DEPLOYMENT MECHANISMS OF A GOSSAMER SATELLITE DEORBITER

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ABSTRACT

A Gossamer Deorbiter system, comprising a 5 × 5 m gossamer sail structure and a telescopic deployment system to distance the sail from the host satellite, was tested and qualified to TRL5/6. Two novel deployable boom concepts were developed: lenticular CuBe tape spring booms and bistable CFRP booms. Deployment tests identified the issue of 'blossoming' of the coiled booms, resulting in an unpredictable deployment and potential damage to the booms. Modifications to the mechanism design and deployment procedure were introduced to mitigate this issue. The CFRP boom concept was demonstrated to successfully deploy the gossamer sail to its full dimensions, and to be capable of carrying the expected operational loads.

1 INTRODUCTION

The accumulation of space debris in low earth orbits over the past decades poses an increasing threat of collisions and damage to spacecraft. One solution is to hasten the removal of satellites from orbit at the end of their functional life. A promising approach is to deploy a large gossamer sail structure from the satellite: the increased aerodynamic drag lowers its orbit, and significantly reduces the satellite's deorbiting time. Such a gossamer deorbiting system would need to be stored for up to 15 years before being deployed, and aim to deorbit the host satellite within a 25 year timespan.

The ESA has funded through its ARTES 5.1 programme a project called "*Deployable Gossamer Sail for Deorbiting*". It entails the conceptual study and advance to a Technology Readiness Level of 5-6 of a system based on gossamer technology for the end-of-life deorbiting of future European space assets.

This paper provides a brief mission analysis of the proposed Gossamer Deorbiter concept, followed by a description of the various mechanical subsystems, with a particular focus on the novel deployable booms and the issues encountered during their deployment testing.

1.1 Mission Analysis

The deorbiting performance of a gossamer sail was analysed using analytical models as well as more detailed numerical models, to help identify specific use-cases for orbit type and host satellite. For drag deorbiting it was found that the sail poses an advantage in raising the ceiling altitude from which objects would de-orbit naturally in 25 years. In Figure 1 it can be seen that a typical satellite takes longer than 25 years to de-orbit if the initial altitude is above 650 km. With the addition of a modest sized gossamer sail – for example, a 10m^2 sail on a 100kg satellite – this upper range can be increased to 800 km.

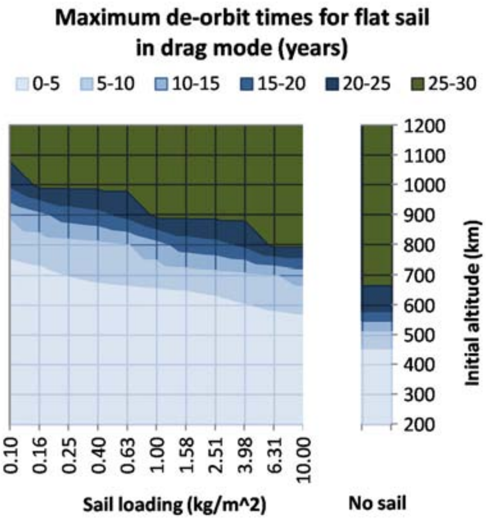

Figure 1: maximum deorbit times for a gossamer deorbiter.

Using a combination of solar sailing and drag-deorbiting in upper LEO (initially solar sailing is used when drag force is insignificant, but switching to drag mode as the altitude decreases) it is possible to deorbit within 25 years from even higher altitudes. The solar sailing operational mode requires active control, whereas drag mode only requires that the drag surface area is maximized. This poses the advantage that a drag-mode deorbiting phase can occur without active control as long as the sail can be passively stabilized. For the proposed gossamer deorbiter design, with a flat sail and a telescopic extension to distance the sail from the host satellite, passive attitude stability is attained at altitudes below 500km. Simple active control techniques can raise this altitude further.

The mission analysis concluded that deorbiting under drag conditions using a gossamer sail is effective in decreasing the risk of in-orbit debris generating collisions, and is a promising approach for impact mitigation of space debris.

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2 GOSSAMER DEORBITER DESIGN

The Gossamer Deorbiter consists of a 5×5m square sail, with four 3.6m long diagonal booms for deployment and support. Prior to sail deployment, the entire system is displaced 0.6m from the host satellite by means of a telescopic enclosure system. This is done to clear any appendages, as well as provide an offset between the centre-of-mass of the host satellite and centre-of-pressure of the sail for passive attitude stabilisation at low altitudes.

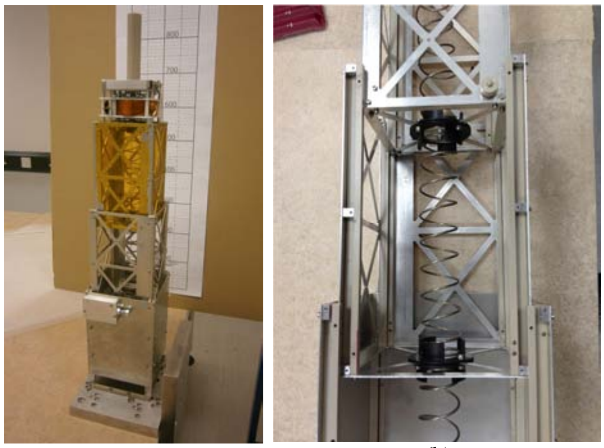
The Gossamer Deorbiter has been designed as a scalable bolt-on system that could be attached to an external facet of a host asset or recessed into its structure. The electrical interface is through a standard DB9 plug mounted on the bottom area of the deorbiter and the mechanical interface is through twelve M4 screws on its bottom plate.

2.1 Telescopic Deployment System

A three-stage telescopic deployment system (TDS) was designed to position the sail structure 0.6m away from the host satellite; see Figure 2. The outer telescopic box serves as an enclosure for the complete system and the inner box houses the stored sail and boom deployment mechanism. A z-folded ribbon cable provides the flexible electrical connection between the boom deployment mechanism and the fixed electronics board at the bottom of the TDS. The lid holding down the telescopic boxes is held in place and released using a low power COTS pin-puller. Spring-loaded hinges lock the lid at a fixed angle so that the lid does not ricochet and damage the TDS or sail after deployment. The deployment is actuated by the energy stored in three compression springs. The long slender springs are prevented from buckling when fully compressed by means of specially designed end stabilizers. Custom-made PEEK rails are used on each box to ensure a low friction mate between every telescopic stage. The telescopic boxes lock in place by means of spring-loaded ball-pins. The last stage has a set of redundant hard stoppers that prevent the sail deployment system from getting jettisoned.

2.2 Sail Deployment System

The 5×5m 7.5μm thick aluminised Kapton sail consists of four separate quadrants, which are individually Z-folded in one direction before being co-wrapped around a single central hub. In its fully deployed configuration the sail is suspended from the tips of four 3.6m long deployable booms. As they are deployed to their full length, the booms unfurl and tension the wrapped sail. During launch the wrapped sail membrane is restrained using a set of Dyneema strings which are cut using a NiChrome burn wire before deployment.



(a) (b)

Figure 2: (a) the telescopic deployment system consists of three telescopic boxes, with the sail deployment system stored in the inner box; (b) the deployment is actuated using three compression springs, and PEEK rails provide low-friction linear guidance between the telescopic boxes.

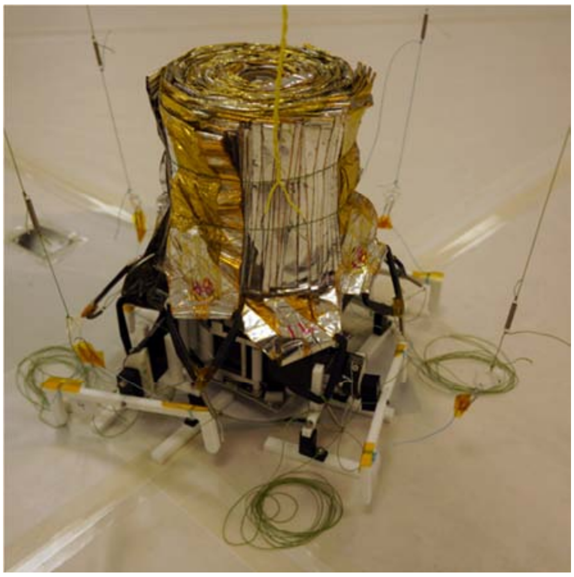


Figure 3: the wrapped sail sits on top of the boom deployment mechanism; the restraining Dyneema strings are cut using a burn wire before deployment, and the sail is unfurled by the extending booms.

The footprint of the sail deployment mechanism was designed to conform to CubeSat specifications, to enable a low-cost flight demonstration mission of the sail deployment concept. This design decision limits the dimensions of the sail deployment system to a cross-sectional area of 100×100 mm and a height of less than 200 mm (2U CubeSat), imposing challenging demands on the dimensions of the mechanism.

2.3 Deployable Booms

The deployable booms that support the gossamer sail are critical to the success of the gossamer de-orbiting system. The booms must be capable of highly compact stowage, while being able to carry the expected operational loads (sail deployment, sail tensioning and aerodynamic drag) despite their extreme slenderness, and thus propensity for buckling. In order to meet these demanding and conflicting requirements, two novel boom concepts were developed. In both cases the four booms are co-coiled around a central hub for stowage, and deployment is controlled by rotating this hub using a motor drive.

2.3.1 CuBe Booms

The first boom concept consists of two Copper-Beryllium (CuBe) tape springs, facing each other to form a lenticular cross-section. The two tape springs are then encased by a Kapton sheath to form a closed cross-section with an improved torsional stiffness and buckling load. As the booms are coiled for storage, the two tape springs will slide with respect to each other inside the Kapton sheath, thereby reducing the amount of shear stress and strain energy stored in the stowed configuration.

Figure 4: two CuBe tape springs face each other to form a lenticular cross-section; a Kapton sheath provides improved torsional stiffness, while enabling the tape springs to slide with respect to each other as the booms are coiled.

The CuBe tape springs are manufactured from 25mm wide and 0.1mm thick CuBe strips, and are given a nominal radius of curvature of 16mm. The natural coiling diameter will be thus be 32mm [5] and the central spindle was dimensioned accordingly. The Kapton sheath was manufactured by spiral-wrapping a narrow strip of 12.5μm Kapton film into a cylinder; it was then flattened before inserting the two tape springs. The CuBe booms have a mass per unit length of 45g/m (each of the 3.6m long booms weighs 162g). In their fully stowed configuration, the four-coiled booms have a total diameter of 87mm and height of 25.5mm.

Analytical or finite element analysis to determine the stiffness or buckling load of the CuBe booms was considered intractable due to the complex interaction between the tape springs and the Kapton sleeve. A series of small-scale and full-scale experiments were therefore done to characterise the booms.

2.3.2 CFRP Booms

The second boom concept is an open-section Carbon Fibre Reinforced Polymer (CFRP) bistable boom. The distinguishing feature of these booms is that they are stable in both their deployed and coiled state, and thus no longer need to be restrained during stowage. The mechanics of these booms is now well understood [2-4]. The bistability is a result of manipulating the Poisson's ratio and material anisotropy of the various layers in the material, by varying the ply angles of the composite laminate lay-up.

The CFRP booms manufactured for this project consist of a symmetric laminate lay-up $[\pm\delta/0/\pm\delta]$ with a single uni-directional 0° ply sandwiched by two surface braid plies (with fibre angle δ with respect to the longitudinal boom axis). A key innovation is that the braid angle is varied linearly from root to tip, respectively ±50° and ±35°. As a result the natural coiling radius will vary linearly along the boom length, and the boom will thus coil into an Archimedean spiral [1]. This ensures that the four co-coiled booms will be in their lowest energy state possible and in a stable configuration, and no edge buckling will take place. Creep effects during long term storage are also reduced with this approach. During deployment the transition zone between the coiled and deployed configuration will propagate along the length of the boom, driving the deployment.

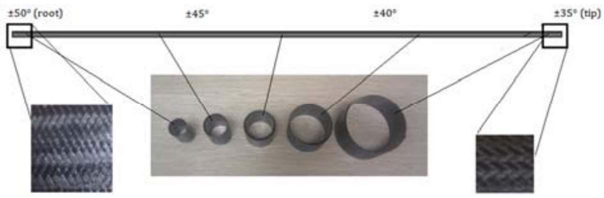


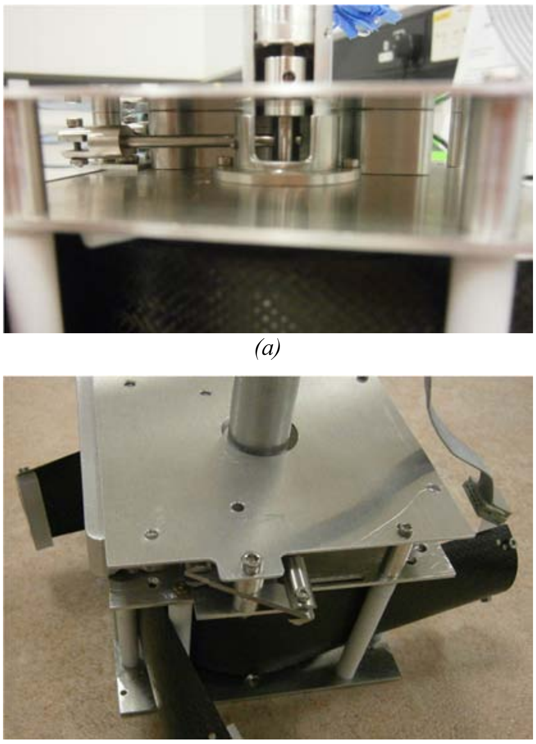
Figure 5: The CFRP booms have a variable ply angle along the boom length; the coiling radius will vary correspondingly.

The manufactured CFRP booms have a nominal thickness of 0.24 mm, while the cross-section has a radius of curvature of 16mm and subtends an angle of approximately 160°. The stored height of the booms is therefore 45mm, and the four co-coiled booms have an outer diameter of 85mm. The mass per unit length of this boom concept is 15g/m, with each of the four 3.6 m booms therefore weighing 65 grams.

Due to the open cross-section of the CFRP booms its shear centre will not coincide with the centroid, and the buckling behaviour will therefore be a complex interaction of torsional and flexural buckling. Modelling the CFRP booms is challenging, as analytical models generally assume isotropic material behaviour, and finite element analysis was complicated by the variable ply angle along the boom length, as well as finding an accurate representation of the mechanics of the CFRP braids in the composite lay-up. A series of experiments therefore provided the structural characterisation of the booms.

2.4 Boom Deployment Mechanism

For both boom concepts the four booms are co-coiled around a central hub for storage, and are guided through two exit rollers during deployment. The deployment is controlled by means of a brushless DC motor placed inside the sail spindle, which effectively *pushes* the booms out from the deployer. A locking pin is passed through the shaft connecting the motor to the boom spindle, and is released using a COTS pin-puller positioned on top of the boom deployment mechanism. The pin-puller force is redirected to the motor adaptor shaft by means of a lever arm mechanism.



(a)

(b)

Figure 6: (a) the boom spindle and motor are locked by passing a pin through the connecting shaft; (b) the locking pin is released through a pin-puller and a lever-arm mechanism.

2.4.1 CuBe Booms

In the coiled configuration a great deal of strain energy is stored in the CuBe booms, and the coil must be constrained during stowage and deployment to prevent premature deployment. The deployment dynamics of coiled tape springs was described by Seffen [5]. It was observed that for equal-sense coiling (the centre of curvature for both the stowed and coiled configuration lies on the same side of the cross-section) the tape spring must transition through a twisted configuration during deployment, and there is thus a small out-of-plane component to the boom deployment mechanics. For the lenticular booms one of the tape springs will be coiled in equal sense, and the coiled booms must therefore also be constrained in out-of-plane direction, as well as radially.

For the CuBe booms a set of spring-loaded rollers constrains the coiled booms radially, while out-of-plane displacement is eliminated by sandwiching the coil between two PTFE plates. The initial design of the boom deployment mechanism consisted of 4 spring-loaded rollers; the PTFE rollers are free to rotate around the aluminium shafts connected to the springs. After initial full-scale boom deployment tests a further four support points were added along the coil circumference, as will be discussed in Section 3.2. The final CuBe boom deployment mechanism is shown in Figure 7. The additional space required to accommodate the springs for the constraining rollers result in an overall height of 60mm for the deployment mechanism.

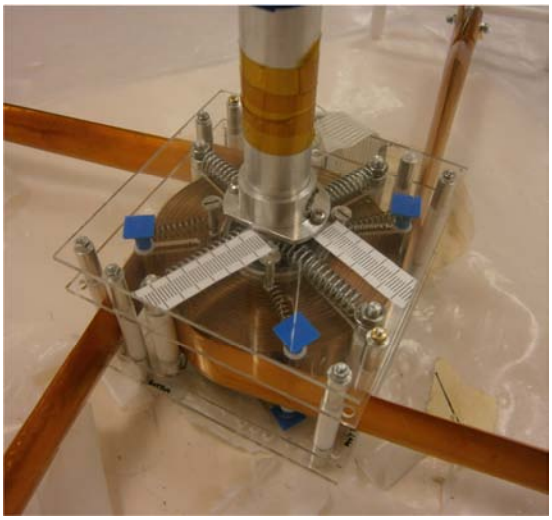


Figure 7: the CuBe boom deployment mechanism with Perspex plates to reveal the internal components. Four primary spring-loaded rollers constrain the coil during deployment, while four secondary rollers provide additional support points along the coil circumference.

2.4.2 CFRP Booms

The root attachment for the CFRP booms is shown in Figure 8. The corner edges are trimmed so that the four booms do not interfere with each other when co-coiled around the spindle.

(a) *(b)*

Figure 8: CFRP boom attachment: (a) root of the booms, and (b) co-attachment to the spindle. Note how the shape of the spindle allows some curvature at the root of the booms in order to increase the bending stiffness.

By virtue of the bistability of the CFRP booms no constraining force is required during stowage, and self-deployment is prevented by the resistance in the motor drive. However, initial full-scale boom deployment tests showed that the coil would *blossom* during deployment, and radial constraining forces were necessary to maintain a compact coil; see discussion in Section 3.2. For the CFRP sail deployment mechanism this was implemented by means of spring-loaded rocker arms, as shown in Figure 9. The design of the rocker arm ensures that the roller always makes contact with the coiled section of the bistable CFRP boom throughout deployment. The spring loading is achieved by means of a set of torsion springs. While the coiled height of 45 mm for the CFRP booms is greater than for the CuBe boom deployment mechanism, no additional height is needed to accommodate the rocker arm mechanism, resulting in an overall height of just 55mm.

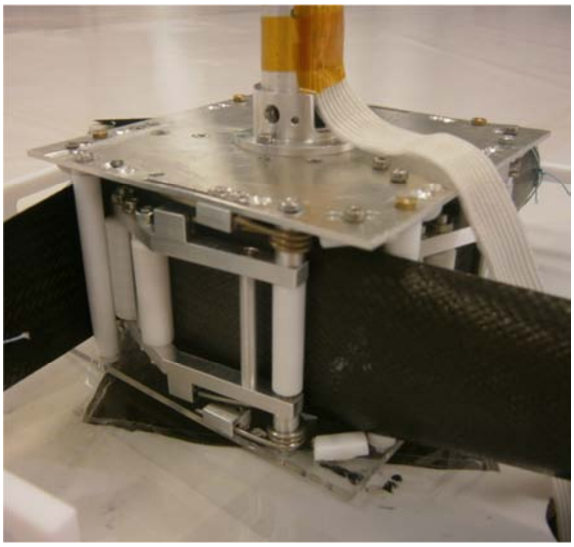


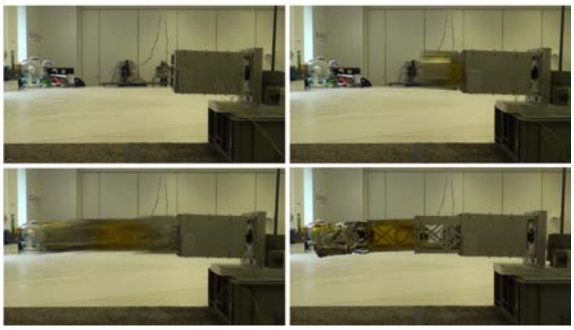
Figure 9: the CFRP boom deployment mechanism with spring-loaded rocker arms providing a constraining force on the coiled booms throughout the deployment.

3 TESTING & QUALIFICATION

The Gossamer Deorbiter was subjected to an extensive test and qualification process. In addition to the functional deployment tests reported here, the entire system successfully passed a range of environmental tests, including vibration testing to represent launch loads, and thermal cycling at high vacuum followed by ambient deployment of the various subsystems.

3.1 Telescopic Deployment

The telescopic deployment system was repeatedly and successfully deployed, as shown in Figure 10. An unexpected issue encountered during the testing of the telescopic deployment system was the effect of the packaging efficiency of the sail membrane. The compactness of the wrapped sail affects the friction between the sail and the inner telescopic box, which determines the deployment velocity of the sail deployment system. In the current design this issue is resolved by using relatively stiff deployment springs (0.5N/mm) that provide a total force of approximately 95N. A next design iteration will aim to reduce the spring stiffness to minimize the final deployment shock loads, by improving the packaging efficiency of the sail.



(a)

(b)

Figure 10: successful horizontal deployment of the telescopic deployment system with CFRP sail deployment system.

3.2 Boom Deployment

A series of preliminary tests had demonstrated the successful functional deployment of the boom deployment mechanisms for short booms (for a 1×1m sail), under high vacuum ($<10^{-6}$ Torr) and extreme temperature (-30°C to 70°C) conditions. Minor design changes were introduced, such as manufacturing the spindle bushings of bearing-grade PEEK to facilitate the deployment at extreme temperatures, but the mechanism designs remained essentially unchanged and were taken forward to the full-scale testing.

However, initial full-scale boom deployment trials revealed a critical issue with the boom deployment mechanisms. During deployment the coils did not rotate rigidly with the boom spindle, but instead the spiralling layers would slide with respect to each other, causing the coil to *blossom*; see Figure 11. The blossoming behaviour is particular to 'pusher' boom deployment systems where the central hub is actuated to push the booms out from the deployer.

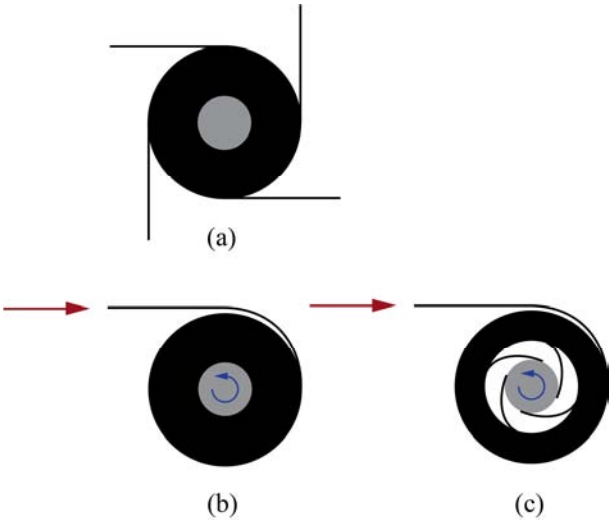


Figure 11: as the boom deploys, (b) the sail deployment forces cause the spiralling booms to separate, and (c) the relative motion between the adjacent booms causes the coil to expand. This results in high bending loads at the boom roots.

The blossoming behaviour has important consequences. Firstly, the hub rotation no longer correlates to the boom tip displacement, as some of the rotation is absorbed by the expansion of the coil. Secondly, the blossoming results in high bending loads on the boom roots, risking damage and fracture. Lastly, as the thickness of the coil reduces during deployment the coiled booms may deform under the applied loads from the spring-loaded rollers, potentially damaging the booms due to the high curvatures; see Figure 13. In order to study the blossoming during the deployment, the aluminium plates in the deployment mechanisms were replaced by PMMA (Perspex) plates. This enabled video recording of the coiled booms during deployment, to assess the efficacy of the solutions to mitigate the blossoming behaviour.

Figure 12: blossoming of the CFRP coil during boom deployment. As the coil expands due to relative motion of the coiled booms, a gap appears between the spindle and coil.

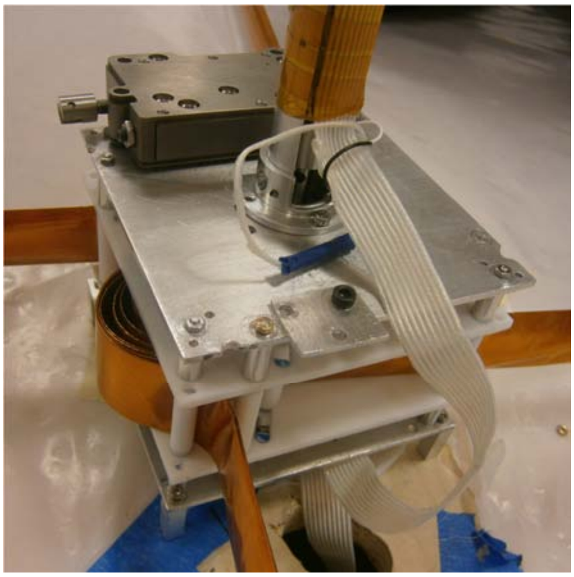
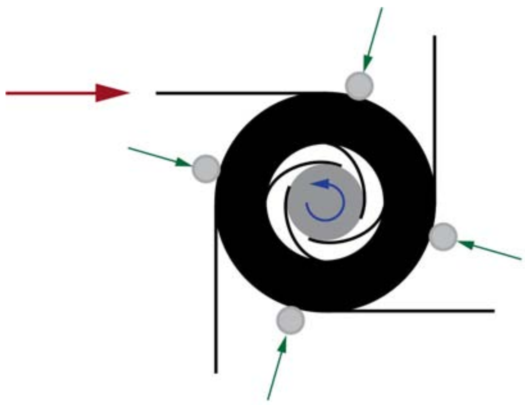


Figure 13: as the coil diameter increases, the coil may deform under the applied forces of the spring-loaded rollers, resulting in high curvatures and potential damage to the booms.

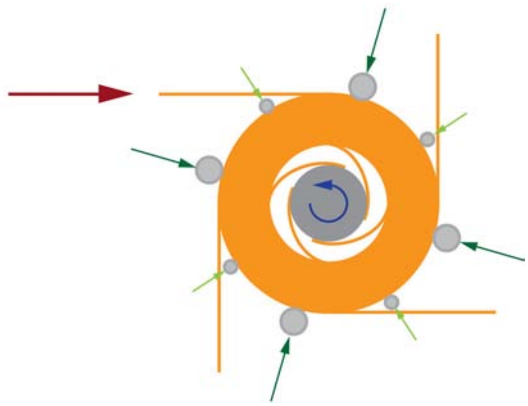
Several approaches to mitigate the blossoming were investigated, including modifications to the test set-up, deployment procedures, and mechanism design.

Firstly, the deployment forces on the booms were reduced. During initial deployment tests it was found that the low friction PTFE film covering the sail deployment table was highly static, attracting the thin sail membrane and significantly increasing the force required to drag the sail across the table. By covering the entire 6×6 m deployment table in a low-friction anti-static film, the sail was allowed to drag freely. Also, the sail deployment system was modified to reduce the force required to unfurl the sail at the initial stage of the deployment which had a large effect on the amount of blossoming. A circular PTFE disk was fixed to the sail spindle, which now freely rotates on another PTFE disk covering the top plate of the boom deployment mechanism. As a result the wrapped sail no longer slides relative to any surface as the sail is dragged out, thus minimizing friction.

Secondly, both the CFRP and CuBe boom deployment mechanisms were modified to mitigate the blossoming of the coiled booms. Although no restraining forces are required for the bistable CFRP booms in their stored state, spring-loaded rocker arms were added to support the coiled booms during deployment and contain the blossoming of the coil. The stiffness for the torsion springs was determined empirically: stiffer springs will provide greater pinching forces to contain the growth of the coil, but will also increase the load on the motor and the friction force acting on the coil, both of which contribute to the blossoming phenomenon. For the CuBe boom concept, two modifications were found to be necessary. The spring stiffness on the existing rollers was increased and springs with a high pre-tension were selected to further increase the constraining forces. Furthermore, four additional spring-loaded rods were added, increasing the number of support points along the coil circumference. These were necessary to avoid the coils from buckling, and the coiled booms getting trapped between the rollers. The underlying principle for these modifications is the increase in friction force between the adjacent coiled booms, to let the coil rotate as a solid with the hub/spindle. Alternatively, the friction coefficient of the boom materials could be increased, but that was not found to be feasible with the present boom designs.



(a)



(b)

Figure 14: the CFRP and CuBe boom deployment mechanisms were modified to mitigate the blossoming of the coil. For the (a) CFRP deployer the new spring-loaded rollers constrained the growth of the coil. In the (b) CuBe deployment mechanism the spring force was increased and four additional rollers were introduced to prevent buckling of the coils between the support points.

Lastly, the deployment procedure was modified. It was found that briefly retracting the booms partway through deployment would tighten the coil and mitigated further blossoming problems.

3.3 Sail Deployment

After the CuBe and CFRP boom deployment mechanisms had been successfully demonstrated, a series of full-scale 5×5m sail deployment tests was carried out.

A prerequisite for the successful testing of large gossamer structures is the development of suitable gravity compensation methods. The slender booms of the Gossamer Deorbiter cannot carry their own weight under gravity conditions, and must therefore be supported along their length during deployment. However, the addition of support points will affect the axial buckling load of the booms, and thus the ability of the booms to fully deploy the sail. A further complication is the fact that the angle at which the booms exit the deployment mechanism will vary, due to the reducing diameter of the coil and the fixed corner rollers in the mechanism.

After investigating several solutions, the gravity off-loading system used for the full-scale functional deployment tests consists of a cross-shaped gantry above the deployment table. The booms are suspended at their tip and midpoint, from small carriages running along the aluminium profiles of the gantry. The sail deployment mechanism is set up to spin freely on a PTFE disk during the sail deployment, thereby automatically adjusting its orientation to align the deploying booms with the gantry. Furthermore, the entire deployment table was covered in a low friction anti-static film (trade name Sentrex) to minimize the effect of the sail dragging over the table. Nevertheless, the gravity compensation system affects the sail deployment: as a result of the additional loads on the booms, buckling was seen to occur before the sail was fully deployed.

For the CFRP boom deployment system the 5×5 m sail deployment was successful, and an illustrative deployment sequence is shown in Figure 15. No manual intervention is required, aside from pausing the boom deployment halfway to attach the midpoint supports. The CuBe booms consistently buckled before reaching their fully deployed length, but sail deployments up to 4×4 m were reliably achieved.

In order to assess the ability of the booms to withstand the sail deployment and other operational loads, boom buckling tests were performed. In these tests individual booms were suspended using helium-filled balloons, before applying an axial load. It was found that the buckling load of the CuBe booms is approximately half that for the CFRP booms. One contributing factor was the initial curvature of the CuBe booms after deployment, which significantly lowers their buckling load. Possible explanations are creep of the Kapton sheath due to prolonged storage, as well as friction between the tape springs and the sheath. Nonetheless, it was found that both the CFRP and CuBe could carry the expected sail deployment, tensioning and further operational loads.

4 CONCLUSIONS

Under the ESA ARTES 5.1 programme a "*Deployable Gossamer Sail for Deorbiting*" was developed and successfully qualified to TRL 5/6. The satellite deorbiting system comprises a 5 × 5 m gossamer sail structure, and a telescopic deployment system to distance the sail from the host satellite.

A critical subsystem of the Gossamer Deorbiter is the mechanism which extends the booms that unfurl and support the sail. Two novel deployable boom concepts were developed: bistable CFRP booms and lenticular CuBe tape spring booms. For both concepts the four booms are co-coiled around a central hub, which is actuated to control the boom deployment. This concept was found to be susceptible to 'blossoming' of the coil, and several modifications were made to the mechanism design and deployment procedure, in order to mitigate the issue and ensure reliable deployment of both the CFRP and CuBe booms.

After a series of full-scale sail deployment and boom buckling tests, it was demonstrated that the CFRP booms can successfully deploy the 5 × 5 m gossamer sail and sustain the expected loads. The CuBe booms were shown to be capable of deploying and supporting a 4 × 4 m gossamer sail.

REFERENCES

[1] Fernandez, J.M., et al. *Bistable Over the Whole Length (BOWL) CFRP Booms for Solar Sails*. in *Proceedings of the Third International Symposium on Solar Sailing*. 2013. Glasgow, Scotland.

[2] Galletly, D. and S.D. Guest, *Bistable composite slit tubes. I. A beam model.* International Journal of Solids and Structures, 2004. **41**(16--17): p. 4517-4533.

[3] Galletly, D. and S.D. Guest, *Bistable composite slit tubes. II. A shell model.* International Journal of Solids and Structures, 2004. **41**(16--17): p. 4503-4516.

[4] Guest, S.D. and S. Pellegrino, *Analytical models for bistable cylindrical shells.* Proceedings of the Royal Society A, 2006. **462**(2067): p. 839-854.

[5] Seffen, K.A. and S. Pellegrino, *Deployment dynamics of tape springs.* Proceedings of the Royal Society A, 1999. **455**(1983): p. 1003-1048.

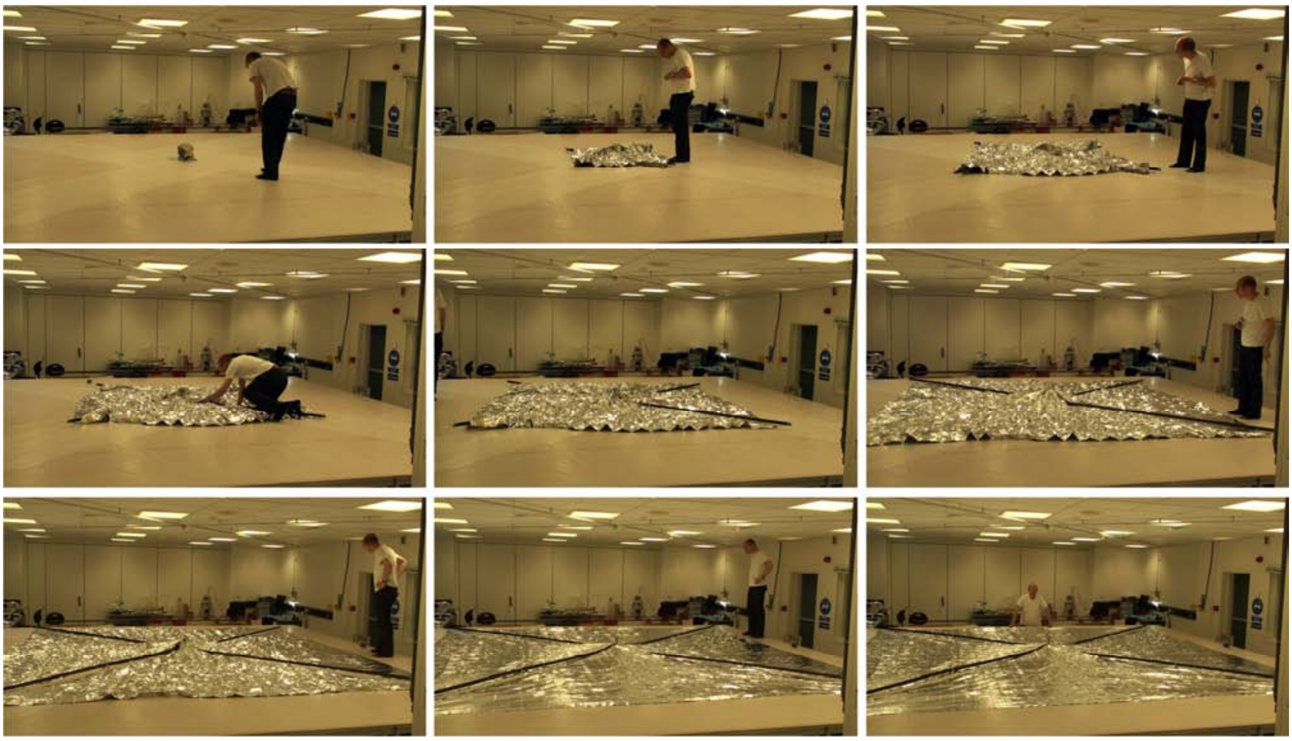


Figure 15: Successful sail deployment test with the CFRP booms. The sail deployment table is covered with an anti-static Sentrex film, and the booms are suspended from a cross-shaped gantry attached to the ceiling at the tip and mid-length points.