FLIGHT RESULTS OF THE INFLATESAIL SPACECRAFT AND FUTURE APPLICATIONS OF DRAGSAILS

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ABSTRACT

The InflateSail CubeSat, designed and built at the Surrey Space Centre (SSC) at the University of Surrey, UK, for the Von Karman Institute (VKI), Belgium, is one of the technology demonstrators for the QB50 programme. The 3.2 kilogram InflateSail is "3U" in size and is equipped with a 1 metre long inflatable boom and a 10 square metre deployable drag sail.

InflateSail's primary goal is to demonstrate the effectiveness of using a drag sail in Low Earth Orbit (LEO) to dramatically increase the rate at which satellites lose altitude and re-enter the Earth's atmosphere. InflateSail was launched on Friday 23rd June 2017 into a 505km Sun-synchronous orbit. Shortly after the satellite was inserted into its orbit, the satellite booted up and automatically started its successful deployment sequence and quickly started its decent. The spacecraft exhibited varying dynamic modes, capturing in-situ attitude data throughout the mission lifetime. The InflateSail spacecraft re-entered 72 days after launch.

This paper describes the spacecraft and payload, and analyses the effect of payload deployment on its orbital trajectory. The boom/drag-sail technology developed by SSC will next be used on the RemoveDebris mission, which will demonstrate the applicability of the system to microsat deorbiting.

INTRODUCTION

In recent years, increasing attention has been given to the problem of space debris and its mitigation.

Figure 1, from the NASA Orbital Debris Program Office shows the number of space objects greater than ~10cm diameter tracked and catalogued by the US Space Surveillance Network up to 2010. The categories of object are broken down into spacecraft (operational and non-operational), orbiting rocket bodies, mission-related debris (e.g. payload shrouds), and fragmentation debris. It can be seen that fragmentation debris is by far the largest contributor to the total number of objects on the graph. Such debris is created when objects collide. For example, in 2009, two artificial satellites: Kosmos-2251 and Iridium-33 collided accidentally, producing a large quantity of debris, which can be seen as the last step change in the fragmentation debris shown on the graph[1]. The two previous step changes were due to deliberate orbital fragmentation events – those of the Chinese satellite FengYun-1C (2007) and the American satellite USA-193 (2008).

Even allowing for such deliberate fragmentations, it is clear from the growth of the number of objects in orbit that the risk posed by debris to operational spacecraft can only get worse, as the probability of collisions increases exponentially with the number of objects present[2]. Therefore, in order to be able to launch new satellites safely, old ones need to be removed as fast as possible. NASA recommends that the process should take less than 25 years if we are to avoid a catastrophic growth in the amount of orbital debris[3] – the so called Kessler syndrome.

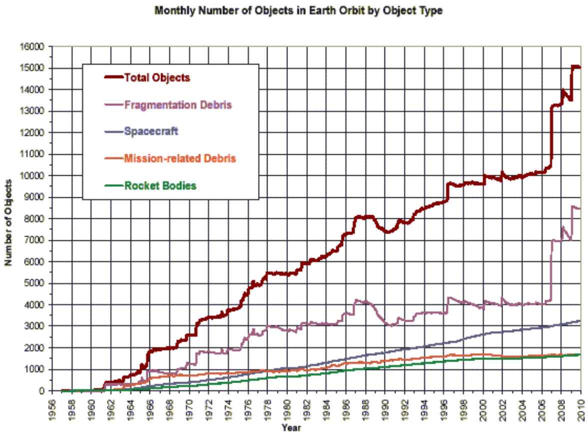

Figure 1. Growth of the Orbital Debris Problem – NASA Orbital Debris Program Office

In order to facilitate this, a form of active removal of such objectives needs to be undertaken.

For low-Earth orbit (LEO), missions (<1000km altitude), the residual atmosphere encountered in the thermosphere offers a potential simple and relatively low cost method of bringing objects down into the upper atmosphere, where, they can be destroyed by the heat of re-entry – that is through the use of some form of deployable drag structure. This is not suitable for every object, as larger objects, depending on their make-up, can survive all the way down to the ground, and as drag effects are highly variable, it is not possible to use such techniques to target a particular unpopulated disposal point (e.g. over the oceans). However, for many satellites in the small satellite category (<500kg mass), such disposal will lead to their harmless vaporization in the atmosphere. Thus, the University of Surrey – Surrey Space Centre (SSC), which specializes in small satellites, has been very active in recent years in developing the technologies needed for enhanced-drag ADR, and, through the InflateSail 3U CubeSat mission, has demonstrated the first successful disposal of a European satellite using this method.

The development of InflateSail was supported by two European Commission (EC) (Framework Program Seven (FP7) projects: DEPLOYTECH and QB50[4, 5].

DEPLOYTECH had eight European partners including Deutschen Zentrums für Luft- und Raumfahrt (DLR), Airbus Defense & Space (France), RolaTube Technology (UK), Netherlands Organisation for Applied Scientific Research (TNO), CGG Safety and Systems (Netherlands), the University of Cambridge (UK) and Athena Space Programmes Unit (Greece). It was assisted by NASA Marshall Space Flight Center. The project ran from January 2012 until the end of December 2014, and its objectives were to advance the technological capabilities of three different space deployable technologies by qualifying their concepts for space use. InflateSail's ADR payload was developed through this project.

QB50, led by Von Karman Institute (VKI) Belgium, is a programme aimed at demonstrating the possibility of launching a network of 50 CubeSats built by CubeSat teams from all over the world to perform first-class science and in-orbit demonstration in the largely unexplored middle and lower thermosphere (380-200km altitude). Most of the QB50 satellites carry one of three different types of science sensor designed to investigate the thermosphere: the Ion-Neutral Mass Spectrometer (INMS), the Flux-Φ-Probe Experiment (FIPEX) and the multi-Needle Langmuir Probe (m-NLP), each developed by Mullard Space Science Laboratory (MSSL) in the UK. However, alongside these science CubeSats, there were a number of in-orbit demonstrator (IOD) CubeSat missions planned, which included the 3U InflateSail, designed and built by Surrey Space Centre (SSC) for VKI, to carry and demonstrate, in orbit, the inflatable mast/drag-sail payload.

INFLATESAIL PAYLOAD AND BUS SYSTEMS

The deorbit device demonstration payload occupies approximately 2U of InflateSail's 3U CubeSat structure, and comprises two elements: a 1m long, 90mm diameter Inflatable-Rigidisable Mast and a 10m^2 transparent polymer drag sail, supported by four carbon fibre reinforced polymer (CFRP) booms. The remaining 1U volume contains the spaceraft's core avionics comprising an electric power system (EPS), attitude determination and control system (ADCS) – which also doubles as the on board computer (OBC),VHF/UHF transceiver (TRXVU) and valve/payload controller board (see Figure 2).

By deploying the drag sail from the end of the mast (i.e. such that it is separated from the spacecraft body), the centre of mass and the centre of pressure of the spacecraft are separated, thereby, in principle, conveying a degree of passive aerodynamic stability, which in turn should maximize the structure's drag (see Figure 3). One of the in-orbit test objectives was to observe if this happens in practice. The mast also ensures that the drag sail is kept clear of any host spacecraft structures which might interfere with sail deployment.

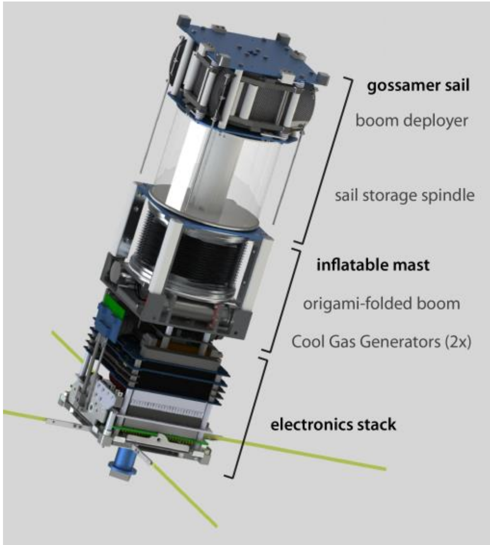

Figure 2. CAD Representation of InflateSail's Internal Layout

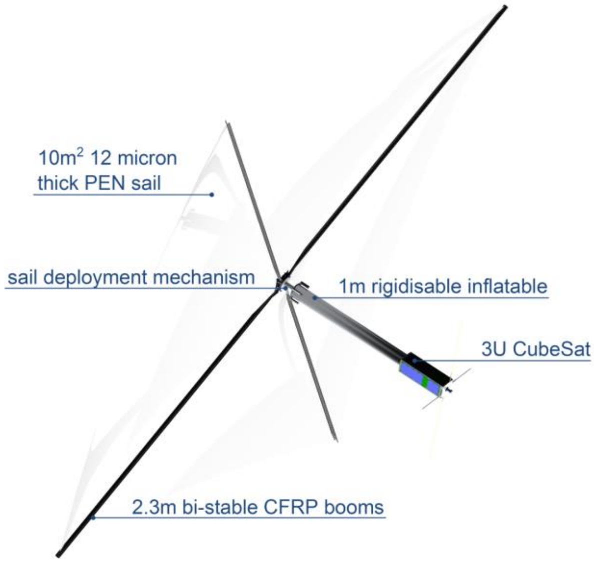

Figure 3. Artist's Impression of InflateSail in Orbit Deployed Configuration Showing the 1m Long Inflatable Cylindrical Mast and the 10m^2 Drag Augmentation Sail Supported by 4 CFRP Booms

Thus, the prime objectives of the InflateSail mission were to verify the functionality of the deployable structures in orbit, and to illustrate the potential of the sail-mast system as an end-of-life deorbiting solution for larger satellites, by increasing the host satellite's aerodynamic drag, and thus reducing its orbital decay time. Additionally, InflateSail was to demonstrate the use of an aluminium-polymer laminate inflatable cylinder as a lightweight deployable structural member, and use a Cool Gas Generator (CGG), developed by CGG Safety and Systems, for storage and release of the inflation gas. Although the payload components were chosen and designed to have a long in orbit life-time prior to deployment (15 years), the deployment of the mast and sail was to be carried out shortly after orbital injection, so that the mission would be completed within the QB50 project timescale – the project was due to end in December 2017.

Concept of Operations

Once safely clear of the host launch vehicle, by stored programme command or ground command, the single deployable panel is opened at one end of the satellite and the inflatable mast is inflated and rigidised using the CGG. The inflatable skin is a metal-polymer laminate, which gains its rigidity once deployed by a slight over-pressurisation, which also removes the storage creases. This "jack-in-the-box" deployment method avoids some of the complexity of a multi-panel opening design, and results in a satellite with solar cells facing in multiple directions, which is an important safety factor when the attitude is not under active control. However, this approach requires a more complicated internal structure, consisting of very smooth inwards-facing walls and a linear guide system to allow the top of the inflatable to move inside the satellite structure without twisting or rotating. Once full mast deployment and rigidisation has occurred, the inflation gas is vented symmetrically through a valve to prevent potential destabilisation due to punctures of a still inflated structure.

The inflation of the mast pushes out the sail deployment mechanism to position it away from the body of the satellite. Once activated, a brushless DC motor, stored in the central shaft of the sail, unwinds four lightweight bistable CFRP booms, developed by RolaTube Technology, which unfold and carry the transparent sail membrane out to its full 10m^2 area.

The sail deployment mechanism is derived from the system described in Fernandez et al.[6], while the inflatable mast was developed specifically for InflateSail.

Once deployed, the ballistic ratio (mass/cross-sectional area) of the spacecraft is dramatically reduced (from ~ 100 kgm^{-2} to ~ 0.2 kgm^{-2}), and the resulting increase in aerodynamic drag forces cause the spacecraft to lose altitude until re-entry is achieved.

Inflatable Mast

The inflatable cylindrical mast consists of a tough aluminium-BoPET (biaxially-oriented polyethylene terephthalate) polymer three-ply laminate. The two outer aluminium plies are each 13µm thick, and the central BoPET ply is also 13µm thick. The total laminate thickness, including adhesive, is 45µm.

A 12µm thick BoPET bladder is used inside the cylinder to improve air-tightness against the vacuum of space. The 1m long, 90mm diameter cylinder is inflated by a CGG to a pressure of approximately 50 kPa, which is sufficient to cause permanent stretching deformation in the metal plies of the laminate (see Figure 4). The inflation gas is then immediately vented in a symmetric pattern. The resulting unpressurised rigidized cylinder has been shown to withstand compressive loads up to 50N, and bending moments up to 2Nm.

Figure 5 shows the mast deployment sequence.

The fold pattern used has five faces around the circumference of the cylinder, and has a repeating unit height of 60mm (see Figure 6). When fully folded and compressed, the cylinder including its end fittings is 63mm in length (see Figure 7).

The fold pattern leaves an internal space 35mm in diameter when folded, providing storage space for an internal normally open solenoid valve.

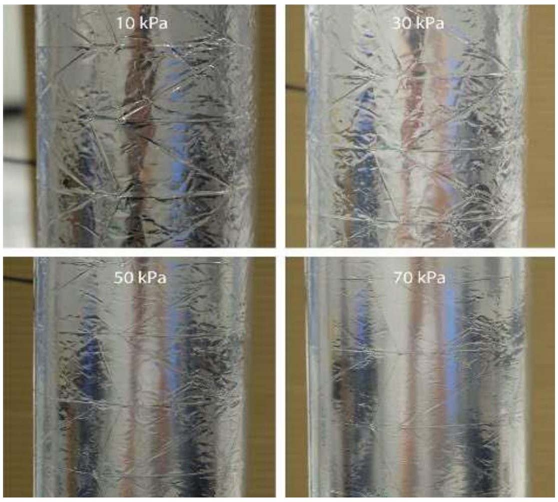

Figure 4. Residual Creases after Depressurisation from Different Inflation Pressures (10–70 kPa)

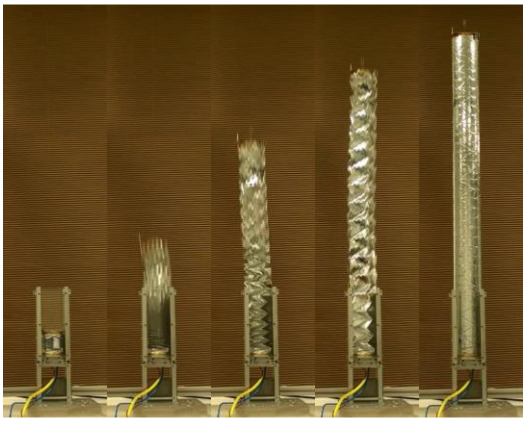

Figure 5. The Inflatable Cylindrical Mast Deployment Sequence

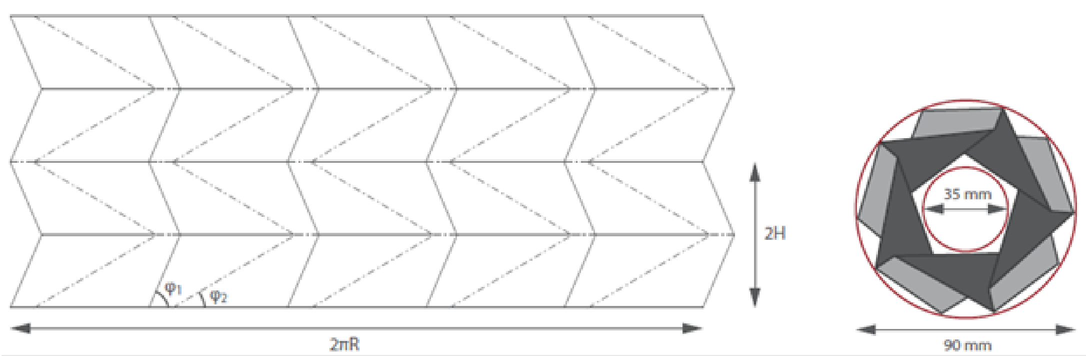

Figure 6. The Fold Pattern Selected for the Inflatable Mast (left), with the Cross-Sectional View of its Fully Folded Configuration (right). The fold pattern is fully defined by its geometric parameters n = 5, φ_1 = 67◦, H/R = 0.67 and R = 45mm. In its fully stowed configuration the diameter of the circumscribed circle is 90 mm, and the open cross-section is at least 35 mm in diameter.

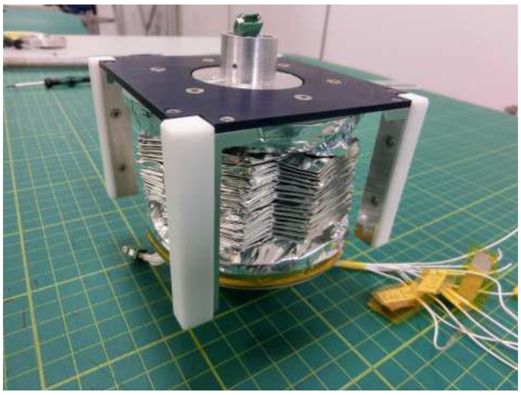

Figure 7. The Inflatable Cylindrical Mast in its Stowed (left) and Deployed (right) Configuration

The inflation system consists of two CGGs, each containing approximately 4g of nitrogen gas. Each of the CGGs is capable of fully deploying and rigidizing the inflatable mast, with two CGGs being included for redundancy.

InflateSail is intended to demonstrate the effectiveness of the sail system as a deorbiting method for a larger host satellite. The combination of a non-chemical rigidisation process, and a CGG based inflation system was chosen to ensure that the system could survive for many years in the pre-deployed configuration before deploying reliably at the end of a host satellite's service life. Metal-polymer laminates have been demonstrated to survive for many years in orbit, and CGGs have also been shown to function without fault after a number of years in orbit. Extensive ground testing was carried out during the development of the system[7, 8].

The Inflatable Mast layout is shown in Figure 8.

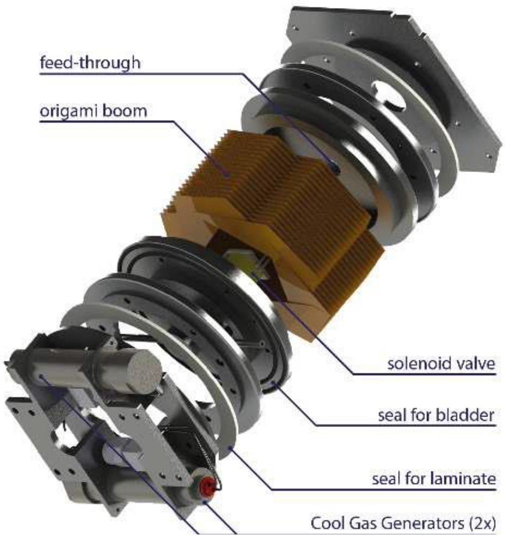

Figure 8. Inflatable Mast (Boom) System Layout

Drag Sail

The sail structure consists of four separate quadrants, making up a total area of 10 m^2. The quadrants are 'Z'-folded, then wrapped around a free spinning central hub. The sail membrane is 12μm thick polyethylene naphthalate (PEN), which is naturally transparent. The membrane was deliberately left un-metallised so as to minimise perturbations from solar radiation pressure – i.e. the team wanted to observe the effects of atmospheric drag alone. There was an expectation that the lack of a metallic film as protection would mean that the polymer membrane was likely to erode quickly in the LEO environment, however, this was not thought to be a problem due to the early operations plans involving InflateSail being deployed into a very low altitude (~300km) LEO, and thus only remain in space for a few days once the sail was deployed. However, the launch was changed and InflateSail was deployed into a much higher, 505km altitude Sun Synchronous Orbit (SSO), and so it remained in space for a much longer period (72 days). None-the-less, the team saw no evidence that the sail was eroded, although from the apparent visual brightness of InflateSail (+4 magnitude), it is suspected that it may have become opaque (white).

The sail support structure comprises four custom made CFRP bistable booms which are co-coiled just above the wrapped sail membrane (see Figure 9). The coiled diameter of the booms in their second, or 'stowed' stable state varies along the length of the booms. This allows the booms to be stowed in their lowest possible energy state, and reduces the mass of the mechanism required to hold the coiled booms in place during launch. The carbon booms can be driven in and out using a precisely controlled brushless DC motor.

The fully deployed sail structure is shown in Figure 10.

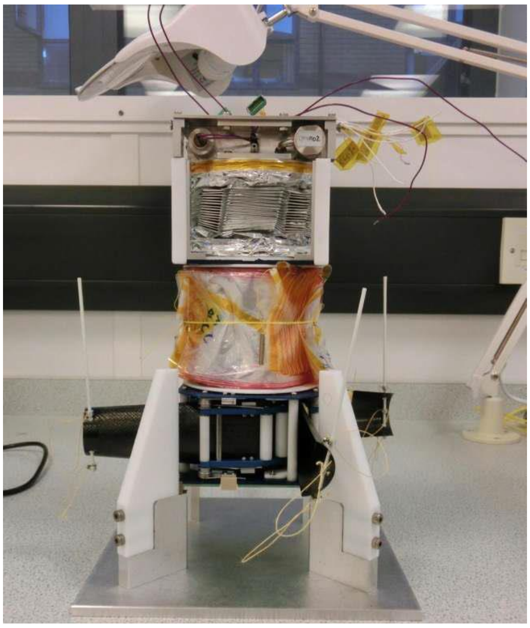

Figure 9. The Complete InflateSail Payload Showing the CFRP Booms (bottom), the Z-Folded Sail Membrane (middle) and the Origami Folded Inflatable Mast with CGGs (top)

Figure 10. InflateSail Inflatable Mast and Drag Sail Deployment Test

Bus Systems

Because of the deployable nature of the payload, InflateSail required a bespoke 3U structure to be manufactured. Similarly, the solar panels had to be bespoke. Both structure and panels were designed and built at the Surrey Space Centre, and great care was taken to make sure that the spacecraft was compliant with the QB50 launch requirements, including fitting the ISIS QuadPack mandated for QB50.

Much of the spaceraft's avionics comprised commercial-off-the-shelf (COTS) bought-in items which are in common use for CubeSat missions. For example, the electric power system (EPS) is based on the GOMspace P31u EPS, with its integral 20Whr battery. The EPS interfaces to the custom solar panels, which are mounted with Azur Space triple-junction solar cells which have 28% efficiency.

A bespoke Valve Control Board (VCB) was designed by SSC to operate the payload systems.

The communications with the ground station are executed through the TRXVU Transceiver procured from ISIS, using the UHF band to transmit and the VHF to receive. The TRXVU interfaces to the ISIS Antennas System featuring deployable dipole antennas. The spacecraft uses the I2C protocol for telemetry and telecommand. All Platform subsystems communicate via I2C with the on-board computer (OBC) acting as master.

The OBC is in fact also the attitude determination and control system (ADCS) computer. The QB50 ADCS unit was designed and developed by the Electronic Systems Laboratory (ESL) at Stellenbosch University and Surrey Space Centre (SSC) at the University of Surrey.

Fifteen ADCS units were officially supplied to the QB50 mission, and it is now available commercially from Stellenbosch's spin-out company, CubeSpace.

The full ADCS unit comprises 3 subsystems:

- CubeSense
- CubeControl
- CubeComputer

It includes:

- CMOS Camera Digital Sun Sensor (fine Sun Sensor)
- CMOS Camera Digital Earth Sensor
- 6 Photodiode-based Course Sun Sensors
- MEMS Gyro
- 3-Axis Magnetoresistive Magnetometer
- 3-Axis Magnetorquer (2 Rods + 1 external Coil or Rod)
- Pitch-Axis Small Momentum Wheel
- Optional GPS Receiver (Novatel OEM615)
- With Extended Kalman Filter (EKF) Control software + SGP4 Orbit Propagator

For InflateSail, a cut down version of the ADCS unit was flown to save volume. The pitch-axis momentum wheel and CMOS cameras were therefore removed, and instead, attitude knowledge was derived from the course Sun sensors, 3-Axis magnetometer and MEMS gyro. The GPS receiver was not fitted, however the magnetorquers were left as actuators for any attitude control needed prior to payload deployment (e.g. de-tumbling).

Bespoke modular flight software was written by SSC to provide full command and control and mission autonomy, whereby each module interfaces only the packet router and a hardware abstraction layer. This runs under a real-time operating system (RTOS)[9].

Each software module is contained in a separate thread or FreeRTOS task and has dedicated timing and memory allocation. Wherever possible tasks will 'suspend' and wait for an incoming message. This uses minimal processing time. Hardware level device drivers such as I2C and CAN are handled as a hardware abstraction layer (HAL) with mutexes to prevent multiple access. Priority inheritance is used to ensure low priority tasks do not block high priority tasks. Only three task priorities are given to reduce context switching between threads.

The InflateSail software has been designed such that mission success can be achieved in the event that contact with the spacecraft cannot be achieved. In addition the hardware and firmware are configured such

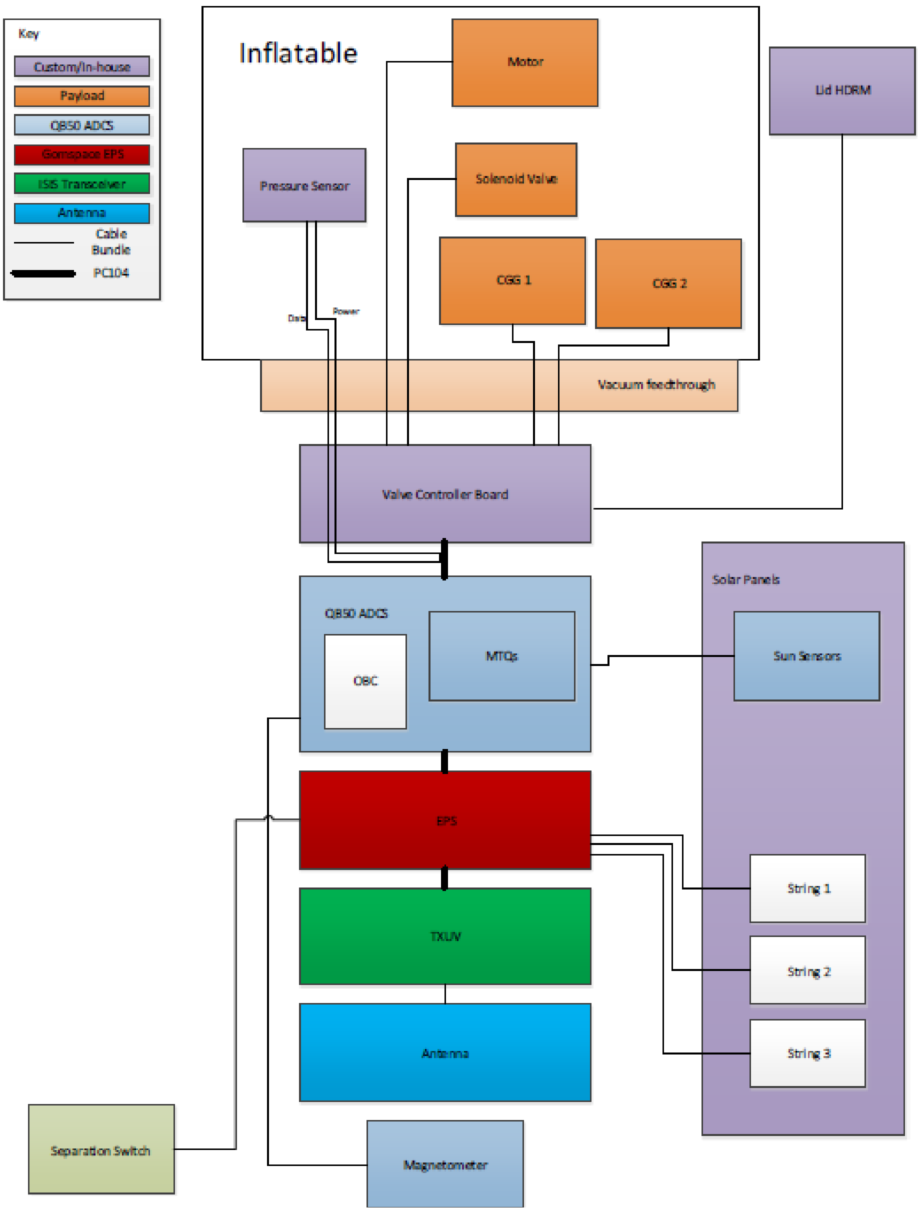

Figure 13. InflateSail System Diagram

that success can be achieved even with the failure of the majority of the spacecraft subsystems.

Figure 13 shows the InflateSail System Diagram.

INFLATESAIL FLIGHT ASSEMBY, INTEGRATION AND TESTING

Using mechanical computer aided design (CAD), a complete payload/bus system layout was designed, and appeared to fit the bespoke 3U structure. However, when practical assembly first took place, it became clear that the clearances were too tight, and that some stripping of components from the bus would be necessary. This was when many of the superfluous items in the ADCS unit were removed. The team also took the opportunity to re-examine the payload controller board, and decided that a new version – the Valve Controller Board (VCB) – would offer higher reliability, even though the previous version had performed well in ground tests. The payload retention strategy was also re-examined, to ensure that the inflateable mast would deploy smoothly. As a result of these late design changes in the summer of 2016, an accelerated programme of final assembly integration and testing (AIT) and environmental testing (EVT) was carried out between November 2016 and April 2017.

The team finished testing InflateSail (See Figure 14) and it was successfully delivered to ISIS (Innovative Solutions in Space) in the Netherlands on 10th April 2017 and integrated into its QuadPack launch Pod on 12th April 2017 (Figure 15).

Figure 14. InflateSail Team with InflateSail Complete and Ready for Delivery

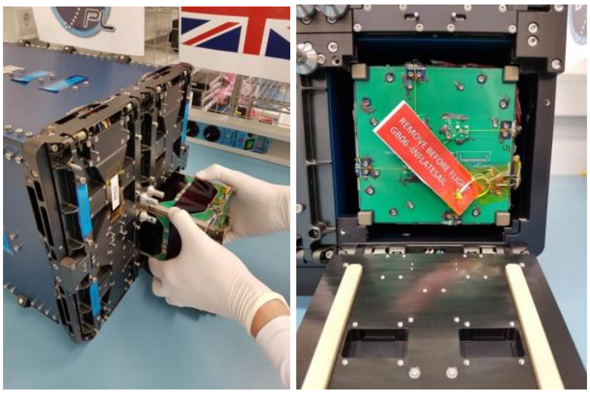

Figure 15. InflateSail Being Integrated into the ISIS QuadPack

INFLATESAIL LAUNCH AND RESULTS

InflateSail was launched on Friday 23rd June 2017 at 4.59 am UTC into a 505km altitude, 97.44^{o} inclination SSO. InflateSail was one of 31 satellites that were launched simultaneously on the PSLV (polar satellite launch vehicle) C-38 from Sriharikota, India.

The first data were received at 09:35am BST on InflateeSail's very first pass over SSC (Figure 16). The spacecraft had been pre-programmed to transmit a beacon signal for 9 seconds every minute, carrying key system telemetry data. The beacon was exactly on the predicted frequency and our automatic demodulation/decoding systems produced excellent telemetry. A quick analysis of the data showed the spacecraft to be in good health – the battery voltage, solar array currents, solar cells charging currents and transmitter powers and reflected powers were all nominal, and the spacecraft rotation rates looked to be very modest ~1 revolution per 2 minutes. Internal temperatures were good – ranging from ~ 20 ^{o}C to ~ -2 ^{o}C.

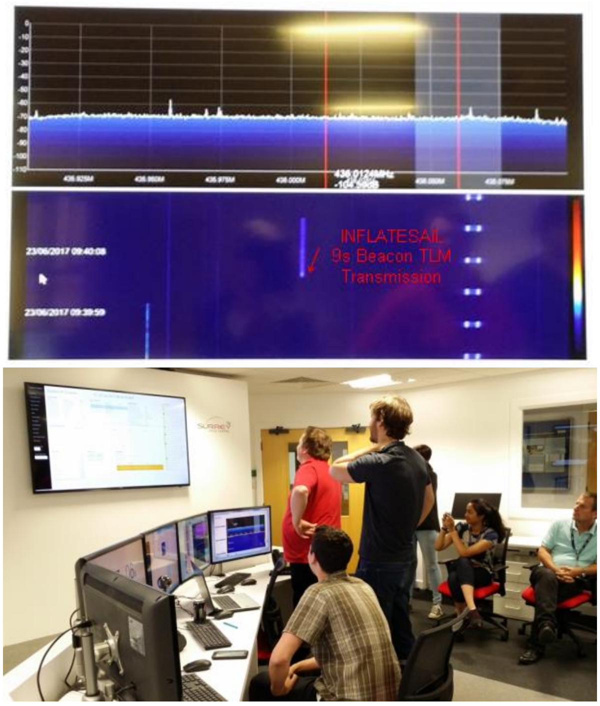

Figure 16. InflateSail's First Signal (top); SSC Mission Operations Ground Station (bottom)

InflateSail had been pre-programmed to deploy its payload automatically without the need for ground command, and, as the telemetry indicated that there had been a single un-commanded OBC reset event recorded before the first pass over SSC, there was the possibility that the payload had already deployed – depending on the precise timing of this reset.

Once the details of InflateSail's orbit were firmly established (i.e. once it could be distinguished from all the other satellites released on the same launch), the team were able to deduce that this indeed had happened. As Figure 17 shows, the behavior of InflateSail was very different to the other 30 satellites deployed from that launch.

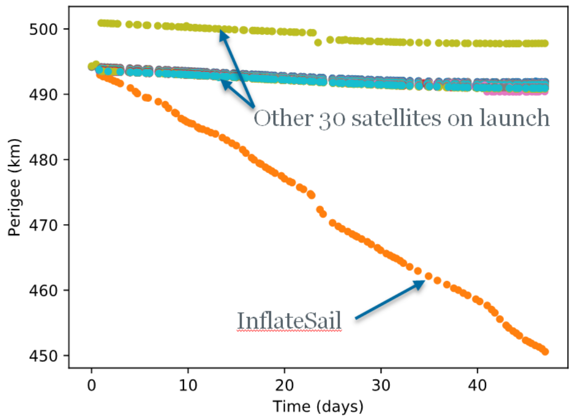

Figure 17. InflateSail's Departure from the Other Satellites Launched on PSLV C-38

Shortly after the satellite was inserted into its orbit, the OBC booted up (as expected) and once clear of the other satellites on the launch, it had automatically started the payload deployment sequence. First the 1m long inflatable mast was inflated using the CGG and then the sail boom motor was activated to extend the four lightweight bistable carbon booms out to their first hold position, 70% deployed.

A few days later, the sail was automatically extended to its full 10m^2 area, and we distinctly saw a change in the spacecraft's rotation rate consistent with this change (Figure 18).

Over the next 70 days the spacecraft was observed to drop in altitude, until it eventually re-entered. Figure 19 shows InflateSail's altitude changes and decay rate over its lifetime. The rapid descent once the spacecraft was below 400km altitude is very clear. The grey line represents URSA MAIOR 3U CubeSat which was ejected on the same launch for comparison.

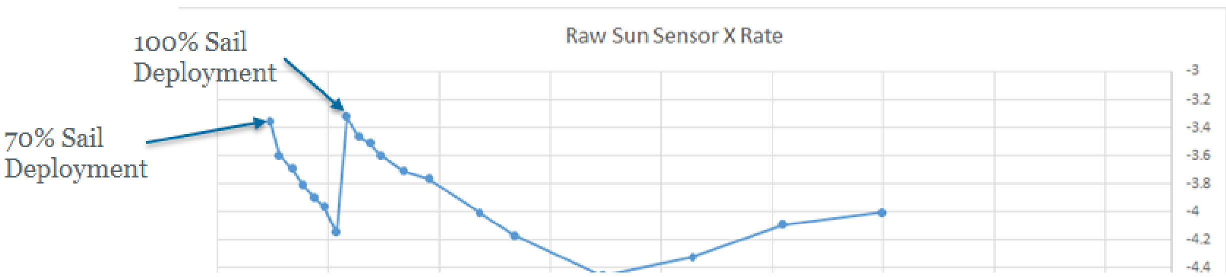

Figure 18. InflateSail's Change in Body Rotation with Sail Deployment

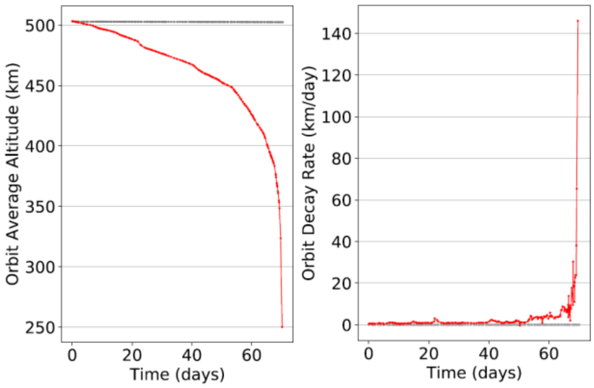

Figure 19. InflateSail's Changes in Altitude and Decay Rate

Analysis of the body dynamics of InflateSail is ongoing, however it is clear the spacecraft underwent a number of attitude changes during its descent. Initially the sail appears to have been essentially "edge on" to the air stream, and towards the end, it was acting so as to give "shuttlecock" stability, and was exhibiting increasing rotation about the inflatable boom in a "wind-milling" action. Figure 20 shows the smoothed rotation rates about the spacecraft body axes. Here, an initial rotation around the X axis (vector orthogonal to the plane of the sail) can be seen reversing direction before the final "wind-milling" phase, whilst the Y and Z axis rotations remain low.

InflateSail came down over South America at 01:27UTC (+/-6min) on 3rd September 2017, just under 72 days since launch. Last contact appears to have been with the SSC groundstation at 21:17UTC on 2nd September 2017. The last data received showed that InflateSail was rapidly increasing its rotation rate about its X-axis (i.e. the sail was acting like a windmill in the air-stream) and it had reached a rate of ~20 degrees per second at last contact.

The mission was a great success, and the team was able to pick up a significant amount of telemetry data as it passed over the SSC Ground Station in Guildford. Much extra data have also been sent to the team by Radio Amateur enthusiasts around the world, who picked up InflateSail's beacon – all of which was much appreciated.

FUTURE APPLICATIONS

The payload of InflateSail is seeing re-use on the RemoveDebris mission, launched to the International Space Station (ISS) in April 2018. RemoveDebris is a low cost mission performing key active debris removal (ADR) technology demonstrations including the use of a net, a harpoon, vision-based navigation (VBN) and a dragsail in a realistic space operational environment. For the purposes of the mission two CubeSats will be ejected and used as targets for experiments instead of real space debris[10].

The craft was launched to the ISS on the 2nd of April 2018, on board a Dragon capsule (SpaceX CRS-14 ISS re-supply mission). From here the satellite is to be deployed via the NanoRacks Kaber system into an orbit of around 400 km altitude.

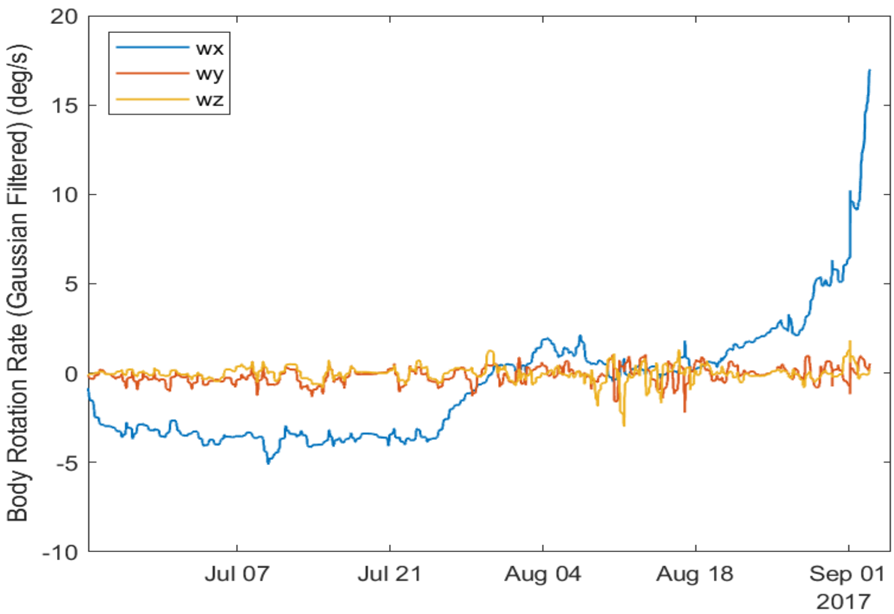

Figure 20. InflateSail's Body Rotation rates throughout mission lifetime

One of the “debris” CubeSats makes use of the same inflateable system as demonstrated on InflateSail to increase the target volume to approximately 1m diameter for demonstration of a net capture technology. The DebrisSat-1 CubeSat is shown below in figure 21 in its stowed and deployed states.

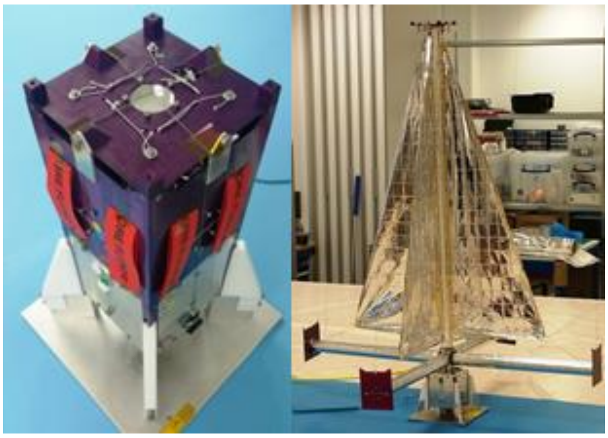

Figure 21. RemoveDebris DebrisSat-1 CubeSat in stowed (left) and deployed (right) states

The dragsail embarked on the RemoveDebris spacecraft is identical to that of InflateSail, albeit with a metalised sail for a longer expected mission duration and electrical and mechanical interfaces appropriate for a microsat. It is shown in figure 22 below.

Having demonstrated the behavior of a sail fitted to a low mass CubeSat on InflateSail, RemoveDebris will demonstrate performance on a 100kg class microsat. It is anticipated the sail will reduce the time to orbit from 2 years to approximately 3 months.

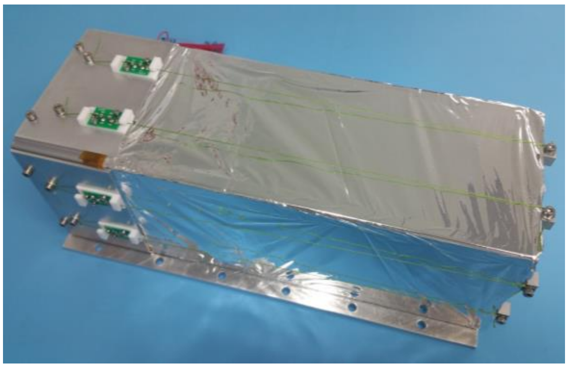

Figure 22. RemoveDebris Dragsail payload

In general, dragsails are a useful technology to mitigate spacedebris by disposal of satellites at the end of their mission lifetimes. Figure 23 shows the performance of a $10m^2$ sail on a typical 100kg class Microsat as measured by time to deorbit versus orbital altitude, as modelled using STELA model from CNES. Performance is shown for the case where the spacecraft is freely tumbling with no attitude control, and for a spacecraft that remains active and therefore able to orient itself and the sail to maximize drag area. It can be seen that a dragsail system can expedite the re-entry of a satellite, but also to allow launch into a higher altitude orbit, whilst retaining compliance with the IADC guidelines stipulating a 25 year lifetime. An increase in initial mission orbital altitude from 610km to 800km is possible through use of a system constituting ~3% of the spacecraft’s total mass. Larger sail systems can be embarked making use of the same technologies.

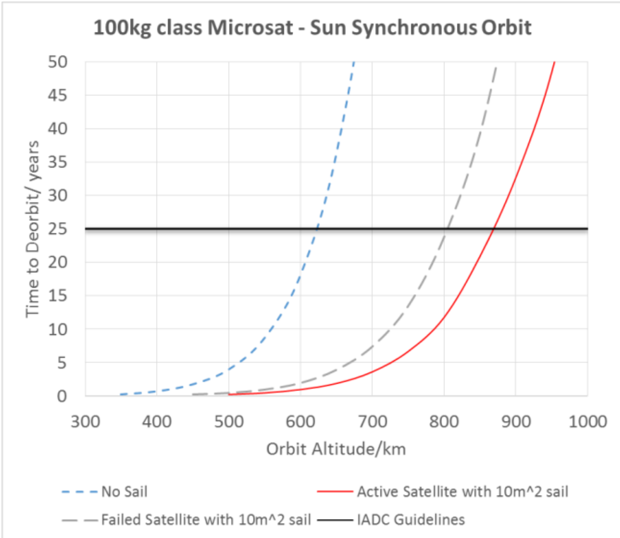

Figure 23. Performance of a $10m^2$ dragsail mounted to a 100kg microsat

CONCLUSIONS

InflateSail has been a highly successful mission, which has demonstrated the practicality of using drag augmentation to actively de-orbit a spacecraft. The boom/drag-sail technology developed by SSC will next be used on the RemoveDebris mission, launched in 2018, which will demonstrate the capturing and de-orbiting of artificial space debris targets using a net and harpoon system.

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