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Drag Augmentation Systems for Space Debris Mitigation

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Abstract

Space debris is recognised as a critical threat for the space industry. The proliferation of small satellites has invited commercialisation and subsequently, the growing number of satellites are adding to the already high number of objects currently in low-Earth orbit (LEO). Low-cost small satellites are under increasing pressure to meet debris mitigation guidelines and failure to comply could result in a launch licence being denied. Drag augmentation systems increase the drag area of a spacecraft, minimising the de-orbit period and thus reducing the probability of significant collisions and supporting the sustainable use of space. In response to the growing number of small satellites (10-500 kg) unable to de-orbit from low-Earth orbit within 25 years, Cranfield University has developed a family of drag augmentation systems (DAS). The DAS are lightweight, cost-effective sails deployed at end of mission and are reliable solutions for deorbiting small satellites, assisting in the conservation of the space environment. Three drag sails designed, manufactured and tested at Cranfield University are currently in orbit, with two sails already successfully deployed. This paper details the sails and will discuss findings from recent studies; examining the system's scalability, the post-deployment vehicle dynamics, the medium-term impact of the sail on the satellite's ability to conduct science and the long-term effect of the sail on the satellite's re-entry and demise. The DAS technology have 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 growth in the number of small satellite missions (defined in this paper as satellites ≤500 kg), and the recognition of space debris as a critical threat to future and on-going missions. Advances in small satellite technologies have made space more accessible to all, but the increase in launches of this class of satellites has added to the already high number of objects in low-Earth orbit (LEO).

Last year almost 80% of total satellites launched were small satellites [1]. Of the 1,680 small satellites launched between 2010 and 2019, 58% were launched within the last 3 years [2]. This proliferation of low-cost small satellites has invited commercialisation and subsequently substantially reduced the costs associated with small satellites. Although it is hard to predict what will happen over the next decade, current consensus and the rise of small launch vehicles suggests this growing trend of small satellite launches is set to continue [3], [4]. This poses a serious challenge for space debris mitigation and has encouraged the development of technologies to enable small satellites to operate without causing further debris.

ESA's Annual Space Environment Report [5] provides a detailed assessment of the concerning evolution of the space debris environment. As of the end of 2018, it was estimated that approximately 14,000 trackable objects (objects with a diameter ≥10 cm [6]) were orbiting Earth in LEO. The number of objects and their combined mass have been steadily rising since the beginning of the space age, leading to involuntary collisions between operational payloads and space debris. The Kessler syndrome [7] describes a theoretical scenario in LEO where each collision generates space debris which further increases the likelihood of subsequent collisions.

Equally problematic is the spatial density distribution of objects across altitudes [8]. An increased number of satellites at certain altitudes will have more severe consequences than others. Natural post-mission re-entry within 25 years [9] is assumed for altitudes below 650 km [10], making them attractive orbits for low-cost small satellite missions with limited de-orbit options. This could potentially result in a cluster of

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objects between 600 km and 650 km. Therefore, when considering space mission architectures, it is imperative not only to focus on the advancements in science and technology, but also to consider the sustainability of spacecraft and their impact on their environment.



Fig. 1. Small Satellites Launched Since 2010 [11]

International organisations such as the Inter-Agency Space Debris Coordination Committee (IADC) and the United Nations Committee on Peaceful Uses of Outer Space (COPUOS) have prioritised standardising debris mitigation measures and creating guidelines for the long-term sustainability of outer space activities. Post-mission disposal is an important mechanism for minimising future population growth of objects in space. These guidelines have been codified as international standards [12] and require satellites to be removed from LEO within 25 years of end of mission. Low-cost satellites are under mounting pressure to meet these debris mitigation guidelines; failure to comply could result in a launch licence being denied. ESA's Annual Space Environment Report contained a detailed analysis of end-of-life (EOL) operations of payloads in LEO, describing their compliance with the 25 year mitigation guidelines. More than 50% of the LEO payloads with an EOL in 2017 were not naturally compliant with the mitigation guidelines and of those payloads, more than 70% made no attempt to be compliant with the guidelines.

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, assisting in the conservation of the space environment. There are a number of approaches to removing a satellite from orbit at EOL, including active de-orbit using propulsion, but drag-augmentation systems can provide an attractive solution for small satellites, particularly those without significant on-board propulsion capability.

Cranfield University is developing a family of scalable drag-augmentation systems (DAS) for de-orbiting small LEO satellites at end of mission, allowing them to be compliant with space debris mitigation guidelines [13]. To date, Cranfield University has developed and qualified two drag-augmentation system designs: Icarus and De-Orbit Mechanism (DOM). Two models of Icarus are currently in orbit (Icarus-1 launched on TechDemoSat-1 in 2014, Icarus-3 launched on Carbonite-1 in 2015) and both have successfully deployed their sails. The DOM was launched on the ESA ESEO satellite in 2018 and has yet to deploy its sail. These devices are an ideal option for small satellites since they are simple, low-cost, reliable solutions and can be fitted to the host satellite at a late stage in the design.

The purpose of this paper is to highlight the advancements made in pursuit of commercialising the Cranfield University DAS family. Studies have been carried out to assess the scalability and adaptability of the sails, leading to new design recommendations for future iterations. Additionally, a deployment dynamics assessment was performed to quantify the effect of sail deployment on the dynamics of the host vehicle and ensure it does not impede the demisability of the satellite at the end of the mission.

2. Cranfield University DAS Family

Research completed at Cranfield University in 2015 identified a number of small satellite LEO missions that would not be compliant with debris mitigation guidelines between 2015 and 2020 without the addition of a de-orbit strategy such as deploying a drag sail [14]. The study, completed using the SpaceTrak™ database (database of future launch schedules) and the CNES software tool STELA, identified the future target market for passive de-orbit devices to be microsatellites (10 – 100 kg) and minisatellites (100 – 500 kg) in LEO, particularly satellites without propulsion.

Constellations were out of scope for this project, given that they will require controlled re-entry, achieved through active de-orbit, to avoid disruption to the constellation during the de-orbiting process. Although spacecraft with a mass higher than 500 kg are often equipped with on-board propulsion, a passive de-orbit option could still be implemented as a back-up device.

Failure analysis of satellite subsystems was performed at Cranfield University to understand which subsystems are most likely to fail and the effect this would have on the de-orbit disposal method [15]. The study concluded that the attitude control subsystem has the worst reliability and its reliability decreases over time. This is particularly relevant for satellites relying on propulsive de-orbit manoeuvres and therefore, a passive de-orbit method could be included in case of failure.

Cranfield University has developed and qualified two drag augmentation systems: Icarus and De-Orbit Mechanism (DOM). They are low-mass, simple designs,

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intended to have a minimal impact on the host satellite, allowing them to be fitted at a late stage in the design. The devices require a brief current pulse to deploy a drag sail at satellite EOL, 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. The size of the sail required depends on the mass of the satellite, its configuration and its orbital altitude. Two models of Icarus are currently in orbit and both have deployed their sails; Icarus-1 deployed on 31st May 2019 and Icarus-3 deployed on 7th November 2018.

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

Within the framework of ESA's Clean Space initiative CleanSat [16], Cranfield University took part in the technology assessment and concurrent engineering phase, focusing on three key areas: design for demise, de-orbiting systems and passivation. The CleanSat study was integral to evaluating the DAS design options and processes, as well as maturing the customers' requirements. The top-level requirements were derived into the following DAS design drivers: reliability, low-mass, low-cost, simple design and interfaces, testability, safety, scalability and no additional debris production. Several of these requirements 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 over 15 Joules (kinetic energy) reaching the surface.
- *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 operate successfully after an operational host satellite period of 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 ATOX environment of a worst-case of de-orbit from 600 km, 25 year re-entry time.
- *Environment:* The device shall ensure the expected performance under the debris/meteoroid environment of a worst-case of de-orbit from 800 km, 25 year re-entry time.

2.1 Icarus-1 and Icarus 3

Icarus-1 was developed by Cranfield University as a demonstrator payload on the TechDemoSat-1 mission (depicted in Fig. 2 and Fig. 3 [17]). During the design process, emphasis was placed on ensuring the sail would pose no additional risk to the host spacecraft. Commercial off-the-shelf (COTS) parts were used due to the short timescale and relatively small budget of the project. The mechanism conformed to additional requirements, including:

- *Safety:* preventing premature deployment and triggering the mechanism with an arm/fire architecture, ensuring the actuation was under the control of the host spacecraft
- *No additional debris production:* posing minimal hazard to surrounding environment
- *Reliability:* minimum of 95% device reliability, assuming overall spacecraft reliability of 90%
- *Low-mass:* ensuring the mass of the device does not exceed mass of propellant needed to achieve de-orbit

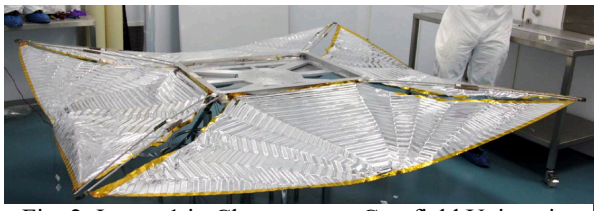


Fig. 2. Icarus-1 in Cleanroom at Cranfield University

The booms were 0.65 m long, rigid struts joined by tape hinges and stowed with the sail in a frame around the edges of one satellite panel. The symmetric design allowed for ease of manufacturing and redundancy. Icarus-1 successfully deployed in March 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. Icarus scalability is limited to the length of the sail strut, which in turn is restricted by the size of the satellite, hence, Icarus-3 was smaller than Icarus-1. Compared to Icarus-1, reliability of deployment was improved by adding torsion springs in addition to the existing tape spring hinges to initiate the deployment motion and the sail folding pattern was simplified.

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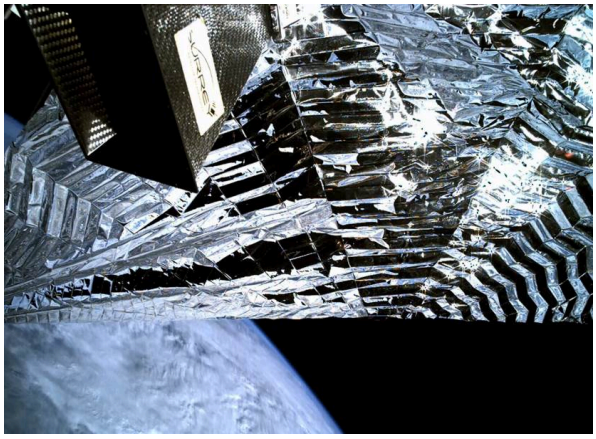


Fig. 3. Image Captured by TechDemoSat-1 Post Sail Deployment (Image courtesy of SSTL)

Icarus-3 successfully deployed in November 2018 at the end of the Carbonite-1 mission. A preliminary analysis completed as part of the Defence Science and Technology Laboratory's (DSTL) Daedalus observation campaign revealed an approximate doubling of the change in mean motion, and therefore drag, of the satellite post sail deployment. This was in line with the expected doubling of Carbonite-1's projected area from 0.6 m^2 to 1.25 m^2 due to the deployment of Icarus-3 and the ensuing tumbling motion. This was further validated by Cranfield University's analysis of the publicly available two-line element set (TLE) B* data (ballistic coefficient adjusted for atmospheric density representing an object's susceptibility to drag) and rate of semi-major axis decay.

A rapid increase in B* is evident shortly after sail deployment and, post sail deployment, the satellite maintained an average B* value double the previous average. 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.

2.2 De-Orbit Mechanism

Cranfield University's DOM was launched on-board the ESA microsatellite ESEO. The DOM is a self-contained unit, significantly smaller than the Icarus models, mounted on one side panel of the host satellite. Copper beryllium booms and sail quadrants are coiled around a central spool, held in place by Kevlar cords. Assembly time was improved by co-reeling the sails and the booms. Contrary to the Icarus models, the effective area of the DOM is not restricted by host satellite side panel lengths, but rather by the booms themselves.

Deployment is actuated by a series of commands activating two CYPRES™ cord cutters which sever the Kevlar cords. Stored strain energy is released and the sail is deployed. The four aluminised Kapton sail quadrants result in a total sail area of 0.5 m^2.

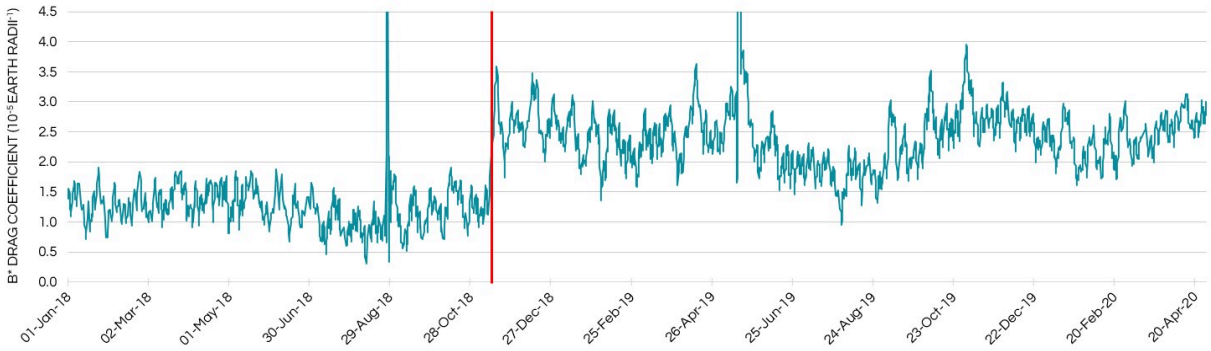


Fig. 4. Change in Carbonite-1 B* Ballistic Coefficient (Red Bar - Sail Deployment Date)

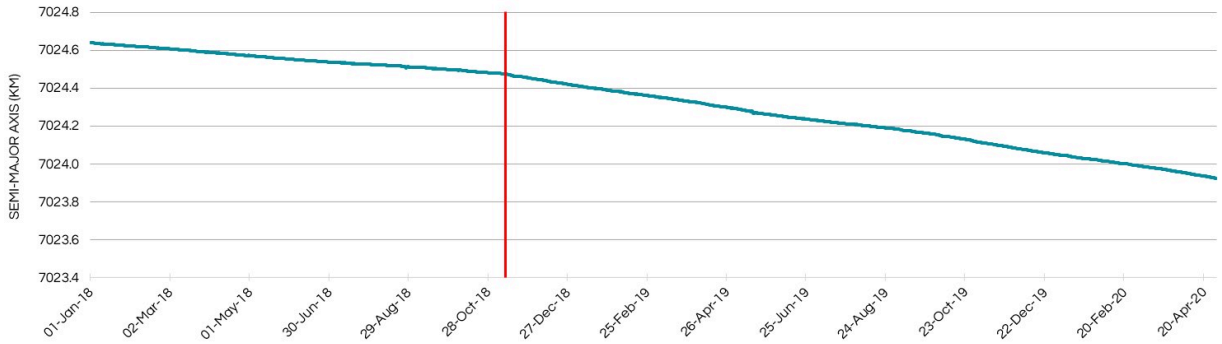


Fig. 5. Change in Carbonite-1 Semi-Major Axis Decay (Red Bar - Sail Deployment Date)

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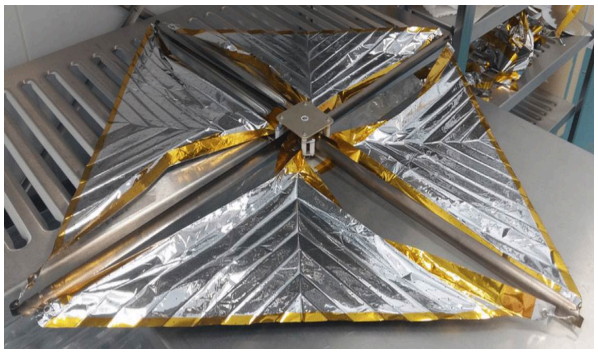


Fig. 4. DOM Flight Model at Cranfield University

2.3 Hybrid Design

The hybrid concept is a modular 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 Icarus and DOM designs, aiming to improve the scalability, adaptability and manufacturability of the sail. The boom module is based on the DOM design and the external sail cartridge is derived from Icarus. Since the design does not require a full side panel of the host satellite for mounting purposes, protruding hardware such as antennas can be accommodated without impeding sail deployment, resulting in a more scalable concept than the heritage designs.

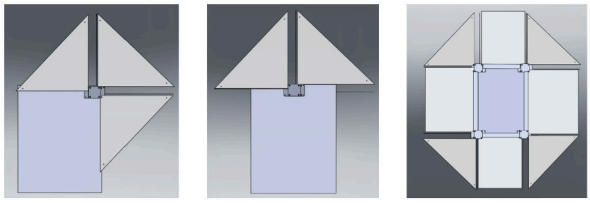


Fig. 5. Proposed Hybrid Concept Based on the Icarus and DOM Designs

On shared opportunity launches, the orbit altitude may change depending on the requirements of the main payload. If the EOL plan needs to be changed, the hybrid sail could be procured rapidly as a late-stage addition to ensure the satellite is still compliant with mitigation guidelines.

The following sections will discuss additional analysis completed at Cranfield University regarding device scalability, adaptability, attitude dynamics, and demisability as well as addressing aforementioned requirements.

3. Scalability: DOM Design Assessment

The scalability of the hybrid concept depends, in part, on the scalability of the DOM module. Experimental results determined the lower maximum length limit of the DOM booms in 1 g testing conditions. These results, combined with theoretical calculations of the DOM module volume, quantify the current scalability of the DOM module in different configurations, without adjusting the DOM housing.

3.1 Scalability: Experimental Results

To calculate the scalability of the DOM booms, experiments were performed at Cranfield University using spring steel tape measures to simulate the c-shaped copper beryllium (CuBe) booms. Spring steel is similar in geometry and behaviour to CuBe, but is easier to manipulate and does not have the toxic properties associated with CuBe. Although spring steel has a higher elastic modulus and is therefore stiffer than CuBe in the extended, deployed configuration, 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. CuBe has optimal structural properties for the booms, hence the results from the experiments performed using the spring steel booms were considered the lower limits of the capabilities of CuBe booms.

Qualifying a product for use in microgravity is expensive and intensive, hence over-engineering a product and testing in 1 g conditions can be cost-effective. The first set of experiments determined the maximum length of a single shell CuBe boom, which could statically support its own weight in 1 g conditions, was approximately 1 m. For longer booms, a different cross-section needed to be considered.

The second set of experiments involved deploying lenticular storable tubular extendable member (STEM) booms to determine the maximum length of boom which could be stored and deployed in the current DOM housing. Compared to single shell booms, the closed-section STEM booms were stiffer at the cost of being more than twice the mass. Initially, the booms were manufactured by taping two opposite-facing spring steel shells together with Kapton tape. This led to 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. This phenomenon is 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 is still magnified in areas of high curvature, such as the DOM spool. The results confirmed that CuBe tape springs are too thick to be used for lenticular STEM booms coiled around a thin spool.

To address this issue, two spring steel shells were held together with a polythene sheath, rather than being bonded with tape. The friction between the tape spring edges in the sheath created a closed cross-section; leading to improvements in torsional stiffness and

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buckling loads by allowing the shells to slide past one another, preventing stress concentrations. In this configuration there was no inner flange buckling.

Currently, the DOM deploys 4 booms simultaneously and symmetrically. The hybrid concept relies on using different numbers of booms in several configurations. To develop the hybrid concept, it is important to determine whether the DOM would still operate successfully if only one or two booms were deployed symmetrically or asymmetrically. The following tests were carried out:

1. Single lenticular sheathed boom, supported deployment
2. Single lenticular sheathed boom, unsupported deployment
3. Two parallel lenticular sheathed booms co-reeled, supported deployment
4. Two parallel lenticular sheathed booms co-reeled, unsupported deployment
5. Two perpendicular lenticular sheathed booms co-reeled, supported deployment
6. Two perpendicular lenticular sheathed booms co-reeled, unsupported deployment

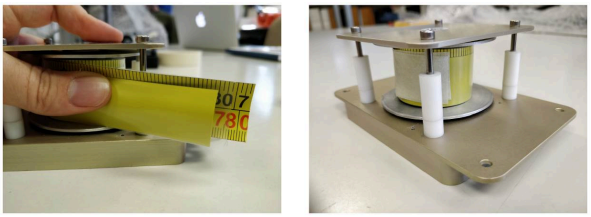


Fig. 6. Test Set-Up: Spring Steel Booms Held Together by Polythene Sheath in DOM Housing

In the supported tests, the booms were deployed on a table. Single boom supported deployments were very successful and convincing. Unsupported tests highlighted two main concerns. Firstly, during a majority of the deployments, the boom would deploy optimally until full deployment, but would then fail due to snap-through buckling. The sudden stop to the rapid deployment caused the booms to vibrate in their weakest axis, resulting in a bend-snap failure. Occasionally, the boom would deploy up to 75% before jamming inside the mechanism. Efforts were made to damp the deployment and add more support to the booms, but these were not successful. It was therefore concluded that the mass of the booms had exceeded the limit at which they were able to remain extended without bend-snap failure, with the given deployment force in a 1 g environment. All three configurations (single boom, two parallel booms and two perpendicular booms) tests yielded the same maximum boom length before failure: 1.5 m supported and 1.1 m unsupported. Thus, 1.1 m represents the lower limit for the scalability two-shelled CuBe booms, more than double the length of booms on the most recent DOM model. As previously discussed, CuBe booms are more resistant to bend-snap failure and will perform better in future experiments.

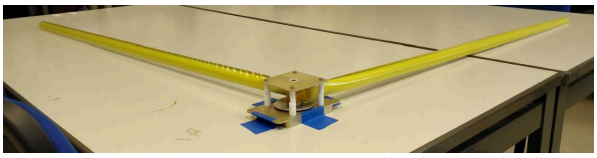


Fig. 7. Test Set-Up: Two Perpendicular Lenticular Sheathed Booms, Supported Deployment

3.2 Scalability: Theoretical Results

In order to calculate the maximum theoretical length of boom which could fit within the existing DOM housing, the total thickness of the co-reeled booms t_t was determined by 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:

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

For a single two-walled structure such as a sheathed lenticular boom, the number of shells is $n = 2$. Empirical data in literature suggested it is safe to assume a packaging efficiency of 25% as a first approximation [18]. The number of windings around the central spool ω was approximated to an Archimedean spiral and calculated using the maximum co-reeled outer coiled radius r_f and the initial coiling radius r_i:

$$\omega = \frac{r_f - r_i}{t_t} \tag{2}$$

The initial coiling radius was equal to the curvature radius of the boom. Finally, to estimate the maximum length L of each boom for a given configuration and number of booms, the following equation was used:

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

The maximum theoretical boom length to fit within the current DOM housing was calculated for 1 to 4 booms. With the original design, the maximum outer radius of the housing is 38 mm. The relationship between increasing the DOM overall housing size and increasing the boom length is not linear. The table shows how increasing the radius to 48 mm significantly increases the maximum boom length, without a significant mass increase.

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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, it was concluded from the tests that changing the configuration and distribution of the booms did not have any adverse effects on deployment. Regardless of configuration, the maximum boom length limits remained the same, there was no observed excess blossoming and it did not appear to hinder the deployment process. Blossoming occurs when the boom starts to uncoil within the deployment 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 will be necessary.

3.3 Light Boom Alternatives

The scalability assessment showed that the boom lengths could be increased from 0.5 m to 1.1 m without changing the housing, the release mechanism or the testing procedure. However, the size of the DOM booms increases disproportionately to their mass. Thus, the scalability not only depends on the physical limits of the mechanism, but also on the mass of the booms. As a weight-saving measure, lightweight composite alternatives were investigated to replace the copper beryllium booms. The composites selected in this paper have been proposed due to their high strength to stiffness ratios and the ability to tailor the directional properties of laminates to optimise properties for design requirements.

The DOM booms have conflicting requirements for their stowed and deployed configurations. For compact storage, reduced creep and predictable deployment dynamics in the stowed configuration, the laminate needs to have a high strain to failure ratio and a low axial Young's modulus. Conversely, in the deployed state, a high axial modulus is required to maximise the boom's stiffness and aid in reducing the slender boom's most common failure mode: global column buckling. A stiffer boom is achieved by increasing the percentage of fibres in the boom's axial direction.

Geometrically, the moments of area about the principal axes need to be maximised while ensuring the flattening and rolling strains limits are not exceeded. Maximising the moments of area involves having the largest possible subtended angle α with the smallest possible web width (depth of bonded edges) ω. It is important to note that the viscoelastic effect in composites is a high risk in the design as creep and stress relaxation effects are significant over long-term storage periods and result in a flatter cross-section, and smaller subtended angle, than originally fabricated. Past studies [20] have shown that a subtended angle greater than 80° will result in unacceptable flattening strains. Widths smaller than 3 mm lead to large shear stresses at the bonded webs. Therefore, a subtended angle of α = 80° and a web width of ω = 3 mm are recommended as the optimal characteristics for the DOM booms.

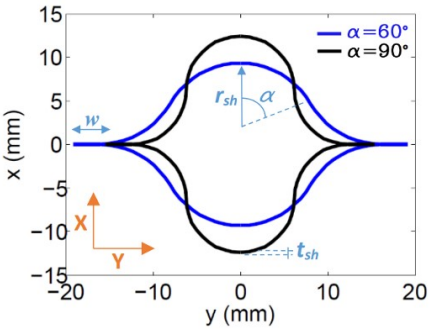


Fig. 8. Examples of Differing Subtended Angles and Web Widths

A collapsible tubular mast (CTM) was determined to be the optimal boom cross-section shape due to its strong mechanical properties and manufacturability. As discussed before, inner flange buckling occurs when bonded lenticular boom is coiled about a spool with a small diameter. To combat this, thin-ply materials need to be used to manufacture CTM booms. A toughened epoxy with a high glass transition temperature and low outgassing should be used.

An asymmetric [-45/0/45] or [0-90PW/45PW] layup is optimal for a compact coiled configuration, depending on materials available. Having a unidirectional inner ply maximises the boom axial stiffness and aids in resistance to creep whereas an outer surface ±45° plain weave (PW) ply provides torsional stiffness and cross-sectional stability. The ±45° ply also 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. Since the laminate is asymmetric across its length, apart from the bonded

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edges, thermal stresses may be introduced in the boom, promoting axial curvature and resulting in a twist in the boom. With this layup, the composite booms will be ~56% the mass of CuBe booms.

Manufacturing of the composite boom could be completed in-house at Cranfield University. A single-step cure process can be performed out-of-autoclave to aid in the scalability of the boom. 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 and is easily removed after the curing process, eliminating 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. A vacuum pressure is maintained until the final cool-down process to prevent the ends of the booms suffering from thermally-induced deformations. With the bonding technologies available in Cranfield University's composite sector, it would be possible to have significantly smaller moulds and bond the booms together in a separate step. This would add an insignificant amount of extra thickness and reduce the cost of the tool massively, although it would take longer to fabricate.

Further research into composite booms is being conducted at Cranfield University along with other advanced concepts, such as inducing bi-stability into the booms18. Adding a second stable coiled configuration into the boom would ensure the mechanism would not have 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.

4. Assessment of Deployment Dynamics and Demisability

In March 2019, Cranfield University and Belstead Research Ltd. presented findings from a UKSA Pathfinder project to analyse drag sail dynamics from deployment to demise. The project addressed three main uncertainties regarding drag augmentation devices:

- 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

Icarus-1 and Icarus-3 were used as case studies for the project. Carbonite-1 and TechDemoSat-1 were simulated in six degrees of freedom over the period of a year in specific scenarios, encompassing sail deployment with and without passivation of the satellites. This motion was also assessed over a shorter 3-day period using a Monte-Carlo simulation of 1,000 runs from differing initial states. The attitude predictions generated within the activity suggested that both satellites are expected to enter into a slow tumbling motion following the passivation of the AOCS and deployment of the Icarus drag sail. This verified that the initial requirement of assuming random tumbling for estimations is correct.

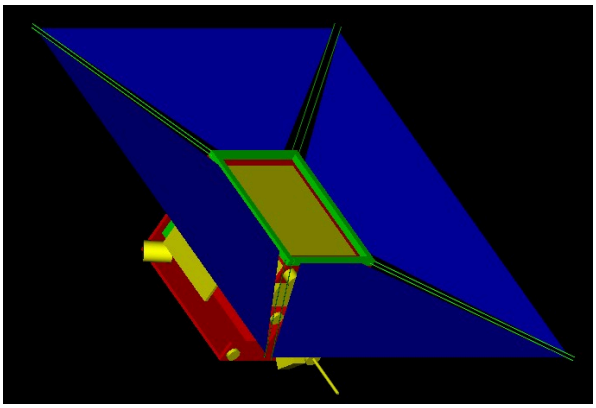


Fig. 9. TechDemoSat-1 with Deployed Sail Model

Assessment of the publicly available TLE data suggests the Icarus-3 deployment was successful and validated the predictions of a tumbling motion. DSTL's Daedalus observation campaign provided observations 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. Together, these results are further evidence that, without a sail specifically designed to promote aerodynamic or solar stability, rapid transition into tumbling motion should be expected following sail deployment. For 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

An assessment of TechDemoSat-1's ability to conduct science post sail deployment yielded positive results. The medium-term impact predicted was small for the power and communication systems of the platform, even when the AOCS is passivated and the satellite is permitted to tumble. Since passivation of the AOCS would make it impossible to maintain specific

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pointing control, the nature of the science that could be conducted would be limited. Despite the sail deployment leading to an increase in system torques, if the AOCS were to remain active, the torques are expected to be within AOCS limits and the satellite should be capable of retaining control authority. The impact of shadowing of the sail is negligible in this scenario, suggesting that there are significant opportunities to conduct science post sail deployment if the AOCS continues to be operational. This also suggests that the sail deployment could be brought forward in the mission, potentially significantly reducing the risk of mission failure before deployment is commanded, and 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.

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, assisting in modifying 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. This issue was recently discussed at ESA's Clean Space Webinar on Design for Demise. Clean Space is working on guidelines for demise verification procedures, including looking at how demise is simulated. Since Cranfield University has two deployed sails, a comparison will be performed between the results of this study's simulations and the actual data from the sails to validate and improve the models.

4.3 Re-Entry and Demise

The results of the TechDemoSat-1 re-entry and demise assessment concluded that entry conditions are expected to be influenced by the presence of Icarus-1. The sail sub-system is predicted to survive intact to the 120 km nominal re-entry interface under most circumstances. Thermomechanical demise tests on the sail material and PTFE plugs connecting the sail booms to the deployment mechanism informed updated material models for this study. The results suggest 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.

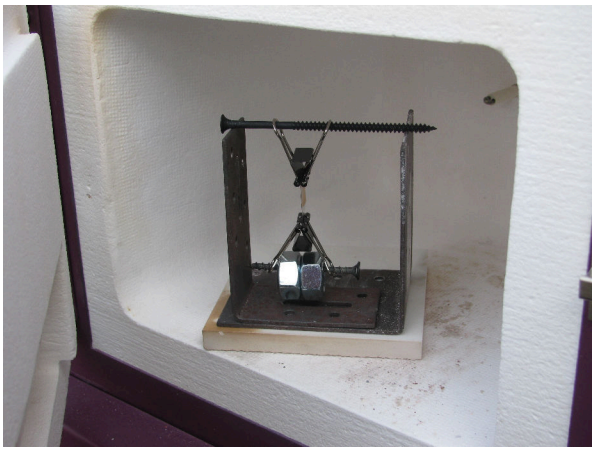


Fig. 10. Thermomechanical Demise Test Set-Up

Simulations of TechDemoSat-1 suggest that the late demise of the drag sail has a small impact on the re-entry conditions of the vehicle. Entry is expected to be 0.08° steeper and some preference for attitudes associated with aerodynamic stability was seen, but these changes were not significant enough to result in a substantial change in expected demise behaviour. Despite the late demise, 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

DAS appear to be a practical and effective means for small satellites to operate sustainably. This paper detailed the work completed at Cranfield University to aid in the commercialisation of the DAS family. The 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 addressed through experimentation and theoretical calculations. By modifying the cross-section shape of the DOM booms, the length of the booms could be doubled without altering the deployment method or the DOM housing, however, this would still result in a significant mass increase. Composite booms, with a high strength to weight ratio, have been proposed as a viable solution.

The deployment dynamics study verified that the satellite will enter into a slow tumbling motion following sail deployment and concluded that operations could potentially continue after sail deployment, allowing for earlier deployment and thus

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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

There are still many requirements relating to the DAS lifetime and the effects of 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 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 will be 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 validating future low-Earth atmospheric models.

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