DE-ORBIT SAIL DESIGN FOR TECHDEMOSAT-1

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ABSTRACT

Space debris mitigation guidelines are widely accepted and increasingly implemented. The guidelines require satellites to be removed from the LEO region within 25 years of their end of mission. This article describes the design of a payload, Icarus, to achieve this for the UK's TechDemoSat-1 (TDS-1) mission.

Icarus was completed well within a year using limited resources. Its design was adapted to enable this while still meeting the requirements. An important driver was the need to pose no significant risk to TDS-1.

The baseline design is for a randomly tumbling spacecraft with nominal orbit height of 686 km. Additional studies have been made to evaluate how this performance can be improved using active attitude control.

The paper discusses issues raised in the development of this low-cost drag sail as a practical example of debris mitigation now waiting for launch on TDS-1.

1 INTRODUCTION

So far use of space has been unsustainable and new ways of building and operating satellites are required. Space debris mitigation is becoming a standard aspect of satellite design. Guidelines were developed by the Inter-agency Debris Coordination Committee (IADC) and these are now being codified as international standards (e.g. ISO 24113). In low Earth orbit (LEO) this means designing methods of removing the satellite from the LEO region within 25 yr once its mission is over.

Many design solutions exist to de-orbit LEO satellites, ranging from carrying extra propellant for a final de-orbit manoeuvre to carrying an additional payload specifically for this purpose. The Space Research Centre at Cranfield University has studied drag augmentation for several years and has developed concepts for de-orbit device payloads suitable for small satellites. The project described here concerns the design, manufacture and test of a drag sail ("Icarus 1") for the UK's TechDemoSat-1 (TDS-1) satellite.

2 DE-ORBIT SAIL DESIGN

The initial concept for Icarus 1 was a small box carried on the satellite's external surface which would deploy its stowed sail at the end of mission. Deployment would either be triggered autonomously or under control from the host spacecraft. However, after following a design process for TDS-1 we arrived at a design which differed significantly from this initial concept.

2.1 TechDemoSat-1

TDS-1 is a UK-funded technology demonstration satellite. It is based on an SSTL-150 bus, and was developed over the period 2010-12; it is due for launch in Q3 2013. The satellite mass is around 150 kg and its size is 0.9 x 0.7 x 0.7 m^3. Figure 1 shows the complete satellite. Payload experiments from 8 UK organisations are carried; Cranfield's payload provides de-orbit at end of life to meet debris mitigation requirements.

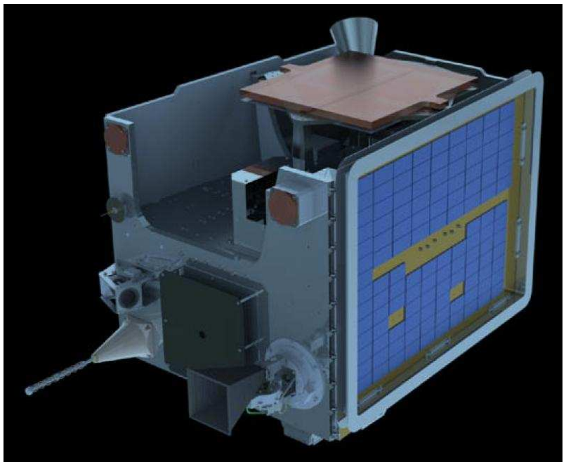

Figure 1. General view of TDS-1 design just prior to build. Icarus 1 is the frame around the panel at right.

2.2 Requirements

Icarus 1 is built to satisfy two top-level requirements:

1. Create no additional risk for the host spacecraft,
2. De-orbit TDS-1 within 25 yr after the end of its

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mission.

Current debris mitigation requirements state the de-orbit reliability should be at least 90% (e.g. ISO 24113). However, the host spacecraft requires a much higher level of reliability in terms of posing no risk and hence this became our primary requirement. Several subsidiary requirements are derived from the top-level requirements.

Primary requirement:

1. Prior to deployment the mechanism shall be restrained to prevent inadvertent release,
2. Actuation shall be triggered with an arm / fire architecture,
3. Actuation shall be under control of the host spacecraft,
4. The payload shall pose minimal hazard to the space environment.

Secondary requirement:

1. The deployed sail shall be large enough to achieve de-orbit within 25 yr,
2. The reliability of operation shall be 90% or better.

In addition, there are several desirable features which we sought to achieve:

- Adopt a simple design since this is generally improves reliability,
- TDS-1 with deployed sail should be aerostable,
- The mass budget is approximately the mass of (chemical) propellant needed to achieve de-orbit.

These requirements were flowed down to detailed requirements on each sub-system / component.

2.2.1 Constraints

Constraints had an important influence on the project. The main constraints are:

- Project timescale ~12 months,
- Budget for the whole project (including labour < £100k),
- Manufacturing / test facilities are those available at Cranfield University or for modest cost elsewhere.

These strongly encouraged the use of simple technology and COTS parts. The requirement which it was most difficult to obtain evidence to validate is the deployment reliability. This has not been formally validated but instead is partially justified from a range of tests feasible on Earth's surface in 1 g.

2.2.2 Requirements Analysis

The first parameter to derive from the requirements was the required sail area. Simple orbit propagation tools were used to estimate the area-time product for TDS-1 with no sail deployed. This product is a constant as the drag area varies (assuming constant mass), and so can be used to estimate the required additional area.

The drag area is estimated using the rule for a randomly tumbling cuboid (e.g. ISO 27852): for TDS-1 this is 0.94 m^2., and the area-time product (actually ballistic coefficient – time product) for an initial circular orbit at 686 km is 1.42 m^2 kg^{-1} yr (a conservative value, perhaps by a factor of 2-3, due to the atmospheric model used – which was based on MSIS and had no time dependence). If a randomly tumbling flat plate is added to the satellite, its area should be $\geq$6.6 m^2 to ensure de-orbit within 25 yr.

From this area, the boom length needed is calculated to be 1.35 m.

2.3 Aerostability

Aerostability, i.e. a tendency for the satellite to acquire a steady attitude relative to the flow, can be beneficial in two ways:

- If drag is maximised for the stable attitude then de-orbit lifetime is minimised,
- Aerostable designs tend to show less variability of lifetime relative to completely flat surfaces.

The sail is designed so that the entire system (spacecraft plus sail) is marginally aerostable, i.e. the aerodynamic torques act to turn the sail so that it is perpendicular to the flow. However, the system is un-damped and so it will oscillate around this state. Perturbations due to changes in atmospheric density may lead to periods of tumbling, but on average the cross-section to the flow compared to a simple tumbling case is increased. Six DOF Monte Carlo simulations of orbital decay using drag sails [1] have shown that a slightly canted sail design, to form a shallow rectangle based pyramid, produces a good balance of robustness of the deorbit time prediction, and minimisation of the deorbit time for a specific sail size.

2.4 Concept of Operation

A simple concept of operation was adopted. This had the benefit of enabling a shorter development time and of providing additional reassurance to the host spacecraft operators. The concept identifies two phases:

1. Payload is stowed from final integration until the end of the operational mission,
2. Release is triggered by the host spacecraft: this starts the de-orbit phase which ends with the satellite burning-up on re-entry into Earth's atmosphere.

No capability apart from the ability to deploy the sail is assumed of the host. If any propulsive capability or

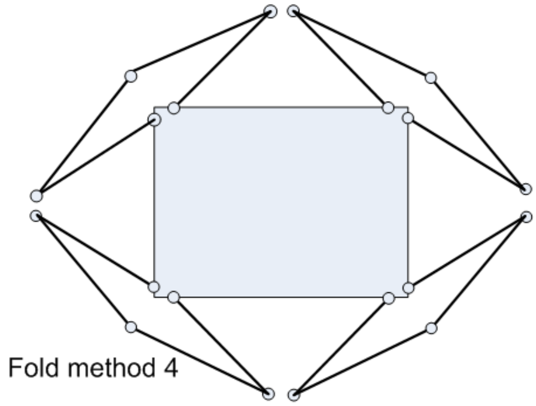

Figure 2. Conceptual design chosen for the booms.

attitude control remains then one or both of these can be used to achieve de-orbit more quickly and reliably. Attitude measurement would help monitor successful deployment of the sail.

2.5 Summary of ICARUS Design

The payload design process involved a set of prototypes to test a range of design concepts. The initial tasks were to identify a configuration for stowing and deploying the sail area. From several design concepts we chose to use rigid struts (aerospace grade Al tubing) joined by tape hinges for the booms, and then to stow these booms and the sail in a frame which fits around the edges of one of the larger spacecraft panels.

Figure 2 shows the conceptual design for the booms made from rigid struts. From prototype tests it seemed that symmetric boom designs were less susceptible to manufacturing inaccuracies: the chosen boom design uses this, which also gives some deployment redundancy. The strut length is constrained by the length of the shortest side of the panel: in our case the strut length was ~0.65 m.

3 MANUFACTURE AND AIT

The design allowed most manufacturing and testing to be done at Cranfield. Where necessary, facilities at other organisations (e.g. Open University large vacuum chamber) were used.

3.1 Manufacture

Manufacturing tasks fall into three categories:

- Local workshops were used for general tasks such as basic machining, finishing, and prototyping.
- Some new processes had to be developed, in particular the copper-beryllium (CuBe) tape spring manufacture and the sail fold pattern.
- Suppliers and specialist facilities were used for some specific tasks (e.g. specialist test, machining of large or complex items).

Figure 3. Test deployment of the drag sail. Icarus is mounted on the frame used for ground handling and the vibration tests; the image also illustrates the sail fold pattern.

Managing a process which involved such a range of partners was one of the main project management challenges.

3.2 Testing

The test plan was derived from our risk register. Several types of test were performed:

- Characterisation: technology not yet well-understood for space use had to be characterised adequately. This included testing some cable cutters and the CuBe tape springs.
- Space compatibility: several materials or components had not been widely used in space before. For these it was necessary to test compatibility with vacuum and the temperatures likely to be experienced. We were less concerned with radiation hardness since no electronic components were used and sensitive areas are shielded from UV.
- Vibration testing: the full payload was subjected to a range of vibration tests, to ensure it would survive launch.
- Functional: Tests to assure us that successful deployment was highly likely were performed. Mechanisms designed to deploy in zero g are difficult to test on Earth's surface.

The first three of these relate to the primary requirement (pose no risk to the host); the final one addresses the second requirement (de-orbit the satellite).

4 DISCUSSION

The project has raised a range of issues which provide lessons for future de-orbit payloads. A few of these are discussed here.

4.1 Lessons Learned

Drag sails / drag augmentation is appropriate for small satellites (up to perhaps 1 tonne) in LEO (to around 700 km). For larger satellites, the mass of the booms increases disproportionally and other technologies are more appropriate. In higher orbits the atmospheric density is too low for drag to usefully de-orbit satellites.

Some practical issues highlighted by the project include:

- Mechanisms designed to operate in zero g are difficult to validate in 1 g. A combination of conservative design, analysis, and partial testing has been used to build confidence in the current design.
- Atmospheric models have to be used with care, since there is significant variability around heights of 400 – 800 km (which is the crucial range for drag augmentation devices). Some of this variability is natural, a useful model must include density variation through the solar cycle since the desired de-orbit time is no more than one or two solar cycles. There is also some disagreement between models which inexperienced users may be confused by.

In a university context, there are many additional benefits of a project like Icarus. Students have been heavily involved and have gained enormous benefit from the experience. The project has also significantly increased the experience of the wider department which has benefits for all aspects of our work – for research and for teaching.

4.2 Attitude Control During De-Orbit

If the host spacecraft has attitude control when the sail is deployed then improved performance can be obtained in two ways:

- Orient the satellite to maximise drag,
- Control attitude to make optimum use of solar radiation pressure (SRP).

The benefits of the first are relatively simple to quantify. Using SRP is more complicated since it can remove energy directly and indirectly and either may be optimal.

4.2.1 Drag Maximisation

Attitude control can be used to increase drag by orienting the maximum drag area perpendicular to the velocity. If a single surface dominates the drag area (e.g. a large deployed sail) then the drag force can be doubled relative to random tumbling. The doubling in drag force means that the same orbit decay rate is now experienced for a satellite higher than the nominal orbit by ln 2 x (atmospheric scale height), i.e. where the density has halved. Figure 4 shows typical values of the scale height for LEO. Since the scale height is 70-100 km at typical orbit heights, the increase in orbit height achievable is approximately 0.693 x 70 ≈ 50 km.

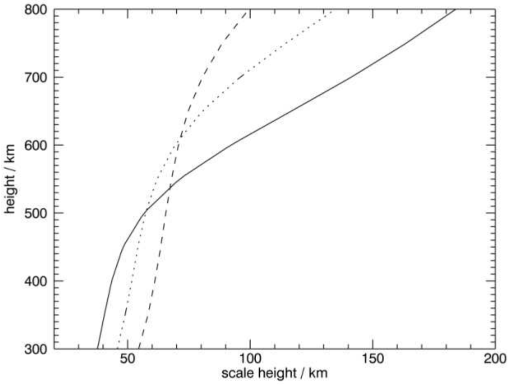

Figure 4. Scale height vs altitude from the MSIS atmosphere at various times in the solar cycle (solid line: 10th percentile, dotted line: mean, dashed line: 90th percentile).

4.2.2 Using SRP

SRP can be used to remove energy from the orbit in two ways. It may be useful at or slightly above the height at which drag and SRP are close in magnitude. The first, a direct method, is to orient the satellite to generate a SRP force which opposes the velocity. This requires a cyclical variation of the attitude synchronised with the orbit period.

The second method is indirect, and uses SRP to increase orbit eccentricity. This tends to lower the perigee, which exposes the satellite to higher atmospheric density and thus increases the rate of orbit decay (since density does not vary linearly with height).

The optimal contribution of SRP to reducing orbit lifetime is not simple to assess. We do not believe that SRP will be widely used for this purpose because of the complex design and control task, and because it appears to be practically useful only for a relatively narrow range of orbit heights.

5 CONCLUSIONS

Icarus 1 has been a successful project for Cranfield University's Space Group. Within severe constraints of time and resource, a de-orbit device payload has been designed, manufactured and tested, and is now integrated on the host spacecraft and ready for launch in Q3 2013. Some of the key project conclusions are:

Drag sails have a useful role to play in debris mitigation: small – medium satellites in LEO can benefit from this low-cost, simple technology.

Requirements need to be carefully analysed. In the current context, the primary requirement is to pose no risk to the host spacecraft; successful de-orbit is then a secondary requirement –albeit an important one.

Technology demonstration missions have an important role to play. TDS-1, as a UK example, had led to a range of innovations and wider benefits now ready for further exploitation across the UK.

6 REFERENCE

1. Roberts, P.C.E., and Harkness, P.G. (2007). Drag sail for end-of-life disposal from low Earth orbit. J. Spacecraft and Rockets, **44**(6), 1195-1203.
2. ISO 24113
3. ISO 27852