InflateSail De-Orbit Flight Demonstration – Observed Re-Entry Attitude and Orbit Dynamics

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Abstract: The InflateSail (QB50-UK06) CubeSat, designed and built at the Surrey Space Centre (SSC) for the Von Karman Institute (VKI), Belgium, was a technology demonstrator built under the European Commission's QB50 programme. The 3.2 kilogram 3U CubeSat was equipped with a 1 metre long inflatable mast and a $10m^2$ deployable drag sail and was one of 31 satellites that were launched simultaneously on the PSLV (polar satellite launch vehicle) C-38 from Sriharikota, India on 23rd June 2017 into a 505km, 97.44^o Sun-synchronous orbit. Shortly after insertion into orbit, InflateSail automatically activated its drag-sail payload, and, as planned, began to lose altitude, causing it to re-enter the atmosphere just 72 days later – successfully demonstrating for the first time the de-orbiting of a spacecraft using European inflatable and drag-sail technologies. This paper discusses the dynamics we observed during the descent, including the sensitivity of the craft to atmospheric density changes. The InflateSail project was funded by two European Commission Framework Program Seven (FP7) projects: DEPLOYTECH and QB50. QB50 was a programme, led by VKI, for launching a network of 50 CubeSats built mainly by university teams all over the world to perform first-class science in the largely unexplored lower thermosphere.

1. INTRODUCTION

In recent years, increasing attention has been given to the problem of space debris and its mitigation. It has been observed that a major source of new space debris is due to the break-up and fragmentation of spacecraft that remain in orbit after the end of their operational mission. As a result, regulations have been drawn-up which require the removal of spacecraft at the end of operation – known as Post-Mission-Disposal (PMD) – to ensure that the spacecraft do not become a new source of space debris. For low-Earth orbit (LEO) missions, the residual atmosphere encountered in orbit offers a potentially simple and relatively low cost method of PMD through the use of deployable drag augmentation devices. The InflateSail (QB50-UK06) CubeSat, designed and built at the Surrey Space Centre (SSC) for the Von Karman Institute (VKI), Belgium, was designed to demonstrate this technique by means of a 3.2 kg 3U CubeSat carrying a $10m^2$ deployable drag-sail mounted on the end of a 1m long inflatable mast.

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 aerodynamic pressure of the spacecraft are separated, thereby, in principle, conveying a degree of passive stability (the weathervane effect), which in turn should maximize the structure's drag by ensuring that the sail is presented normal to the free-stream air flow (see Fig. 1). The mast also ensures that the drag sail is kept clear of any host spacecraft structures which might interfere with sail deployment.

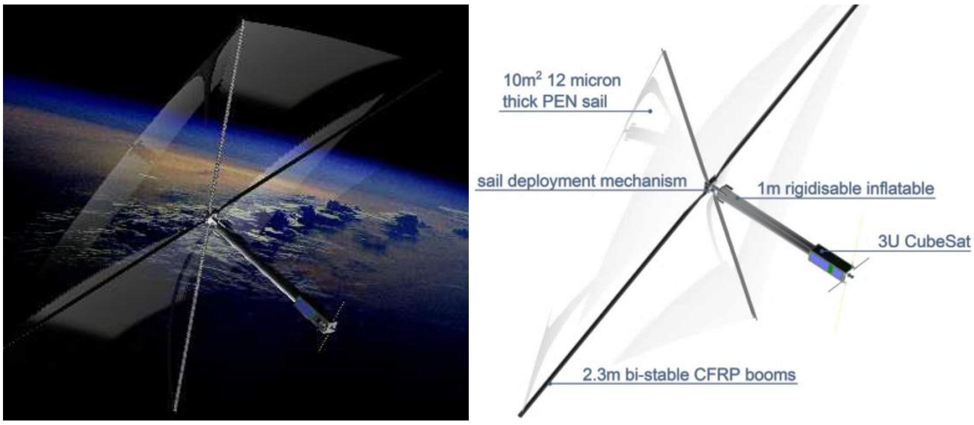

Fig. 1. (left) Artist's Rendition of InflateSail in Orbit with the PMD Mast/Sail Payload Deployed and (right) Labelled Parts of the PMD Payload

2. INFLATESAIL SPACECRAFT AND PMD PAYLOAD

InflateSail's PMD payload was developed through the European Commission (EC) Framework Program Seven (FP7) project: DEPLOYTECH [1], and comprised a 1m long inflatable, rigidisable, aluminium-polymer laminate mast [2] terminated in a deployable $10m^2$ four-quadrant transparent polymer drag-sail supported by four Bistable Rigid Composite (BRC) carbon-fibre reinforced polymer (CFRP) booms [3]. When stowed, the payload occupied approximately 2U of a standard 3U CubeSat structure. The remaining 1U volume contained the spacecraft's core avionics stack comprising a Commercial-Off-The-Shelf (COTS) Electric Power System (EPS), a specially developed Attitude Determination and Control System (ADCS) that also doubled as the On Board Computer (OBC), a COTS VHF/UHF Transceiver (TRXVU) and a bespoke Valve/Payload Controller Board (VCB) (see Fig. 2).

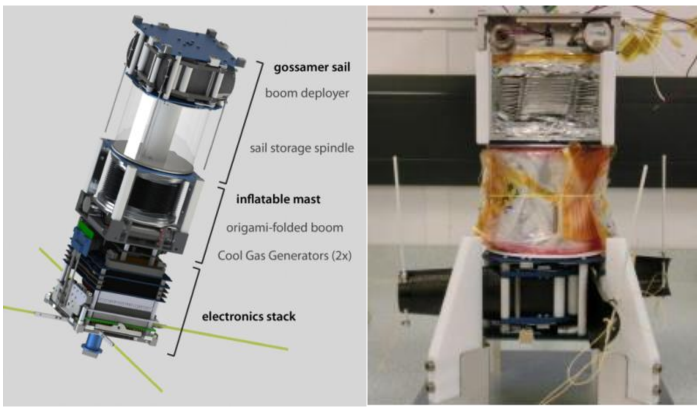

Fig. 2. (left) CAD Rendition of the Internal Systems of InflateSail and (right) the PMD Payload (upside down) Ready for Integration into the Spacecraft

The inflatable cylindrical mast consisted of a tough aluminium-BoPET (biaxially-oriented polyethylene terephthalate) polymer three-ply laminate, stored in the spacecraft by using an origami folding technique. The fold pattern used has five faces around the circumference of the cylinder, and has a repeating unit height of 60mm. The fold pattern leaves an internal space 35mm in diameter when folded, providing storage space for an internal normally open solenoid valve. When fully folded and compressed, the cylinder including its end fittings is 63mm in length (see Fig. 3).

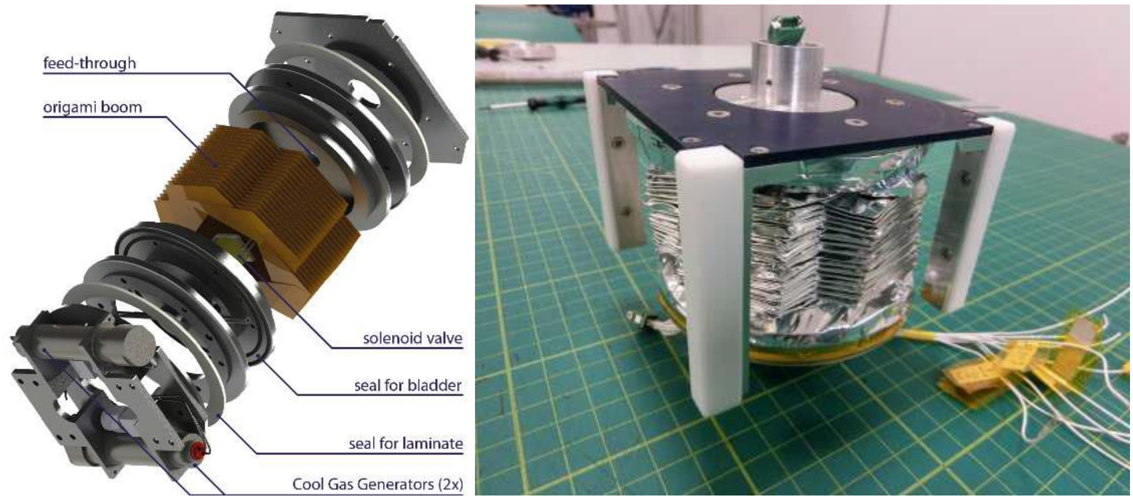

Fig. 3. (left) Inflatable Mast System Layout; (right) The Inflatable Mast in its Stowed Configuration

The two outer aluminium plies were each 13µm thick, and the central BoPET ply was also 13µm thick. The total laminate thickness, including adhesive, was 45µm. A 12µm thick BoPET bladder was used inside the cylinder to improve air-tightness against the vacuum of space. The 1m long, 90mm diameter cylinder was inflated by a Cool Gas Generator (CGG) developed by TNO and CGG Safety & Systems BV (now HDES Service & Engineering), to a pressure of approximately 50 kPa, which was found to be sufficient to cause permanent stretching deformation in the metal plies of the laminate (see Fig. 4). After inflation, the inflation gas was immediately vented in a symmetric pattern (to prevent applying a torque to the spacecraft). The resulting unpressurised rigidized cylinder has been shown to withstand compressive loads up to 50N, and bending moments up to 2Nm [4]. Thus, the inflatable structure does not depend upon long term gas-tightness for its rigidity.

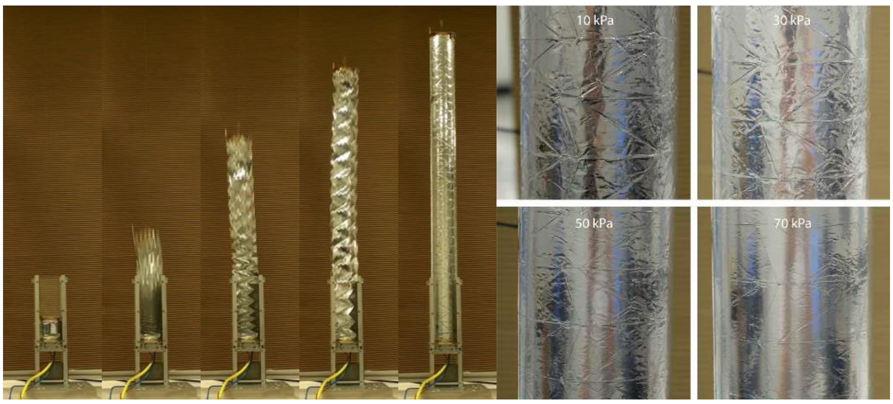

Fig. 4. (left) The Inflatable Cylindrical Mast Deployment Sequence; (right)
Residual Creases after Depressurisation from Different Inflation Pressures (10–70 kPa)

The gossamer drag sail and its deployment mechanisms were developed by SSC. The sail structure consists of four separate quadrants, making up a total area of $10m^2$. 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. For the InflateSail mission, the membrane was deliberately left un-metallised so as to minimise perturbations from solar radiation pressure as the team wanted to observe the effects of atmospheric drag alone for comparison with the science results from the other QB50 spacecraft deployed alongside InflateSail. The sail support structure comprised four custom made carbon-fibre reinforced polymer (CFRP) bistable booms, which were co-coiled just above the wrapped sail membrane. These booms, developed by a UK company: RolaTube Technology (www.rolatube.com), have the property that they are mechanically stable both in coiled and deployed modes. The CFRP booms are driven in and out using a precisely controlled brushless DC motor. The fully deployed sail structure is shown in Fig. 5.

Fig. 5. InflateSail Inflatable Mast and Drag Sail Deployment Test

3. INFLATESAIL LAUNCH AND RESULTS

The InflateSail CubeSat mission was developed and executed as part of the EC FP7 project QB50 [5]. The spacecraft underwent final assembly integration and testing (AIT), full environmental testing (EVT) and full system end-to-end testing with the SSC ground-station between November 2016 and April 2017. It was 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 (see Fig. 6).

Fig. 6. (left) InflateSail Team with InflateSail Ready for Delivery; (centre, right) InflateSail Being Integrated into the ISIS QuadPack

InflateSail was launched on Friday 23rd June 2017 at 3.59 am UTC into a 505km altitude, 97.44^o inclination SSO. It 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 (08:35 UTC) on InflateSail's very first pass over Surrey. A quick analysis of the real-time telemetry data from the first passes showed the spacecraft to be in good health and the spacecraft rotation rates looked to be very modest ~0.5 revolutions per minute i.e. ~3^o/s (see Fig. 7).

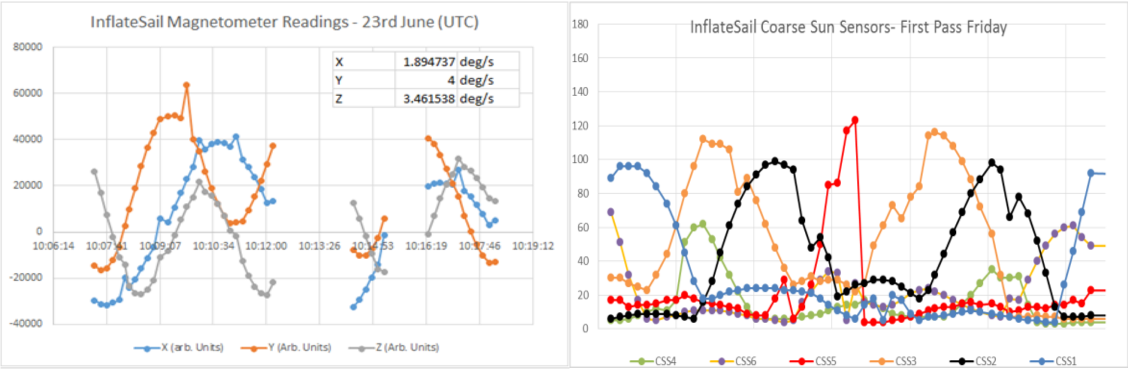

Fig. 7. (left) Initial Magnetometer Data (2nd Pass); (right) Coarse Sun Sensor Data (1st Pass: 08:34 to 08:43 UTC Friday 23rd June 2017) – Arbitrary Units

These initial results showed that InflateSail was in a relatively slow but rather complex rotation primarily about the X- (i.e. the mast) axis. Further, we noted that the B* drag value for "Object F" (later confirmed to be InflateSail) was very much higher than all the other CubeSats deployed from the launch. Both these pieces of evidence seemed to indicate that the InflateSail PMD payload might have already deployed.

We had built in some fail-safes into the spacecraft's operating software, such that the mission would be completed autonomously in the event of prolonged loss of ground communications. Detailed analysis of the system telemetry showed that this fail-safe mode had indeed been activated due to an unexpected on-board computer (OBC) reset occurring with a particular set of system recovery timings. We saw that the PMD payload had deployed automatically around 50-60 minutes after ejection from the launch pod and around three hours before the first pass over Surrey.

3.1 InflateSail Attitude Dynamics

InflateSail's attitude data was derived from the ADCS unit designed and developed by the Electronic Systems Laboratory (ESL) at Stellenbosch University and SSC at the University of Surrey specifically for the QB50 project. Table 1 gives the specifications of the unit. Fifteen ADCS units were officially supplied to the QB50 project, and it is now available commercially from Stellenbosch's spin-out company, CubeSpace.

Table 1. ADCS Unit Specifications

Sensors and Actuators	**Type**	**Range/ Field-of-View**	**Error (RMS)**
Magnetometer	3-Axis Magneto-resistive	±60 µT	< 40 nT
Sun Sensor	2-Axis CMOS Imager	Hemi-sphere	< 0.2^o
Nadir Sensor	2-Axis CMOS Imager	Hemi-sphere	< 0.2^o
Course Sun Sensor	6 Photo-diodes	Full Sphere	< 10^o
Rate Sensor	MEMS Gyro	±85^o/s	< 0.05^o/s
Pitch Momentum Wheel	Brushless DC Motor	±1.7 mNms	< 0.001mNms
Magnetorquers	Ferro-Magnetic Rods and Air Coil	±0.2Am^2	<0.0005Am^2

The full QB50 ADCS unit (Fig. 8) comprises:

- CubeSense
- CubeControl
- CubeComputer

These include:

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

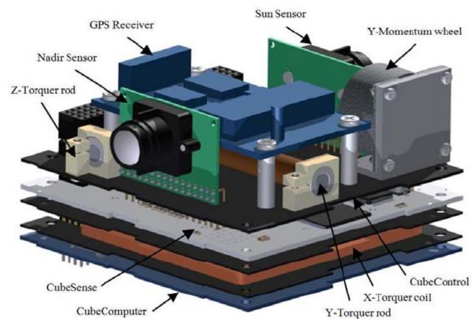

Fig. 8. QB50 ADCS Unit (Cubespace)

For InflateSail, the GPS Receiver and the Pitch-Axis Momentum Wheel were not flown to save space and also due to the attitude being controlled "passively" via the weathervane effect once the PMD payload had deployed. Fig. 9 shows InflateSail's axis system. The mast and sail deploy from the +X facet and the X-Axis is the mast axis, normal to the sail. Table 2 gives the course sun sensor allocation.

Table 2. Coarse Sun Sensor Layout

Sensor	Axis
CSS1	-Y
CSS2	+Y
CSS3	-Z
CSS4	-X (Mast Axis – Dipole Antennas Side
CSS5	+X (Mast Axis – Deployed ADR Mast/Sail Side
CSS6	+Z

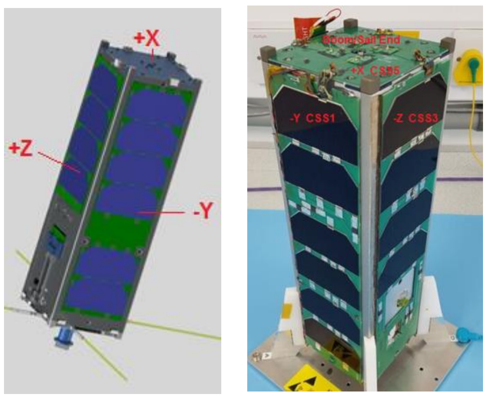

Fig. 9. InflateSail's Axes and CSS Locations

The ADCS unit provides its own independent estimate of the body rates by on-board analysis of the ADCS data. Fig.10 shows these estimates over the mission lifetime.

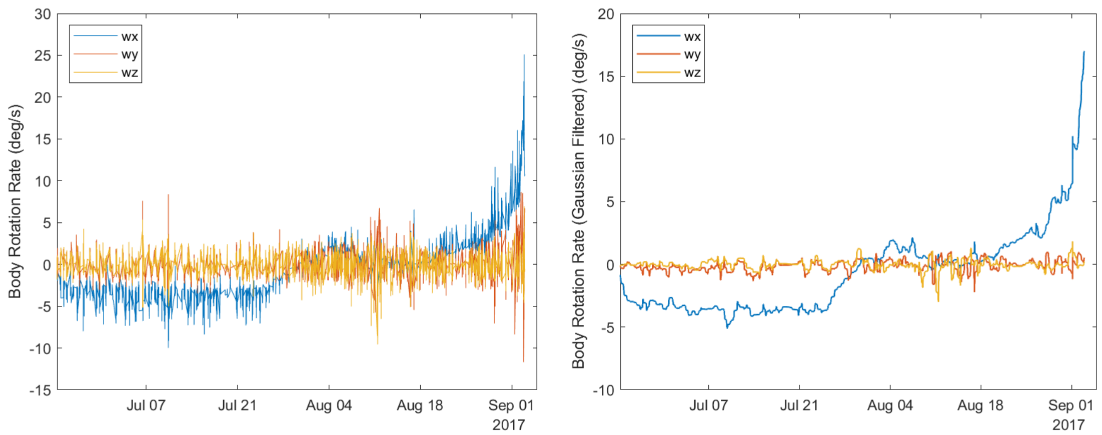

Fig. 10. ADCS Internal Body Rate Estimator Data: (top) Raw; (bottom) Smoothed

The body rate rotations for the Y-Axis (orange) and Z-Axis (yellow) are very small indeed – close to zero degrees per second. The X-Axis body rate (blue) is seen to increase initially to around -4°/s and stay there until the last week in July, when a steady decrease in X-rate occurs, approaching near zero for most of August. The early X-axis spin increases appear to show a transfer of angular momentum to the maximum moment of inertia axis – i.e. the X-axis. We suspect that this happens because of the flexible nature of the mast/sail structure, allowing such behaviour to occur. In mid-to-late August the body motion becomes complex – but everything happens at a slow rate. Beyond ~20th August, the X-rate gradually increases (positively) until re-entry occurs. We last record it at being around +20°/s. It should be noted that the body-rate estimator error bars are quite large for such slow rates ~ ±2°/s for the raw values and ~ ±0.5°/s for the smoothed values.

We interpret these body dynamics as being due to the increasing effect of atmospheric density as the satellite falls. A distinct change in body dynamics – possibly due to increasing Weathervane stability – seems to occur around the end of July, when the spacecraft has dropped to ~470km altitude. The body rates essentially go to zero.

From late August, when the satellite dropped below 450km, the increasingly positive X-Axis body rate seems to indicate a “wind-milling” effect – that is the satellite is spinning increasingly rapidly about the mast, normal to the sail, with the sail quadrants acting like the sails of a windmill. The phenomenon continues at increasing rate until contact was lost at ~250km altitude.

3.2 InflateSail Orbit Dynamics

During the first few days of monitoring, it became clear that Inflatesail was behaving very differently to the other CubeSats released from the PSLV C-38 launch. It was observed to be dropping rapidly and accelerating ahead of the others.

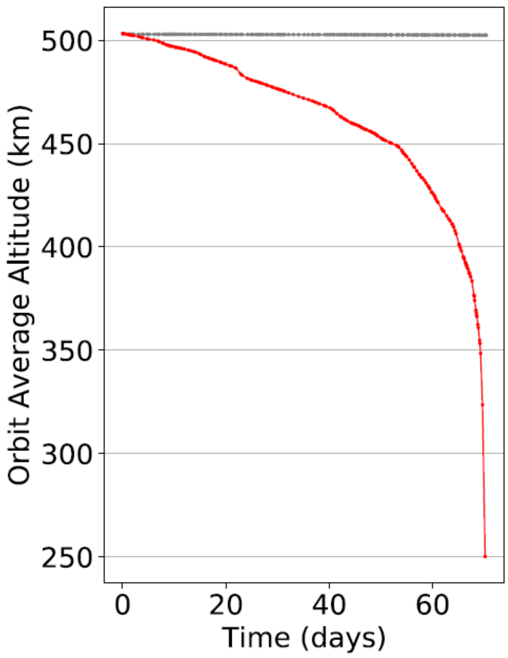

Fig. 11. InflateSail Orbit Average Altitude (red) Compared to the URSA-MAIOR 3U CubeSat Deployed at the Same Time (grey)

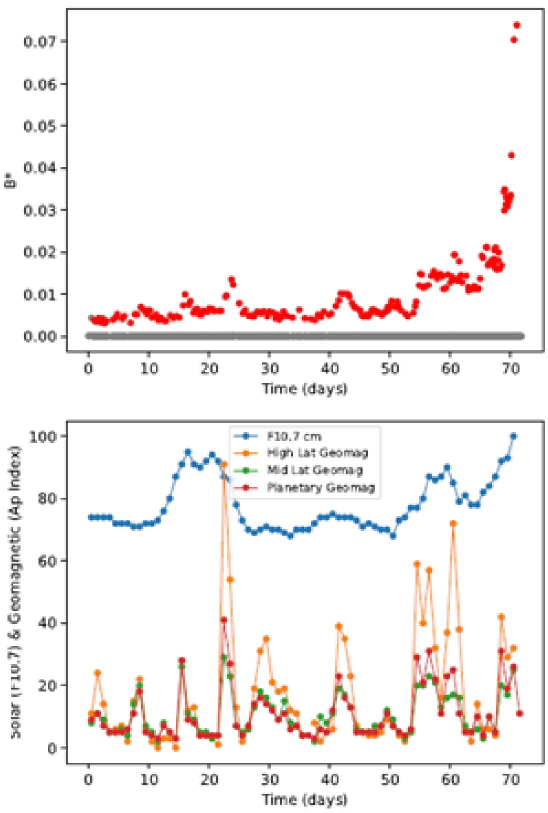

Fig. 12. (top) B* Drag Term (InflateSail = red) (bottom) NOAA Space Weather Indices

Figure 11 shows the drop in perigee altitude (as determined from the two-line element (TLE) sets provided by the North American Aerospace Defense Command – NORAD). The rapid descent of InflateSail (red) compared to the URSA-MAIOR 3U CubeSat (grey), prior to its deployment of its own drag sail, is clear. The step changes in descent rate are related to space weather phenomena – particularly noticeable for mission day ~23 (15^{th} July) following an M2 class solar flare on 14^{th} July 2017.

Figure 12 shows the B* drag term for the PSLV C-38 satellites. The drag is much greater for InflateSail (red) than for the others (grey). The variation in B* correlates very well with the National Oceanic and Atmospheric Administration's (NOAA's) geomagnetic indices – i.e. the effects of space weather show up very clearly on the orbital behavior.

4. CONCLUSIONS

The InflateSail mast/sail PMD system proved itself to be very effective, and InflateSail dropped from 505km to re-entry (250km) in just less than 72 days. InflateSail came down over South America at 01:27 UTC (±6 minutes) on 3rd September 2017. The last radio contact appears to have been with the SSC ground-station at 21:17 UTC on 2^{nd} September 2017. During the descent, InflateSail's attitude and orbit dynamics changes gave insight into the effects of the atmosphere on drag sails at different altitudes and under different space weather conditions. Once below 400km, the rate of descent becomes very rapid and the sail quadrants spin like the sails of a windmill.

Acknowledgements

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