysed the dynamics of two drag augmentation systems from deployment to demise. The team presented their results in March 2019, addressing three main uncertainties regarding drag sails:

- The impact of sail deployment on short-term vehicle dynamics and the implications for Space Situational Awareness (SSA) and Space Surveillance Tracking (SST) programmes
- The influence of a deployed sail on mission dynamics and the ability to extend the mission into a drag augmented disposal phase
- The effect of drag sails on the re-entry and demise of the spacecraft

4.1 Short-Term Vehicle Dynamics

The impact of both the Icarus-1 and Icarus-3 sails on TechDemoSat-1 and Carbonite-1 respectively have been assessed within the activity. The dynamics of each vehicle in the 3 day period after sail deployment was investigated using a set of small 100 simulation Monte-Carlo analyses. These assessed the evolution of the motion of each satellite in six degrees-of-freedom. The resulting population was profiled in terms of the average total angle of attack in three hour windows, as exemplified by Fig. 11Fig. 11.

Aerostability, i.e. a tendency for the satellite to acquire a steady attitude relative to the flow, was a desirable feature and was considered during the design phase of the Icarus sails. Aerostable designs maximises the drag of the structure, therefore minimising its de-orbit period, and tend to show less variability of lifetime compared to completely flat surfaces. The Icarus sails designs included a slightly canted sail design (as seen in Fig. 12), to form a shallow rectangle-based pyramid, in an attempt to encourage the system to be marginally stable [21]. Since the system is un-damped, it is expected to oscillate around this stable state, leading to periods of tumbling, but an overall increase in the average cross-section relative to a simple tumbling case.

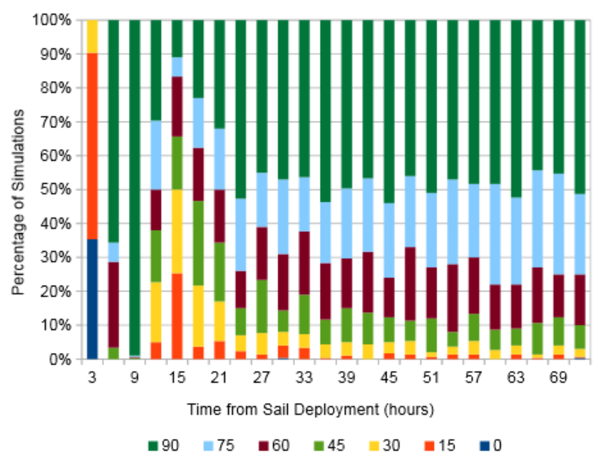

Fig. 11: Carbonite-1 Total Angle of Attack Post Sail Deployment Motion Profile

Initially all simulations predicted stable behaviour of the sail, with an average total angle of attack of less than 15 degrees. However, this constrained motion rapidly died away as a greater proportion of the population took on larger attitude motion. By the end of the 3 day period only 20% of the population had an average angle of attack of less than 60 degrees and in all cases over 40% of the population exhibited an average angle of attack of 90 degrees or more. Thus it is clear that the attitude motion of the drag sail is not stable. Interspersed in this general trend toward larger amplitude motion were periods where this trend reversed. It is speculated that these occur when perturbations align to reinforce aerodynamically stable motion for a short period. However, the overall motion is tumbling.

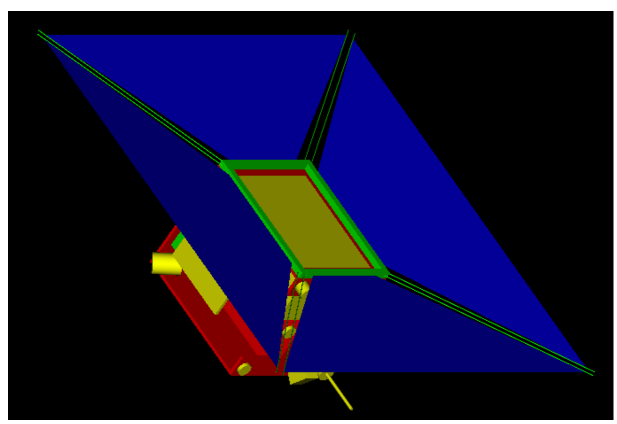

Fig. 12: TechDemoSat-1 with Deployed Sail Model

The expected attitude behaviour during the year after deployment was also investigated. Initially the baseline decay of the orbit over the year prior to sail deployment was assessed using the COSPAR CIRA-2012 atmosphere with the vehicles being held in their nominal attitude. This suggested that drag experienced over the period was between 150% and 180% of that predicted by the low solar activity profile. This tuned atmosphere model was then used to propagate the orbit forward from deployment to generate a nominal orbit prediction with unconstrained motion of the vehicles. Again, these simulations predicted that both satellites were expected to enter into a slow tumbling motion following the passivation of the AOCS and deployment of the drag sails. Bounds for the expected range of orbit evolution were also established by considering cases where the sail was not deployed, resulting in low drag, and sail deployment with the AOCS remaining active, resulting in the maximal drag configuration. Finally, the delay in observing satellite passes resulting from the increased drag of the sail was evaluated. This was done by comparing the timing of passes of a drag enhanced vehicle with those generated by a spacecraft with no sail. This suggested that the impact on the orbit would be expected to be less than one second for up to 15 days after deployment, and took between 25 and 40 days to reach 5 seconds.

Subsequent assessment of the publicly available TLE data suggests the Icarus-3 deployment was successful and validated the predictions of a tumbling motion (as seen in Figure 3 and Figure 4). DSTL's Daedalus observation campaign provided results from ground radars at Chilbolton and Herstmonceux. Preliminary analysis of the observations revealed changes in elevation and azimuth angles after the deployment epoch consistent with an increase in drag, and therefore, a successful deployment of the sail. However, the observed increase in drag is consistent with a tumbling motion, and is clearly insufficient to suggest that the motion is stable.

Together, these results are further evidence that, without a sail specifically designed to promote aerodynamic or solar stability, a rapid transition into tumbling motion should be expected following sail deployment. Further, as the higher drag observed is well approximated by a random tumbling prediction, when undertaking future analysis, it would be reasonable to utilise a three degree of freedom system based on average drag for the evaluation of re-entry times.

4.2 Potential Mission Extension

The second key focus of the project was to evaluate the impact of sail deployment on the ability of TechDemoSat-1 to continue nominal operations. The motion of TechDemoSat-1 was modelled for one year after sail deployment on the 7th November 2018. The satellite model was enhanced with specific 'sensitive' surfaces with a cone of activity for each surface. For example, the antennas had an active cone half angle of 35° as determined by their field of view. The focus of the analysis was on SSTL-150 bus instruments, which are common to other satellites, and the data was divided into five main categories: the effect of sail deployment on power generation, communications, GPS instrumentation, and star tracker instrumentation, as well as the induced torque. This analysis sought to establish the medium-term effects of the sail deployment on the instrument operations. In each scenario, the *no sail deployed* and *deployed sail* cases were compared to determine whether instrument performance decreased after sail deployment. The following aspects were considered:

- The ability of instruments and communication systems to maintain line of sight with their intended targets once the sail has been deployed
- The capability of the attitude and orbit control

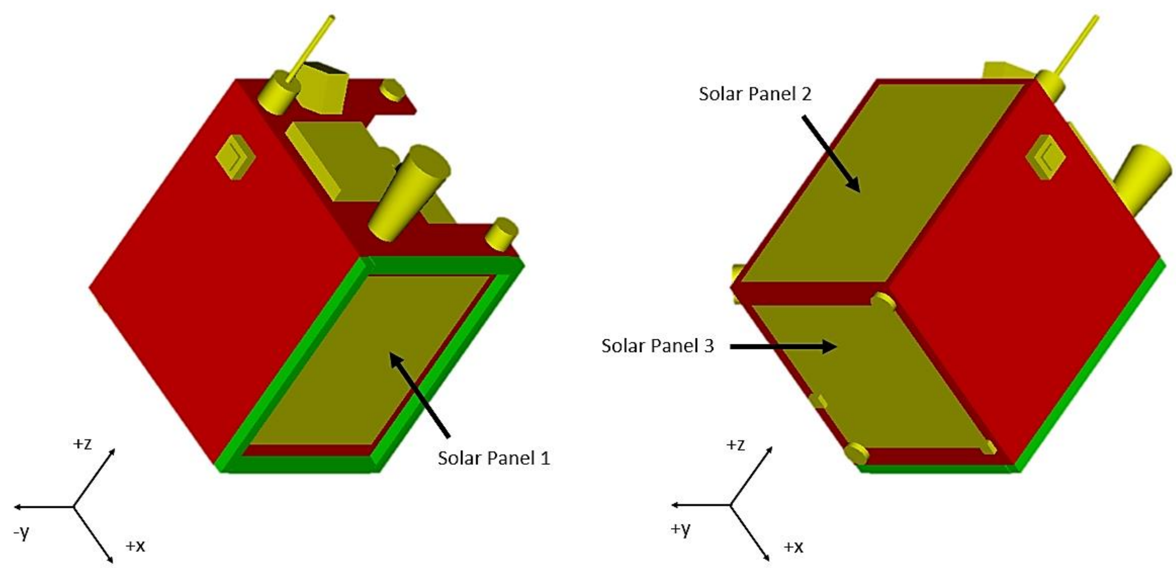

Fig. 13: TechDemoSat-1 Reference Frame

system (AOCS) to maintain required attitudes despite the increased torques and the impact of these increased torques on the rate of fuel consumption
- The potential for power systems, notably solar arrays, to receive enough sunlight to continue to power the platform

As part of the study, three scenarios were considered:
1. Nominal case (baseline): AOCS maintains the vehicle in its normal mission attitude, travelling in the +x direction (see Fig. 13)
2. High-drag case: vehicle is rotated about the z axis such that the drag sail is deployed behind the satellite relative to its direction of travel. Nominal attitude is maintained by AOCS.
3. Ballistic case: vehicle is aligned in the high drag attitude, AOCS is passivated and vehicle is permitted to tumble.

The assessment of TechDemoSat-1's ability to continue operations post sail deployment yielded positive results. The medium-term impact predicted was minor for the power and communication subsystems of the platform. Since the satellite has fixed solar panels and communication antennas, power and communications depend heavily on the orientation of the spacecraft. During the first two scenarios, the nominal satellite attitude is maintained by the AOCS and any reduction in power and communications is due to drag sail shadowing, where the sail obstructs the line of sight between the sun and the solar panels or the antenna cone of activity and the ground station. During the third scenario, the satellite attitude is not fixed and as a result, charging and communication times are more sporadic.

Power is an essential parameter in satellite operations and the three gallium arsenide solar panels were the first components to be assessed. Due to the distribution of the solar panels relative to the location of the drag sail, the shadowing effect of the sail on the panels was minimal, with the most significant effect seen on solar panel 3. Overall, a minimal decrease in power was observed across the three scenarios. The most notable difference in power was seen in the tumbling scenario, in which case the satellite would still be able to generate adequate power for nominal operations 98% of the time.

Once it was established that there would be a negligible impact on power, communication between the satellite and the ground station was investigated. The satellite is equipped with several antennas on the +z and –z faces of the satellite. During nominal operations and in a high-drag configuration, communication times could be decreased by up to 19% due to the sail obstructing the line of sight between the antenna cone of activity and the ground station. In the tumbling scenario, this increases to 40%. Other instruments, such as the star tracker and GPS, were not impacted by sail deployment in the nominal and high-drag configurations, but were heavily impacted by the satellite being permitted to tumble.

A preliminary analysis of the on-board AOCS and the induced torques resulting from sail deployment in the nominal and high-drag configurations highlighted that the torques are expected to be within AOCS limits and the satellite should be capable of counteracting the sail deployment torques. Taking into account that the impact of sail shadowing is negligible in these configurations, these are the optimal scenarios for continuing operations after sail deployment, with significant opportunities to continue operations post sail deployment.

Satellites are passivated at EOL; discharging batteries and shedding remaining fuel to reduce the risk of future explosions. In this case, this would include deactivating the on-board AOCS. As the drag sail is deployed, the induced torques would not be counteracted and the satellite would be permitted to tumble.

Initiation of the de-orbit process is inherently linked to a satellite's EOL. As a fully-operational satellite approaches EOL, operators are often presented with a choice; extend the mission lifetime of the satellite or de-orbit the satellite. However, the longer a satellite is in orbit, especially for an extended mission, the higher the risk of subsystem failure. If operations are able to continue post sail deployment, and the AOCS is able to maintain a nominal attitude, sail deployment could be activated before EOL, at the start of a mission extension, removing the risk of satellite subsystem failure before deployment is commanded, which would otherwise result in the creation of long-lived space debris. Deploying the sail earlier, along with other measures to further minimise the impact of sail deployment, such as adjusting the satellite attitude to minimise drag during nominal operations, are worthy of further investigation.

In addition to accounting for the drag sail during the design phase of the host satellite, the design of the drag sail could be optimised to minimise its effect on the mission performance. Section 2.3 described the hybrid drag sail concept currently under development at Cranfield University. These discrete self-contained modules could be adapted to different host satellite architectures and integrated in a variety of configurations. Rather than a single large sail, smaller individual sail quadrants could be deployed at different locations and times to maximise the mission performance and the overall impact of the drag sail. This would be a balance between enhancing the de-orbit efficiency, managing the risk of satellite failure before sail deployment and the challenges associated with continuing operations after deployment of a sail. Not only could the drag of the satellite be adjusted, but deploying sails in stages could aid in avoiding shadowing effects while the satellite is still operational.

One of the goals of simulating the behaviour of the satellite post sail deployment is to inform space situational awareness and space surveillance and tracking programmes, in order to assist the modification of collision avoidance and tracking algorithms. The complex models used to propagate the satellite's orbit yielded drastically different results depending on the chosen atmospheric model and, in particular, solar flux conditions, as seen in Fig. 14. The team will continue monitoring the de-orbit rate of the two deployed Icarus sails, comparing their period to simulated results.

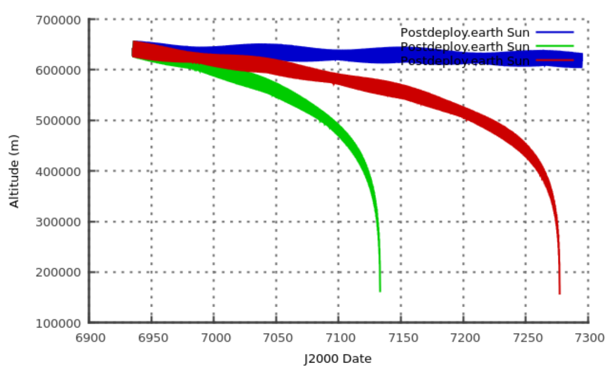

Fig. 14: Re-Entry Times for Moderate (Blue), Short-Term High (Green) and Long-Term High (Red) Solar Activity Profiles

4.3 Re-Entry and Demise

The final aspect considered within the activity was the impact of a drag sail on the re-entry and demise of the vehicle. It has been shown in other studies [22], [23] that the demise of spacecraft is driven by a complex interaction between the composition of its parts and the environment that it is exposed to during re-entry. Whilst sails are relatively delicate structures, incapable of withstanding the aerodynamic forces and heating associated with re-entry, their influence on the vehicle's ballistic coefficient and the possibility of their generating a preferential aerodynamic attitude may change the re-entry profile and influence demise behaviour. Therefore, when considering the influence of drag sails on arbitrary spacecraft the critical question is whether it can be demonstrated with reasonable confidence that the sail demises early enough in the re-entry that it does not influence the conditions at re-entry. Or, if that cannot be ascertained, that the influence is not significant enough to require the inclusion of the impact of the drag sail within more general studies of a vehicle's demise.

A small campaign of thermomechanical demise tests on the sail material and PTFE plugs connecting the sail booms to the deployment mechanism were conducted within the activity using a kiln (see Fig. 15). These tests suggest that the PTFE plugs holding the sail booms will fail at a lower temperature than the sail material itself. The timing of the PTFE plug failure was significantly later than expected, as the plugs do not melt quickly, and fail about 200 °C above the melt temperature. However, the sail melts at approximately the aluminium melt temperature. These results informed updated PTFE and sail material models for this study. Further, they suggest that the sail panels should demise before the booms separate, driving the demise of the overall sub-system. The timing of the sail demise is subject to the condition that the long-term exposure to atomic oxygen does not adversely affect the sail's structural integrity. Further studies on the impact of atomic oxygen on the Kapton sail material are being conducted at Cranfield University, which could have a significant impact of the predicted re-entry of vehicles with drag sails [24].

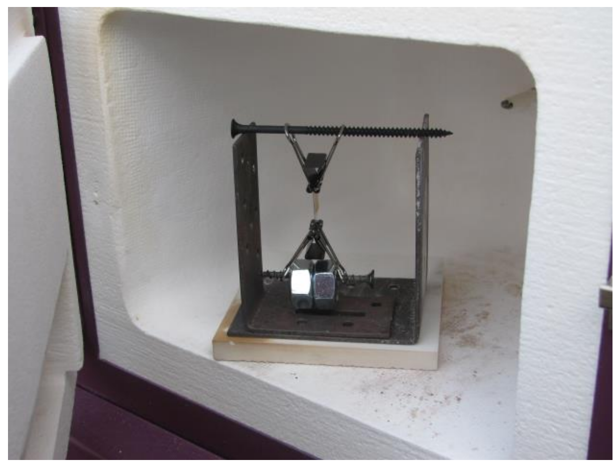

Fig. 15: Thermomechanical Demise Test Set-Up

The assessment of demise was conducted using a Monte-Carlo of 1000 simulated re-entries of a simplified TechDemoSat-1 geometry, comprising 17 components representing the sails, booms, deployment mechanism and satellite body. These simulations were initiated at a nominal 250km altitude and ran to an entry at 90km. The results provided corroboration that the boom joints are predicted to fail at a lower altitude than the sail material, as shown in Fig. 16. It is also clear that no significant failure is predicted prior to a nominal re-entry interface at 120km. Therefore, the possibility that the use of a drag sail has an impact on the re-entry and demise of the vehicle cannot be dismissed, although this result might be revised based on the impact of atomic oxygen on the sail material.

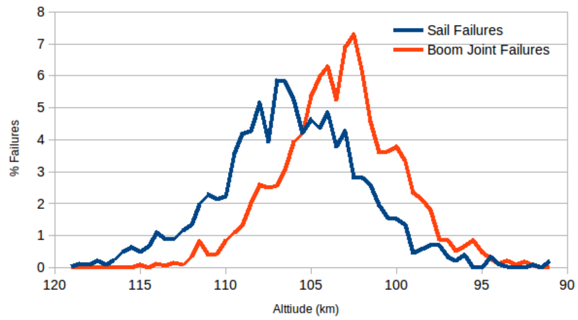

Fig. 16: Sail and Boom Joint Failure Altitudes

Comparing these re-entry simulations with a set of 250 similar predictions where the sail is not deployed, shows that the average flight path angle at 120km is 0.08° steeper in the case where the sail is deployed. Therefore, whilst in this instance the sail does lead to a broader range of steeper entries, the change is not significant and will not alter the nature of the demise experienced by the vehicle. In general, most uncontrolled re-entries of spacecraft would be expected to have a re-entry angle between 0° and -0.3°, which is driven by the planet oblateness.

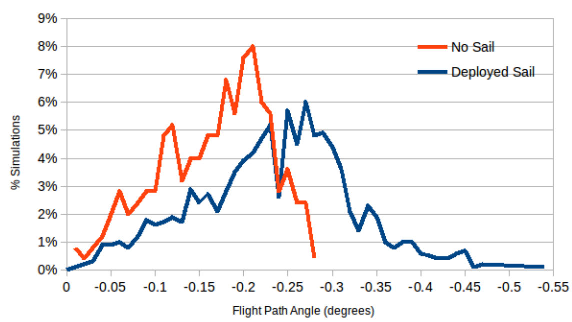

Fig. 17: Predicted Flight Path Angle at 120km

A simplified examination of the potential for preferential attitudes has been undertaken by examining the instantaneous attitude of the vehicle in each of the 1000 simulations as it crosses the 120km nominal re-entry interface, as shown in Fig. 17. Whilst there is a broad scatter of results, there are some indications of a small cluster at +/- 180° angle of attack and -15° sideslip. An angle of attack of 180° corresponds to the aerodynamically stable attitude with the drag sail behind the body of the vehicle in the direction of travel. Given the symmetry of the simplified geometry in use the reason for the trim angle of -15° in the angle of sideslip is not clear. Nevertheless, no such preferential cluster is seen in the results when the sail is not deployed.

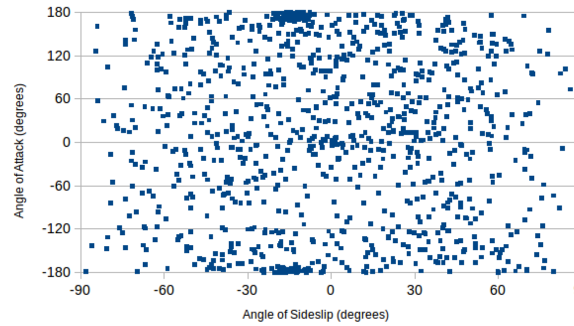

Fig. 18: Predicted Instantaneous Attitude at 120km

Therefore, although some preference for an aerodynamically stable attitude is predicted, it is not seen to be dominant. As a consequence, the impact of alignment generated by the sail is not expected to be significant for geometries similar to TechDemoSat-1.

In summary, this analysis suggests that, subject to the caveats around the impact of atomic oxygen on the integrity of the sail panels, the late demise of the drag sail has a small impact on the re-entry conditions of the vehicle. However, these changes are not significant enough to result in a substantial change in expected demise behaviour. Despite the relatively late demise predicted for the drag sail subsystem, a simplified three degree of freedom simulation based on average tumbling aerodynamics should be sufficient to assess the impact of the drag sail on re-entry.

The Pathfinder study concluded that there are significant opportunities to improve drag sail proposition through the continued operation of the host satellite post sail deployment.

5. Conclusions

The DAS appear to be a practical and effective means for small satellites to operate sustainably and responsibly. This paper amalgamated the work completed at Cranfield University to aid in the further development and commercialisation of the DAS family. Studies conducted at Cranfield University assessed the scalability and adaptability of the drag sails, the short- and medium- term deployment dynamics of the Icarus sails and the demisability of the Icarus sails.

The scalability of the DOM module, and in turn the hybrid design, was studied experimentally and estimated theoretically. By modifying the shape of the boom cross-section, the length of the DOM booms could be doubled without altering the deployment process or the DOM housing, however, this would still result in a significant mass increase. Composite booms have been proposed and designed as a viable alternative weight-saving solution.

The UKSA Pathfinder deployment dynamics study verified that, if the satellite was passivated prior to sail deployment, the satellite will enter into a slow tumbling motion following sail deployment. The study concluded that operations could potentially continue after sail deployment, allowing for sail deployment earlier in the satellite lifetime, thus reducing the risk of deployment failures. The sails are currently not expected to have a significant impact on the vehicle's demise, but this will be reassessed after studying the impact of atomic oxygen on the Kapton sails in greater detail.

5.1 Future Work

Work continues on the further development and eventual commercialisation of the DAS family, and in particular the hybrid design. Through ESA's Fly Your Thesis! parabolic flights, the team will qualify the new design for deployment in microgravity, assess the scalability of the sails, test new boom materials, study the impact of deployment on the host satellite, and validate a ground-based microgravity test setup for future microgravity testing.

There are still many requirements related to the DAS lifetime and the degradation of the devices in the LEO environment which need to be addressed before the sails can be commercialised. These include investigating the effects of long-term storage in LEO, ensuring the devices are compatible with ground storage, and validating that the design will be able to achieve the expected performance for a worst-case de-orbit scenario of 25 years re-entry time.

Additionally, the data from the deployed Icarus sails continues to be monitored and compared to predictive models, validating previous simulations and highlighting areas for further research and improvement. This research will benefit the wider space community by improving the understanding of long-term material degradation in LEO and its effect on performance, and by validating future low-Earth orbit atmospheric models.

Acknowledgements

The support of the UK Space Agency in funding the Pathfinder programme is gratefully acknowledged.

References

[1] Euroconsult, "Prospects for the Small Satellite Market: Forecasts for 2028," 2019.

[2] Satellite Applications Catapult, "Small Satellite Market Intelligence Report Q4 2020," 2021.

[3] Euroconsult, "Satellites to be Built & Launched by 2028," 2019.

[4] M. Puteaux and A. Najjar, "Analysis | Are smallsats entering the maturity stage?," *Space News*, 2019. [Online]. Available: https://spacenews.com/analysis-are-smallsats-entering-the-maturity-stage/. [Accessed: 22-May-2020].

[5] ESA Space Debris Office, "ESA's Annual Space Environment Report," 2020.

[6] T. Maclay and D. Mcknight, "Space Environment Management: Framing the Objective and Setting Priorities for Controlling Orbital Debris Risk," in *70th International Astronautical Congress*, 2019.

[7] D. J. Kessler and B. G. Cour-Palais, "Collision frequency of artificial satellites: The creation of a debris belt," *J. Geophys. Res. Sp. Phys.*, vol. 83, no. A6, p. 2637, 1978.

[8] G. Peterson, M. Sorge, and W. Ailor, "Space Traffic Management in the Age of New Space," 2018.

[9] IADC, "IADC Space Debris Mitigation Guidelines," 2007.

[10] IADC, "Support to the IADC Space Debris Mitigation Guidelines," 2014.

[11] V. Braun, "Small Satellite Constellations and End-of-Life Deorbit Considerations," in *Handbook of Small Satellites*, Springer International Publishing, 2020, pp. 1–23.

[12] BSI Standards Publication, "Space Systems - Space Debris Mitigation Requirements BS ISO 24113:2011 BSI," 2011.

[13] C. Palla, J. Kingston, and S. Hobbs, "Development of Commercial Drag-Augmentation Systems for Small Satellites," in *7th European Conference on Space Debris*, 2017.

[14] C. Palla and J. Kingston, "Forecast analysis on satellites that need de-orbit technologies: future scenarios for passive de-orbit devices," *CEAS Sp. J.*, vol. 8, no. 3, pp. 191–200, Sep. 2016.

[15] C. Palla, M. Peroni, and J. Kingston, "Failure analysis of satellite subsystems to define suitable de-orbit devices," *Acta Astronaut.*, vol. 128, pp. 343–349, Nov. 2016.

[16] S. Val Serra, D. Briot, J.-C. Meyer, and S. Shojaee, "CleanSat Study: Technology Assesment and Concurrent Engineering in Support of LEO Platform Evolutions," Italy, 2017.

[17] SSTL, "TechDemoSat-1 On-Board Camera Captures Drag Sail Deployment," *Surrey Satellite Technology Limited*, 2019. [Online]. Available: https://www.sstl.co.uk/media-hub/latest-news/2019/techdemosat-1-on-board-camera-captures-drag-sail-d. [Accessed: 16-Jan-2020].

[18] A. J. Lee and J. M. Fernandez, "Mechanics of Bistable Two-Shelled Composite Booms," in *AIAA Spacecraft Structures Conference*, 2018, no. 210019.

[19] J. M. Fernandez, G. K. Rose, and C. J. Younger, "NASA's Advanced Solar Sail Propulsion System for Low-Cost Deep Space Exploration

and Science Missions that uses High Performance Rollable Composite Booms," in *4th International Symposium on Solar Sailing*, 2017.

[20] J. M. Fernandez, "Advanced Deployable Shell-Based Composite Booms for Small Satellite Structural Applications Including Solar Sails," in *4th International Symposium on Solar Sailing*, 2017.

[21] S. Hobbs *et al.*, "De-Orbit Sail Design for Techdemosat-1," in *6th European Conference on Space Debris proceedings*, 2013.

[22] J. Beck, I. Holbrough, T. Schleutker, and A. Guelhan, "Improved representation of destructive spacecraft from analysis of high enthalpy wind tunnel tests of spacecraft and equipment," *Acta Astronaut.*, vol. 194, pp. 287–296, 2019.

[23] J. Beck, I. Holbrough, J. Merrifield, N. Joiner, and S. Bainbridge, "Progress in hybrid spacecraft/object oriented destructive re-entry modelling using the SAM code," in *7th European Conference on Space Debris*, 2017.

[24] Z. Serfontein *et al.*, "Effects of Long-term Exposure to the Low-Earth Orbit Environment on Drag Augmentation Systems," in *71st International Astronautical Congress*, 2020.

Highlights

- Drag augmentation systems for end-of-life de-orbit of satellites
- Low-cost, simple solutions for future space debris mitigation
- Assessment of drag sail scalability, deployment dynamics and demisability
- Impact of drag sail on host satellite; short- and long-term vehicle dynamics
- Potential mission extension; de-risking de-orbit device

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

[redacted]

Drag augmentation systems for space debris mitigation

Serfontein, Zaria

2021-06-01

Serfontein Z, Kingston J, Hobbs S, et al., (2021) Drag augmentation systems for space debris mitigation. Acta Astronautica, Volume 188, November 2021, pp. 278-288

https://doi.org/10.1016/j.actaastro.2021.05.038