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SSO-A Orbital Debris Assessment Report (ODAR)

This report is presented in compliance with NASA-STD-8719.14, APPENDIX A.

Report Version: 1, 5/11/2018

Document Data is Not Restricted.

This document contains no proprietary, ITAR, or export controlled information.

DAS Software Version Used In Analysis: v2.1.1
solarflux_table.dat dated 2018/03/29

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VERSION APPROVAL and/or FINAL APPROVAL*:

Jeffrey Roberts
SSO-A Mission Director
Spaceflight, Inc.

*Approval signatures indicate acceptance of the ODAR-defined risk.

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Self-assessment of the ODAR using the format in Appendix A.2 of NASA-STD- 8719.14:

A self assessment is provided below in accordance with the assessment format provided in Appendix A.2 of NASA-STD-8719.14.

Orbital Debris Self-Assessment Report Evaluation: SSO-A Mission

Requirement #	Launch Vehicle				Spacecraft			Comments
	Compliant	Not Compliant	Incomplete	Standard Non Compliant	Compliant or N/A	Not Compliant	Incomplete	
4.3-1.a	☐	☐	☐	☐	☒	☐	☐	No Debris Released in LEO.
4.3-1.b	☐	☐	☐	☐	☒	☐	☐	No Debris Released in LEO.
4.3-2	☐	☐	☐	☐	☒	☐	☐	No Debris Released in GEO.
4.4-1	☐	☐	☐	☐	☒	☐	☐	
4.4-2	☐	☐	☐	☐	☒	☐	☐	
4.4-3	☐	☐	☐	☐	☒	☐	☐	No planned breakups.
4.4-4	☐	☐	☐	☐	☒	☐	☐	No planned breakups.
4.5-1	☐	☐	☐	☐	☒	☐	☐	
4.5-2	☐	☐	☐	☐	☒	☐	☐	
4.6-1(a)	☐	☐	☐	☐	☒	☐	☐	
4.6-1(b)	☐	☐	☐	☐	☒	☐	☐	
4.6-1(c)	☐	☐	☐	☐	☒	☐	☐	
4.6-2	☐	☐	☐	☐	☒	☐	☐	Spacecraft does not go to GEO.
4.6-3	☐	☐	☐	☐	☒	☐	☐	Spacecraft does not go beyond LEO.
4.6-4	☐	☐	☐	☐	☒	☐	☐	
4.7-1	☐	☐	☐	☐	☒	☐	☐	
4.8-1	▨	▨	▨	▨	☒	☐	☐	No tethers used.

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Assessment Report Format:

ODAR Technical Sections Format Requirements:

As Spaceflight, Inc. is a US company; this ODAR follows the format recommended in NASA-STD-8719.14, Appendix A.1 and includes the content indicated at a minimum in each section 2 through 8 below for the SSO-A Mission. Sections 9 through 14 apply to the launch vehicle ODAR and are not covered here.

ODAR Section 1: Program Management and Mission Overview

Project Manager: Jeffrey Roberts

Foreign government or space agency participation: No foreign Government participation.

Schedule of upcoming mission milestones:

Launch: September or October 2018

Mission Overview:
The SSO-A Mission is a commercial rideshare mission with the primary objective of deploying over 100 customer spacecraft into a planned sun-synchronous circular orbit of 575 x 575 km mean altitude at 97.75 degrees inclination. The launch vehicle will deploy four customer spacecraft and two free-flying spacecraft, called the Upper Free Flyer (UFF) and the Lower Free Flyer (LFF), which each deploy additional customer spacecraft within several hours of liftoff.
(*Each of these satellite customers are responsible for obtaining an FCC or ITU license as appropriate and do not constitute debris*). After a mission lifetime of twenty-four hours, the UFF and LFF spacecraft will then deploy a drag sail and rely on atmospheric drag to fully de-orbit. The UFF and LFF have no solar panels, attitude control, propulsion, or pressure vessels.

ODAR Summary:

- No debris released in normal operations;
- No credible scenario for breakups;
- The collision probability with other objects is compliant with NASA standards;
- The estimated mean decay lifetime due to atmospheric drag is under 25 years following operations: 7.2 years for the UFF and 4.3 years for the LFF after one day of nominal operations, as calculated by DAS 2.1.1.
- For an off-nominal mission in which no secondary payloads are successfully deployed, DAS 2.1.1 predicts maximum orbit lifetime to be 16.3 years for the UFF and 5.2 years for the LFF.

Launch vehicle and launch site: Falcon 9, Vandenberg AFB, CA

Proposed launch date: September or October 2018

Mission duration:

Maximum Nominal Operations: One day after launch for both the UFF and LFF.

Post-Operations Orbit lifetime:

- The UFF has a mean of ~10.3 years (maximum of ~16.0 years) until reentry via atmospheric orbital decay. These values are across all possible orientations assuming each is held for the entire orbit lifetime. If we assume the UFF tumbles randomly spending equal time in all orientations, the predicted orbit lifetime is ~7.2 years.
- The LFF has a mean of ~5.2 years (maximum of ~16.8 years) until reentry via atmospheric orbital decay. These values are across all possible orientations assuming each is held for the entire orbit lifetime. If we assume the LFF tumbles randomly spending equal time in all orientations, the predicted orbit lifetime is ~4.3 years.

Launch and deployment profile, including all parking, transfer, and operational orbits with apogee, perigee, and inclination:

	Apogee Altitude	Perigee Altitude	Inclination	Max. Dwell
Deployment	575 km	575 km	97.75 deg	<1 days
End-of-Life Orbit*	575 km	575 km	97.75 deg	<17.0 years

*These orbits are the same for the UFF and LFF.

ODAR Section 2: Spacecraft Description

Physical description of the spacecraft:

The mission objective is accomplished with Flight Support Equipment consisting of three main elements: a Multiple Payload Container (MPC), the Upper Free Flyer (UFF) and Lower Free Flyer (LFF). The MPC is a passive element with no avionics or batteries and remains bolted to the launch vehicle through the launch vehicle's de-orbit maneuver. Therefore, it is not covered by this ODAR. The UFF and LFF spacecraft contain avionics and batteries to enable the deployment of multiple customer spacecraft. The UFF and LFF are very different in terms of structure, mass, and envelope so they will be reported separately as their orbit lifetimes are unique.

The UFF is mainly primary structure comprised of two large cylindrical carbon composite structures and two large cylindrical aluminum structures all bolted in series. Adapter plates (one composite honeycomb sandwich panel and the remainder machined aluminum) are bolted to the primary structure. CubeSat dispensers and microsat deployment devices are then attached to the adapter plates. The UFF's envelope is approximated by a 3.1 m diameter right cylinder with a height of 3.1 meters with customer spacecraft attached. The UFF's post-customer spacecraft separation envelope is approximated by a 2.0 m diameter right cylinder with a height of 3.1 meters. The UFF does not have attitude control capability.

The LFF is mainly primary structure comprised of machined aluminum plates bolted together. CubeSat dispensers, avionics, and batteries are bolted directly to this structure. The LFF's envelope is approximated by a 1.7 m diameter right cylinder with a height of 0.9 meters both before and after deployment of customer spacecraft from cubesat dispensers. The LFF does not have attitude control capability.

Total satellite mass at launch, including all propellants and fluids: (including all allocated mass growth allowances and uncertainties)

Spacecraft	Total Mass
UFF	2,271 kg

LFF	421 kg
Total	**2,692 kg**

Dry mass of satellites at launch, excluding solid rocket motor propellants: (including all allocated mass growth allowances and uncertainties)

Spacecraft	**Dry Mass**
UFF	2,271 kg
LFF	421 kg
Total	**2,692 kg**

Dry mass of satellites at end of mission, excluding solid rocket motor propellants:

Spacecraft	**Nominal Mission**
UFF	1,072 kg
LFF	260 kg
Total	**1,332 kg**

Description of all propulsion systems (cold gas, mono-propellant, bi-propellant, electric, nuclear):

The UFF spacecraft has no propulsion system. The LFF spacecraft has no propulsion system.

Identification, including mass and pressure, of all fluids (liquids and gases) planned to be on board and a description of the fluid loading plan or strategies, excluding fluids in sealed heat pipes: N/A

Fluids in Pressurized Batteries: None. The two sets of avionics (LFF and UFF) are comprised of nine battery packs, two primary batteries that are lithium iron disulfide chemistry and seven secondary (rechargeable) batteries are nickel-metal hydride. The LFF avionics use one primary and three secondary batteries while the UFF use one primary and four secondary batteries.

Description of attitude control system and indication of the normal attitude of the spacecraft with respect to the velocity vector:

None. Neither the UFF nor LFF have attitude control.

Description of any range safety or other pyrotechnic devices: A space rated European Standard Initiator (ESI) is used to release the clampband to separate the UFF from the launch vehicle. The clampband and its components are non-debris generating.

Description of the electrical generation and storage system: Standard commercial lithium iron disulfide and nickel-metal hydride battery cells are charged prior to payload integration and provide electrical energy during the mission.

Identification of any other sources of stored energy not noted above: None.

Identification of any radioactive materials on board: None.

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ODAR Section 3: Assessment of Spacecraft Debris Released during Normal Operations

Identification of any object (>1 mm) expected to be released from the spacecraft any time after launch, including object dimensions, mass, and material: There are no intentional releases other than customer spacecraft deployments (see Mission Overview).

Rationale/necessity for release of each object: N/A.

Time of release of each object, relative to launch time: N/A.

Release velocity of each object with respect to spacecraft: N/A.

Expected orbital parameters (apogee, perigee, and inclination) of each object after release: N/A.

Calculated orbital lifetime of each object, including time spent in Low Earth Orbit (LEO): N/A.

Assessment of spacecraft compliance with Requirements 4.3-1 and 4.3-2 (per DAS v2.1.1)

4.3-1, Mission Related Debris Passing Through LEO: COMPLIANT

4.3-2, Mission Related Debris Passing Near GEO: COMPLIANT

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ODAR Section 4: Assessment of Spacecraft Intentional Breakups and Potential for Explosions.

Potential causes of spacecraft breakup during deployment and mission operations:

There is no credible scenario that would result in spacecraft breakup during normal deployment and operations.

Summary of failure modes and effects analyses of all credible failure modes which may lead to an accidental explosion:

An in-mission failure of a battery protection circuit could lead to a short circuit resulting in overheating and a very remote possibility of battery cell explosion. The battery safety systems discussed in the FMEA (see requirement 4.4-1 below) describe the combined faults that must occur for any of seven (7) independent, mutually exclusive failure modes to lead to explosion.

Detailed plan for any designed spacecraft breakup, including explosions and intentional collisions:

There are no planned breakups.

List of components which shall be passivated at End of Mission (EOM) including method of passivation and amount which cannot be passivated:

No components require passivation at EOM.

Rationale for all items which are required to be passivated, but cannot be due to their design:

N/A

Assessment of spacecraft compliance with Requirements 4.4-1 through 4.4-4:

***Requirement 4.4-1*:** Limiting the risk to other space systems from accidental explosions during deployment and mission operations while in orbit about Earth or the Moon:

For each spacecraft and launch vehicle orbital stage employed for a mission, the program or project shall demonstrate, via failure mode and effects analyses or equivalent analyses, that the integrated probability of explosion for all credible failure modes of each spacecraft and launch vehicle is less than 0.001 (excluding small particle impacts) (Requirement 56449).

Compliance statement:

Required Probability: 0.001.

Expected probability: 0.000.

Supporting Rationale and FMEA details:

Battery explosion:

Effect: All failure modes below might theoretically result in battery explosion with the possibility of orbital debris generation. However, in the unlikely event

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that a battery cell does explosively rupture, the small size, mass, and potential energy, of the selected space-rated commercial battery cells is such that while the spacecraft could be expected to vent gases, most debris from the battery rupture should be contained within the battery housing / containment device due to the lack of penetration energy.
Probability: Extremely Low. It is believed to be a much less than 0.1% probability that multiple independent (not common mode) faults must occur for each failure mode to cause the ultimate effect (explosion).

Failure mode 1: Internal short circuit.
Mitigation 1: Qualification and acceptance shock, vibration, thermal cycling, and vacuum tests followed by maximum system rate-limited charge and discharge to prove that no internal short circuit sensitivity exists.
Combined faults required for realized failure: Environmental testing and functional charge/discharge tests must both be ineffective in discovery of the failure mode.

Failure Mode 2: Internal thermal rise due to high load discharge rate.
Mitigation 2: Cells were tested in lab for high load discharge rates in a variety of flight-like configurations to determine like likelihood and impact of an out of control thermal rise in the cell. Cells were also tested in a hot environment to test the upper limit of the cells capability. No failures were seen.
*Combined faults required for realized failure: S*pacecraft thermal design must be incorrect and external over-current detection and disconnect function must fail to enable this failure mode.

Failure Mode 3: Excessive discharge rate or short circuit due to external device failure or terminal contact with conductors not at battery voltage levels (due to abrasion or inadequate proximity separation).
Mitigation 4: This failure mode is negated by a) qualification-tested short circuit protection on each external circuit, b) design of battery packs and insulators such that no contact with nearby board traces is possible without being caused by some other mechanical failure, c) obviation of such other mechanical failures by proto-qualification and acceptance environmental tests (shock, vibration, thermal cycling, and thermal-vacuum tests).
Combined faults required for realized failure: An external load must fail/short-circuit and external over-current detection and disconnect function failure must all occur to enable this failure mode.

Failure Mode 4: Inoperable vents.
Mitigation 5: Battery vents are not inhibited by the battery holder design or the spacecraft.
Combined effects required for realized failure: The final assembler fails to install proper venting.

Failure Mode 5: Crushing.
Mitigation 6: This mode is negated by spacecraft design. There are no moving

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parts in the proximity of the batteries.
Combined faults required for realized failure: A catastrophic failure must occur in an external system and the failure must cause a collision sufficient to crush the batteries leading to an internal short circuit and the satellite must be in a naturally sustained orbit at the time the crushing occurs.

Failure Mode 6: Low level current leakage or short-circuit through battery pack case or due to moisture-based degradation of insulators.
Mitigation 7: These modes are negated by a) battery holder/case design made of non-conductive plastic, and b) operation in vacuum such that no moisture can affect insulators.
Combined faults required for realized failure: Abrasion or piercing failure of circuit board coating or wire insulators and dislocation of battery packs and failure of battery terminal insulators and failure to detect such failure modes in environmental tests must occur to result in this failure mode.

Failure Mode 7: Excess temperatures due to orbital environment and high discharge combined.
Mitigation 8: The spacecraft thermal design will negate this possibility. Thermal rise has been analyzed in combination with space environment temperatures showing that batteries do not exceed normal allowable operating temperatures, which are well below temperatures of concern for explosions.
Combined faults required for realized failure: Thermal analysis and thermal design and mission simulations in thermal-vacuum chamber testing and over-current monitoring and control must all fail for this failure mode to occur.

Requirement 4.4-2: Design for passivation after completion of mission operations while in orbit about Earth or the Moon:

Design of all spacecraft and launch vehicle orbital stages shall include the ability to deplete all onboard sources of stored energy and disconnect all energy generation sources when they are no longer required for mission operations or postmission disposal or control to a level which cannot cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft (Requirement 56450).

Compliance statement:
The UFF and LFF avionics are designed such that when mission operations begin, all energy from the secondary batteries will dissipate within 24 hours. For the primary batteries of the UFF and LFF avionics, they will dissipate all energy within 30 days. Additionally, the UFF and LFF battery charge circuits include overcharge protection and active thermal monitoring to limit the risk of battery failure. However, in the unlikely event that a battery cell does explosively rupture, the small size, mass, and potential energy, of these small batteries is such that while the spacecraft could be expected to vent gases, most debris from the battery rupture should be contained within the vessel due to the lack of penetration energy.

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Requirement 4.4-3. Limiting the long-term risk to other space systems from planned breakups:

Compliance statement:
This requirement is not applicable. There are no planned breakups.

Requirement 4.4-4: Limiting the short-term risk to other space systems from planned breakups:

Compliance statement:
This requirement is not applicable. There are no planned breakups.

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ODAR Section 5: Assessment of Spacecraft Potential for On-Orbit Collisions

Assessment of spacecraft compliance with Requirements 4.5-1 and 4.5-2 (per DAS v2.0.2, and calculation methods provided in NASA-STD-8719.14, section 4.5.4):

Requirement 4.5-1: Limiting debris generated by collisions with large objects when operating in Earth orbit:
For each spacecraft and launch vehicle orbital stage in or passing through LEO, the program or project shall demonstrate that, during the orbital lifetime of each spacecraft and orbital stage, the probability of accidental collision with space objects larger than 10 cm in diameter is less than 0.001 (Requirement 56506).

Large Object Impact and Debris Generation Probability:

Spacecraft	Nominal Mission	Status
UFF	0.00065	COMPLIANT
LFF	0.00015	COMPLIANT

Note: “failed mission” mass and cross-sectional area were assumed.
Results for “nominal mission” will be lower (better).

Requirement 4.5-2: Limiting debris generated by collisions with small objects when operating in Earth or lunar orbit**:**
For each spacecraft, the program or project shall demonstrate that, during the mission of the spacecraft, the probability of accidental collision with orbital debris and meteoroids sufficient to prevent compliance with the applicable postmission disposal requirements is less than 0.01 (Requirement 56507).

Small Object Impact and Debris Generation Probability:
Collision Probability: 0.0000; COMPLIANT.

The SSO-A mission duration of <24 hours is so short that the probability of collisions with small objects in Earth orbit affecting its mission is effectively zero.

Identification of all systems or components required to accomplish any postmission disposal operation, including passivation and maneuvering:
The UFF and LFF will deplete their batteries in less than 24 hours after separation. An independent, redundant avionics system in the DragSail will actuate on both the UFF and LFF 24 hours after separation. Neither the UFF nor LFF have propellants or pressure vessels.

Additional Re-Contact Analysis: Although beyond the scope of a standard orbital debris analysis, Spaceflight has conducted extensive testing and modeling so as to limit the risk that individual spacecraft that will be deployed on this mission will re-contact with each other after release. Spaceflight has performed analysis on the probability and consequence of recontact between the satellites on the mission following deployment and is presenting data to support that there is both a low probability of recontact and for the where potential recontact occurs, the consequence to the general space environment is negligible.

Spaceflight developed a six degree of freedom orbital trajectory analysis tool to measure the relative distance between every customer spacecraft and the two Spaceflight carrier spacecraft. The purpose of this analytical tool is twofold. First, it allows Spaceflight to calculate the probability of recontact between the customer spacecraft during the mission in order to quantify the recontact risk. Second, it allows Spaceflight to reduce the recontact risk by optimizing the mission deployment sequence. The analysis was performed from launch through two orbits following the last customer spacecraft separation. During this time period, customer spacecraft are not permitted to employ their own propulsion or other maneuvering systems. After the first two orbits and following the last separation, the spacecraft will continue to diverge. At that point, customer spacecraft with propulsion or other maneuvering capability will be allowed to use their own systems, which is outside the scope of the analysis.

Risk is classically defined as the probability of an event occurring, and the consequences of the event. In analyzing the mission risk of spacecraft recontact, Spaceflight considered both the probability of recontact as well as the potential consequence of any recontact. A series of 5,000 simulations showed that the probability of recontact is less than 0.002. In the rare occasion where a recontact event was observed, the closing velocity between the objects was 1.8 meters per second or less, which is equivalent to dropping an object from 0.17 meters (6.7 inches) off the ground. Contact at this low speed may cause minor damage to a spacecraft, but little or no debris. The recontact instances observed in Spaceflight's analysis are unique from an orbital collision; most orbital collisions are measured at hypersonic velocities (over 1,700 meters per second). Sub-one-meter per second contacts are not considered debris generating events. Therefore, the combination of low probability of recontact and negligible consequences of the low-velocity recontact to the general space environment result in an overall low mission risk of spacecraft recontact.

Spaceflight notes that, as with any rideshare mission, there is a possibility that one or more customers will either not be ready, not be able to meet one or more of Spaceflight and/or SpaceX's readiness criteria for flight or, choose to remove their spacecraft from the mission. Removed customers will be replaced by a non-separating mass model to keep the various launch and mission analyses valid. Since the UFF and LFF do not have any attitude control system, the separation dispersion is dependent on the momentum change after each deployment. This momentum change is based on the specific mass of each spacecraft and the spring energy in their separation system. Therefore, replacing a separating customer spacecraft with a non-separating mass model will change the momentum of the respective Free Flyer, and thus the deployment vector for subsequent spacecraft. In such event, a new recontact analysis will be run to verify that the mission cumulative recontact probability is 0.002 or less. If the probability of recontact would be greater than this threshold, a new sequence will be developed and tested to ensure that this threshold is met.

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Spaceflight has met NASA’s Orbital Debris Office and Joint Space Operations Center (JSpOC) to address how the mission was organized to minimize recontact between spacecraft and Spaceflight’s probability analysis. At these meetings, representatives of both agencies expressed their concurrence with the analysis presented.

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ODAR Section 6: Assessment of Spacecraft Post-mission Disposal Plans and Procedures

6.1 Description of spacecraft disposal option selected: Both free-flyers (UFF and LFF) will de-orbit naturally by atmospheric re-entry with the use separate but identical DragSail systems from Surrey Space Centre. Once deployed (24 hours after launch), the DragSail provides 16 m² of drag area. Due to mounting constraints, some of this deployed area overlaps with free-flyer body drag area in certain orientations. Since neither free-flyer has attitude control, a simulation was developed to assess the projected drag area of 5400 equally-spaced orientations using 3D models of each free-flyer with the deployed de-orbit system. Two configurations were assessed for each free-flyer: a nominal mission case where all customer spacecraft are successfully deployed and a failed mission case where no customer spacecraft are deployed. For the failed mission scenarios, the 3D model is identical to that of the free-flyer's launch configuration save it be for the deployed de-orbit device.

6.2 Plan for any spacecraft maneuvers required to accomplish postmission disposal:

Neither the UFF nor LFF have propulsion or attitude control. There is no plan for postmission disposal maneuvers.

6.3 Calculation of area-to-mass ratio after postmission disposal, if the controlled reentry option is not selected:

Spacecraft Mass:

	Nominal Mission	Failed Mission
UFF	1,072 kg	2,271 kg
LFF	260 kg	421 kg

Cross-sectional Area: (arithmetic mean for random tumbling attitude)

	Nominal Mission	Failed Mission
UFF	12.372 m²	13.549 m²
LFF	8.235 m²	8.173 m²

Area to mass ratio: (arithmetic mean for random tumbling attitude)

	Nominal Mission	Failed Mission
UFF	0.011541 m²/kg	0.0059660 m²/kg
LFF	0.031675 m²/kg	0.0194364 m²/kg

6.4 Assessment of spacecraft compliance with Requirements 4.6-1 through 4.6-5 (per DAS v 2.1.1 and NASA-STD-8719.14 section):

Requirement 4.6-1: Disposal for space structures passing through LEO:
A spacecraft or orbital stage with a perigee altitude below 2000 km shall be disposed of by one of three methods:
(Requirement 56557)
a. Atmospheric reentry option:

- *Leave the space structure in an orbit in which natural forces will lead to atmospheric*

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reentry within 25 years after the completion of mission but no more than 30 years after launch; or

- *Maneuver the space structure into a controlled de-orbit trajectory as soon as practical after completion of mission.*

b. Storage orbit option: Maneuver the space structure into an orbit with perigee altitude greater than 2000 km and apogee less than GEO - 500 km.

c. Direct retrieval: Retrieve the space structure and remove it from orbit within 10 years after completion of mission.

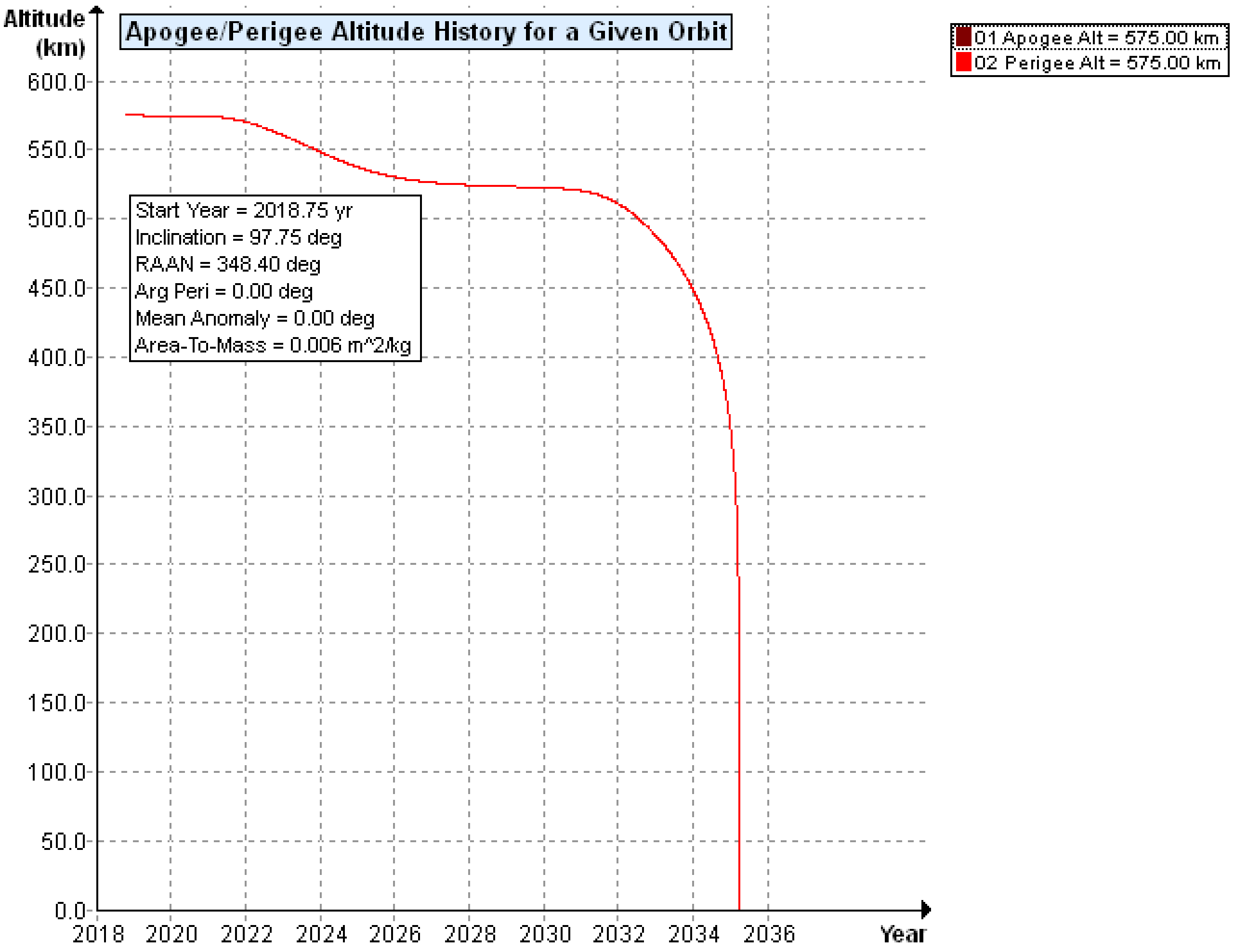

Figure 2 UFF (mission failure) orbit history with apogee (brown) & perigee (red)

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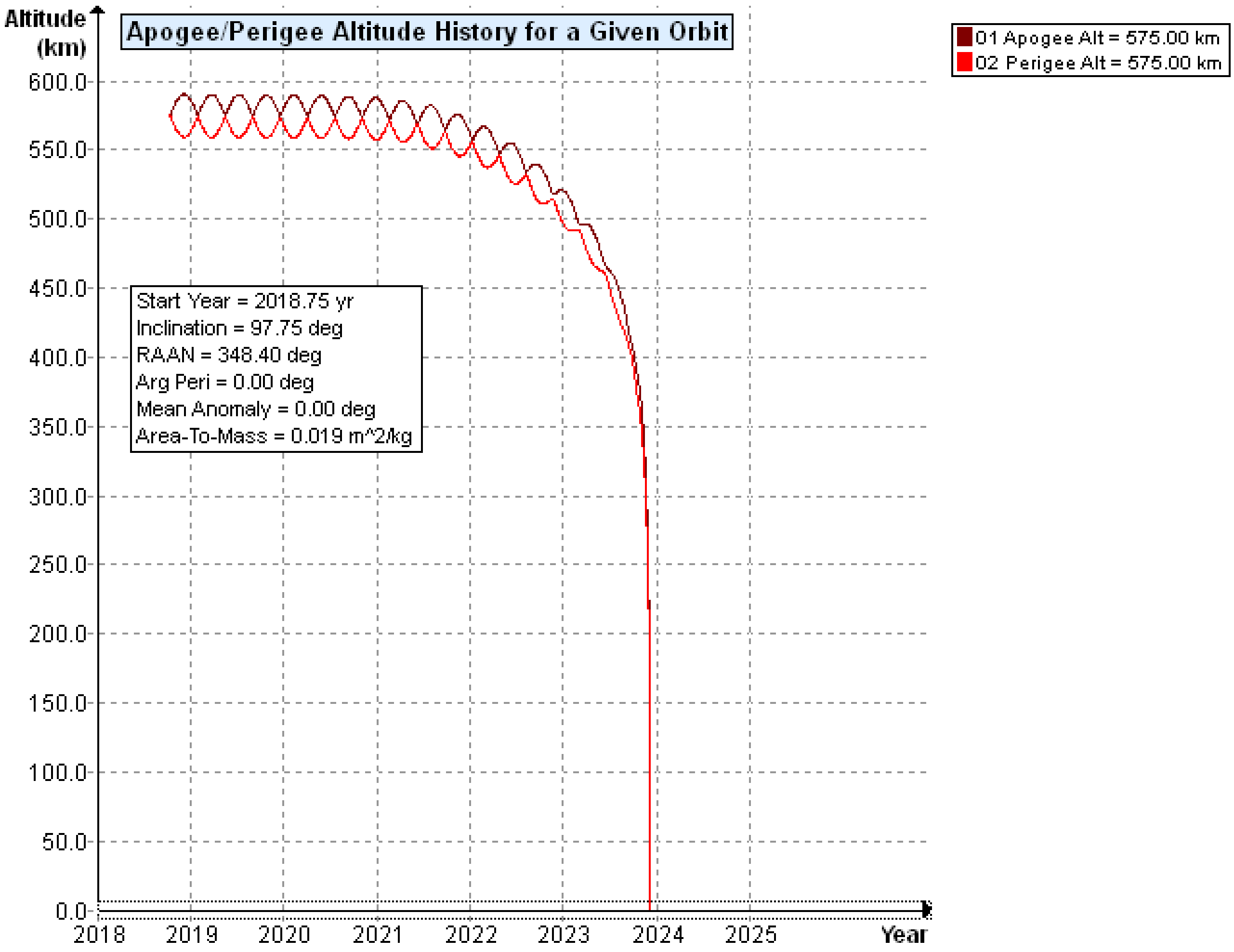

Figure 3 LFF (mission failure) orbit history with apogee (brown) & perigee (red)

Analysis: Both UFF and LFF satellite reentry is COMPLIANT using method “a”.

Satellite Name	UFF	LFF
BOL Orbit (Drop off)	575 x 575 km	
Operational Orbit	575 x 575 km	
EOM Orbit*	575 x 575 km	
Total Lifetime	7.2 years	4.3 years
Post-ops Life	7.2 years	4.3 years
Lifetime if Mission Failure	16.3 years	5.2 years

Requirement 4.6-2. Disposal for space structures near GEO.

Analysis: Not applicable.

Requirement 4.6-3. Disposal for space structures between LEO and GEO.

Analysis: Not applicable.

Requirement 4.6-4. Reliability of Postmission Disposal Operations

Reliability of DragSail: The DragSail has flight heritage on a similar system (InflateSail) which successfully operated in Low Earth Orbit on a previous flight. For the SSO-A Mission, the following changes have been made:

- The sail material has been replaced with one more resilient to degradation due to exposure to atomic oxygen. This sail material has been demonstrated on the International Space Station for eight months.
- The booms are slightly larger due to the increase size of the sail.
- The DragSail enclosure has been customized to the SSO-A mission mechanical interface as well as mechanical loads.

The SSO-A-specific configuration of the DragSail is in the process of a full qualification and acceptance test campaign. The DragSail electronic system is independent of the UFF and LFF avionics, and will not be impacted by an avionics system anomaly.

A more extensive description of the Dragsail system and flight heritage is attached as Annex A to this ODAR presentation.

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ODAR Section 7: Assessment of Spacecraft Reentry Hazards

Assessment of spacecraft compliance with Requirement 4.7-1:

> ***Requirement 4.7-1:*** Limit the risk of human casualty:
> *The potential for human casualty is assumed for any object with an impacting kinetic energy in excess of 15 joules:*
> *a) For uncontrolled reentry, the risk of human casualty from surviving debris shall not exceed 0.0001 (1:10,000) (Requirement 56626).*

Summary Analysis Results:

AHaB (Atmospheric Heating and Breakup) was used by the Aerospace Corporation to evaluate the UFF. The AHaB model reports 1:100,000 probability of human casualty due to the UFF reentry, and thus meets the requirement. The ceramic UHF antennas are the only components that survive reentry.

DAS calculates the LFF has a 1:18,800 risk of human casualty and thus that spacecraft meets the requirement.

> Requirements 4.7-1b, and 4.7-1c below are non-applicable requirements because the SSO-A Mission does not use controlled reentry.
>
> 4.7-1, b) **NOT APPLICABLE.** For controlled reentry, the selected trajectory shall ensure that no surviving debris impact with a kinetic energy greater than 15 joules is closer than 370 km from foreign landmasses, or is within 50 km from the continental U.S., territories of the U.S., and the permanent ice pack of Antarctica (Requirement 56627).
> 4.7-1 c) **NOT APPLICABLE.** For controlled reentries, the product of the probability of failure of the reentry burn (from Requirement 4.6-4.b) and the risk of human casualty assuming uncontrolled reentry shall not exceed 0.0001 (1:10,000) (Requirement 56628).

ODAR Section 8: Assessment for Tether Missions

Not applicable. There are no tethers in the SSO-A mission.

END of ODAR for the SSO-A Mission

Annex 1

SPACEFLIGHT

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Deorbit Device Summary for the SSO-A Mission 22 May 2018

Summary

Surrey Space Centre (Surrey, England) is providing a deorbit device based on their flight proven technology. The deorbit device is an atmospheric drag sail unit that will increase the surface area of both the Upper Free Flyer (UFF) and Lower Free Flyer (LFF) on Spaceflight's SSO-A Mission. The device creates increased drag and faster orbital decay. The DragSails are programed with a timer that will deploy the sail to begin the deorbit process after the SSO-A mission is complete. The DragSail is an independent unit; it does not need any external inputs such as power or commands to operate. The DragSail will be subjected to qualification testing, acceptance testing, and deployment functional tests to ensure it will operate on orbit. The DragSail components and functions have been demonstrated on the InflateSail mission in 2017 (https://www.surrey.ac.uk/surrey-space-centre/missions/inflatesail) and are installed on the RemoveDebris microsat that launched to the International Space Station on a Falcon9 rocket on 2 April 2018 (https://www.surrey.ac.uk/surrey-space-centre/missions/removedebris).

Functional Details

The DragSail is a 16m^2 sail structure consisting of 4 separate triangular quadrants. The quadrants are 'Z'-folded, then wrapped around a free spinning central hub. When actuated, the side panels of the DragSail are released, exposing the sail and booms to space. The deployment motor spins the central hub, which extends carbon fiber reinforced polymer (CFRP) bi-stable booms. The sails are suspended between the booms and unfurl as the booms deploy. Once the booms reach their maximum length, the motor turns off and the deployment is complete. A dedicated Electrical Initiator System (EIS) is used to provide long-term storage and on-demand power to the system without requiring any power or commands from the UFF or LFF. The DragSail has a dual redundant internal timer that activates upon separation from the launch vehicle, and is completely independent from the spacecraft avionics system. A video of a drag sail deployment can be viewed at https://www.youtube.com/watch?v=9LDbxmtwFY4

Figure 1: Deorbit Device in stowed configuration, deployed configuration, and the fully deployed sail.

Deorbit Lifetime

The UFF and LFF will each have their own independent deorbit device; the two devices are same model. Because the UFF is roughly four times heavier than the LFF, the UFF served as the design case for sail sizing. The sail is sized to deorbit the UFF in less than 25 years for the worst case scenario where the avionics are dead-on-orbit, and no customer spacecraft are separated. By DAS methodology calculation, the post-mission deorbit lifetimes for the LFF and UFF will be 4.3 years and 7.2 years, respectively. In the worst case in which the LFF and UFF avionics are dead-on-orbit, their post-mission deorbit lifetimes will be 5.2 years and 16.3 years.

Relevant Deorbit Device Heritage

Surrey Space Centre has extensive subsystem and full mission experience. Surrey Space Centre's latest accomplishments include leading the ESA Gossamer Deorbiter project and Astrium back CubeSail projects which resulted in integrated deorbit systems appropriate for microsats and CubeSats. Further heritage and history of Surrey Space Centre's devices are detailed below.

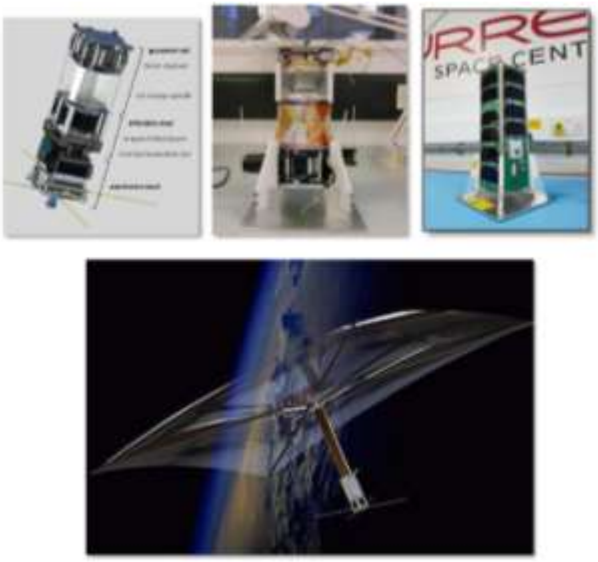
DeOrbitsail (2015)

The first university owned CubeSat from the United Kingdom was designed to demonstrate a deorbiting sail technology for mitigation of space-debris. Surrey Space Centre lead a consortium including JPL/CalTech, Astrium France and DLR to develop the mission. The DeOrbitSail payload consisted of four cartridged sail quadrants for a total 16m^2 sail area, deployed by driven carbon fiber booms. The project resulted in a stable platform, but the deorbiting sail payload failed to deploy. The issue was traced to a failure between the connections to the motor drive system. The lessons learned from this mission informed design, build and test processes which contributed to successful follow-on missions.

InflateSail (2017)

The InflateSail CubeSat demonstrated deployment of a dragsail and a novel inflatable boom system to provide passive spacecraft stability. The debris removal demonstration payload occupies approximately 2U of the 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 fiber reinforced polymer booms. The remaining 1U volume contains the spacecraft core avionics. The payload section was held in an ambient storage state for three years prior to launch to demonstrate long term storage capability. Launched on June 23, 2017, the mission achieved rapid success through a successful deorbit from a 500km altitude orbit in only 72 days. InflateSail was the first successfully deployed sail from a European spacecraft and the first successful use of inflatable structures on a CubeSat. The InflateSail mission provides in-orbit demonstration of key technologies being used in the upcoming RemoveDebris mission and is the basis for the DragSails to be used by Spaceflight.

Figure 2: SSC's InflateSail mission launched in 2017.



RemoveDebris

The RemoveDebris mission is a collaboration of major European organizations led by Surrey Space Centre to demonstrate active debris removal technologies in orbit. The RemoveDebris mission is based around a 100kg class microsat provided by Surrey Satellite Technology Ltd. hosting multiple payloads, including two active target CubeSats developed by Surrey Space Centre. These CubeSats act as uncooperative targets for tracking and net retrieval, making use of a Surrey Space Centre developed inter-satellite link to transmit attitude and orbital data. The RemoveDebris mission is planned to deploy from the International Space Station in 2018 after undergoing extensive qualification to provide high level NASA for delivery to the station.

The final demonstration of the RemoveDebris Mission is to deorbit the spacecraft via the DragSail system. This payload is based on the InflateSail payload with adapted mechanical interfaces. The Dragsail makes use of an inflatable boom system prior to sail deployment of $10m^2$. The Dragsail payload is powered from the RemoveDebris spacecraft with an in-built automatic sequence deploying the sail within 15 minutes of switch on.

Heritage Systems on DeorbitSail

The DragSail builds upon the flight heritage of the earlier systems referenced above The DragSail uses the same boom deployer, sail deployer, and Electrical Controller System (ECS) as on previous missions. DragSail uses the same booms, hold down and release mechanism, hinged springs, and harnessing as previous mission which have been modified to accommodate the DragSail size. The new design elements on DragSail include the sail, body chassis, panels, Electrical Imitator System (EIS) and battery pack. The sail is an improved design provided by JAXA (Japanese Space Agency) and the EIS is a more robust and capable design to meet the SSO-A mission requirements.

References

Surrey Space Centre, "Deorbit Device Proposal", 11 January 2018
Surrey Space Centre, "SpaceFlight DragSail Preliminary Design Review", 13 March 2018