Orbital Debris Assessment Report (ODAR) for the Orbital Test Bed (OTB) Satellite

Document Number

OTB-DOC-000638-03

Dated: June 2015

This document supports the Surrey Satellite Technology US Orbital Test Bed Satellite FCC license and has been prepared in accordance with:

NASA Technical Standard NASA-STD-8719.14A (inc change 1, 25-5-2012) Process for Limiting Orbital Debris.

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DAS Software version used in analysis V 2.0.2

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APPROVALS

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APPROVAL AGENCY

Program / Project Management…………………..……………………………………………………… Dated ………………………

Office of Safety and Mission Assurance - Orbital Debris Manager………………………….Dated ………………………

Sponsoring Mission Directorate Associate Administrator …………………………………….Dated ………………………

Chief Safety and Mission Assurance (FDR ODAR)……………………………… ……..Dated………………………

RECORD OF REVISIONS

Rev	Date	Author	Description of changes
1	Aug '13	M Brown	Initial issue for comment
2	Aug '13	M Brown	Addition of Section 7A hazardous materials data. Updated spacecraft design information.
3	Apr '15	T Murphy	Updated contacts in 1.1.2, updates to sections 1.1.4, 1.1.7, 2.1.9, 6.1.4, and 6.1.6, figures 2-1 and 2-2 updated, as well as minor grammatical corrections throughout

APPLICABLE DOCUMENTS

1) NASA Technical Standard NASA-STD-8719.14A (inc change 1, 25-5-2012) Process for Limiting Orbital Debris.

2) NASA Debris Assessment Software (DAS) V 2.0.2

3) GUIDANCE ON OBTAINING LICENSES FOR SMALL SATELLITES DA: 13-445 Released: March 15, 2013. Federal Communications Commission 445 12th St., S.W. Washington, D.C. 20554

4) Background Information on the Orbital Test Bed Satellite for the FCC. Document Number OTB-DOC-000639-02, August 2013. Surrey Satellite Technology, US LLC. 345 Inverness Drive South, Suite 100, Englewood, CO 80112.

TABLE OF CONTENTS

ODAR SELF ASSESSMENT

Orbital Debris Assessment Report Evaluation: Orbital Test Bed Mission

Note: SST-US is not responsible for the launch vehicle ODAR.

Reqm't #	Launch Vehicle				Spacecraft			Comments
	Complaint	Not Compliant	Incomplete	Standard Non-Compliant	Compliant or N/A	Not Compliant	Incomplete	Note: SST-US is not responsible for the launch vehicle ODAR.
4.3-1.a	☐	☐	☐	☐	x	☐	☐	
4.3-1b	☐	☐	☐	☐	x	☐	☐	
4.3-2	☐	☐	☐	☐	x	☐	☐	
4.4-1	☐	☐	☐	☐	x	☐	☐	
4.4-2	☐	☐	☐	☐	x	☐	☐	
4.4-3	☐	☐	☐	☐	x	☐	☐	
4.4-4	☐	☐	☐	☐	x	☐	☐	
4.5-1	☐	☐	☐	☐	x	☐	☐	
4.5-2	☐	☐	☐	☐	x	☐	☐	
4.6-1(a)	☐	☐	☐	☐	x	☐	☐	
4.6-1(b)	☐	☐	☐	☐	x	☐	☐	
4.6-1(c)	☐	☐	☐	☐	x	☐	☐	
4.6-2	☐	☐	☐	☐	x	☐	☐	
4.6-3	☐	☐	☐	☐	x	☐	☐	
4.6-4	☐	☐	☐	☐	x	☐	☐	
4.7-1	☐	☐	☐	☐	x	☐	☐	
4.8-1	☐	☐	☐	☐	x	☐	☐	

PREAMBLE

This document has been prepared in accordance with reference [1] using DAS software version 2.0.2 [2].

This document supports Surrey Satellite technology's application for an experimental license [3].

Further supporting information is provided in reference [4].

1. PROGRAM MANAGEMENT AND MISSION OVERVIEW

1.1.1 Identification of the Headquarters Mission Directorate sponsoring the mission and the Program Executive.

Surrey Satellite Technology US LLC (SST-US) is a Delaware corporation with its principal place of business at 345 Inverness Drive South, Suite 100, Englewood, Colorado, 80112.

1.1.2 Identification of the responsible program / project manager and senior scientific and management personnel.

William Thompson – Project Manager	**wthompson@sst-us.com**
Matt Yavorsky – Systems Engineer	**myavorsky@sst-us.com**
Doug Gerull – Chief Operating Officer	**dgerull@sst-us.com**
Becky Yoder – Chief Financial Officer	**byoder@sst-us.com**

1.1.3 Identification of any foreign government or space agency participation in the mission and a summary of NASA's responsibility under the governing agreement(s).

1) Foreign government or space agency – none.

2) A significant payload hosted by the OTB satellite is the Deep Space Atomic Clock (DSAC) provided by NASA / Jet Propulsion Laboratory (JPL) under sub-contract number 1468935-04 to SST-US.

1.1.4 Clear schedule of mission design and development milestones from NASA mission selection through proposed launch date, including spacecraft PDR and CDR (or equivalent) dates.

Preliminary Design Review	**18th September 2013**
Critical Design Review	**January 2014**
Payload Integration	**October 2015**
Flight Readiness Review	**April 2016**

1.1.5 Brief description of the mission.

The SST-US 'Orbital Test Bed' (OTB) satellite is an internally funded small LEO experimental satellite that will provide an in-orbit test bed for the experimentation and demonstration of scientific, research and prototype payloads, subsystems and equipments. A number of 'hosted' payloads are sponsored by external parties:

1. **Deep Space Atomic Clock (DSAC) – sponsored by the Jet Propulsion Laboratory (JPL) under subcontract No 1468935. http://www.nasa.gov/mission_pages/tdm/clock/**

2. **iMESA-R – A space weather monitor built by the USAF Academy and sponsored through AFRL (Space Experiments Review Board (SERB)). http://www.usafa.edu/df/dfe/dfer/centers/sparc**

3. **Modular Solar Array (MSA) - built by Vanguard and sponsored through AFRL (Space Experiments Review Board (SERB)).**

4. **CUSP - A microprocessor and memory storage experiment built by the University of Colorado at Boulder. www.colorado.edu**

5. **SSC Electronics Test Bed – An experiment designed to monitor the effects of spaceflight on new electronics components, co-sponsored by the Surrey Space Centre at the University of Surrey and SST-US.**

In addition, SST-US primary payloads are also included:

1. **FlexRx – A new spacecraft RF receiver design.**

2. **Radiation Monitor – A new spacecraft radiation monitor device.**

3. **Custom Experimental Solar Panel – A new solar panel technology.**

1.1.6 Identification of anticipated launch vehicle and launch site.

SpaceX (Falcon Heavy Launch Vehicle), STP-2 (US Air Force). Space Launch Complex 40 at Cape Canaveral AFS. SST-US is not sponsoring the launch.

1.1.7 Identification of the proposed launch date and mission duration.

Launch date from 2016 onwards. Mission duration is 5 years.

1.1.8 Description of the launch and deployment profile, including all parking, transfer and operational orbits with apogee, perigee and inclination.

OTB has no means of altering the orbit into which it is delivered. The orbit will be a 720km +/-18.5 km altitude LEO circular orbit of 24deg inclination.

1.1.9 Reason for selection of operational orbit(s) (such as ground track, SSO, GEO sync, instrument resolution, co-locate with other spacecraft,….)

OTB is an evolved heritage design based on previous Surrey missions which is inherently designed for operation in LEO. As there are no imaging experiments and the ground track / instrument resolution is not a requirement, a LEO orbit is adequate. The selection of operational orbit is based on timeframe for launch and the available shared launch opportunity.

1.1.10 Identification of any interaction or potential physical interference with other operational spacecraft (Note: This does not include potential for RF interaction unless it affects the risk of generating orbital debris.)

None identified.

2. SPACECRAFT DESCRIPTION

2.1.1 Physical description of the spacecraft, including spacecraft bus, payload instrumentation, and all appendages, such as solar arrays, antennas, and instrument or attitude control booms.

Overview

The OTB satellite is an evolution of the ESPA compatible SSTL-150 spacecraft, first flown in 2007 for LANL. http://www.sst-us.com/downloads/datasheets/sstl_150-feb-09

The avionics suite is based on a heritage set of units with minor updates for mission specific requirements. The outline OTB platform block diagram is shown in figure 2-1 and the physical configuration of the OTB satellite inc. solar arrays, antennae etc. is shown in figure 2-2.

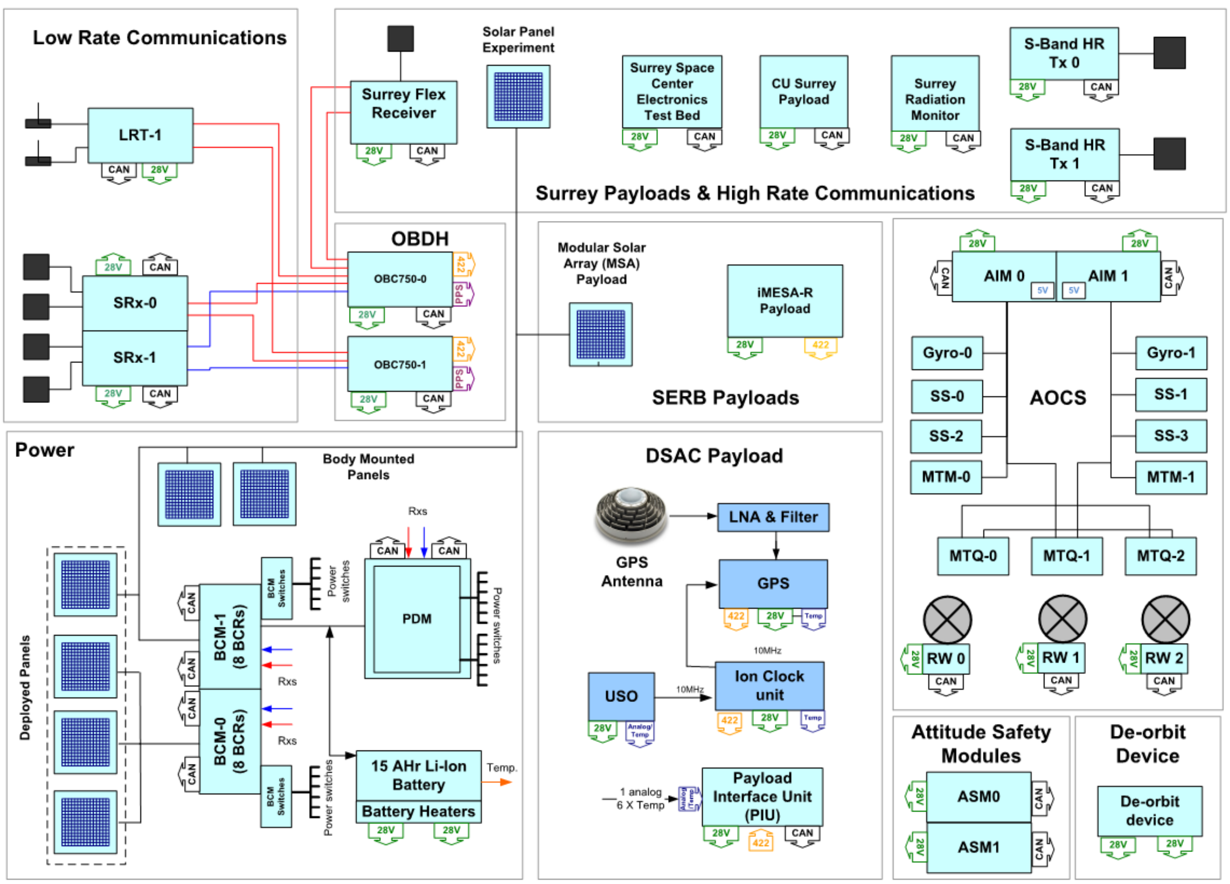


Figure 2-1 OTB platform block diagram

Acronyms

AOCS – Attitude & Orbit Control System; AIM – Attitude Interface Module; BCM – Battery Charge Module; LNA – Low Noise Amplifier; LRT – Low Rate Transmitter; MTM – Magnetometer; MTQ – Magnetorquer; OBDH – On Board Data Handling; PCM – Power Conditioning Module; RW – Reaction Wheel; SRx – S Band Receiver; SS – Sun sensor USO – Ultra-stable Oscillator.

2.1.2 Detailed illustration of the entire spacecraft in the mission operation configuration with clear overall dimensional markings and marked internal component locations.

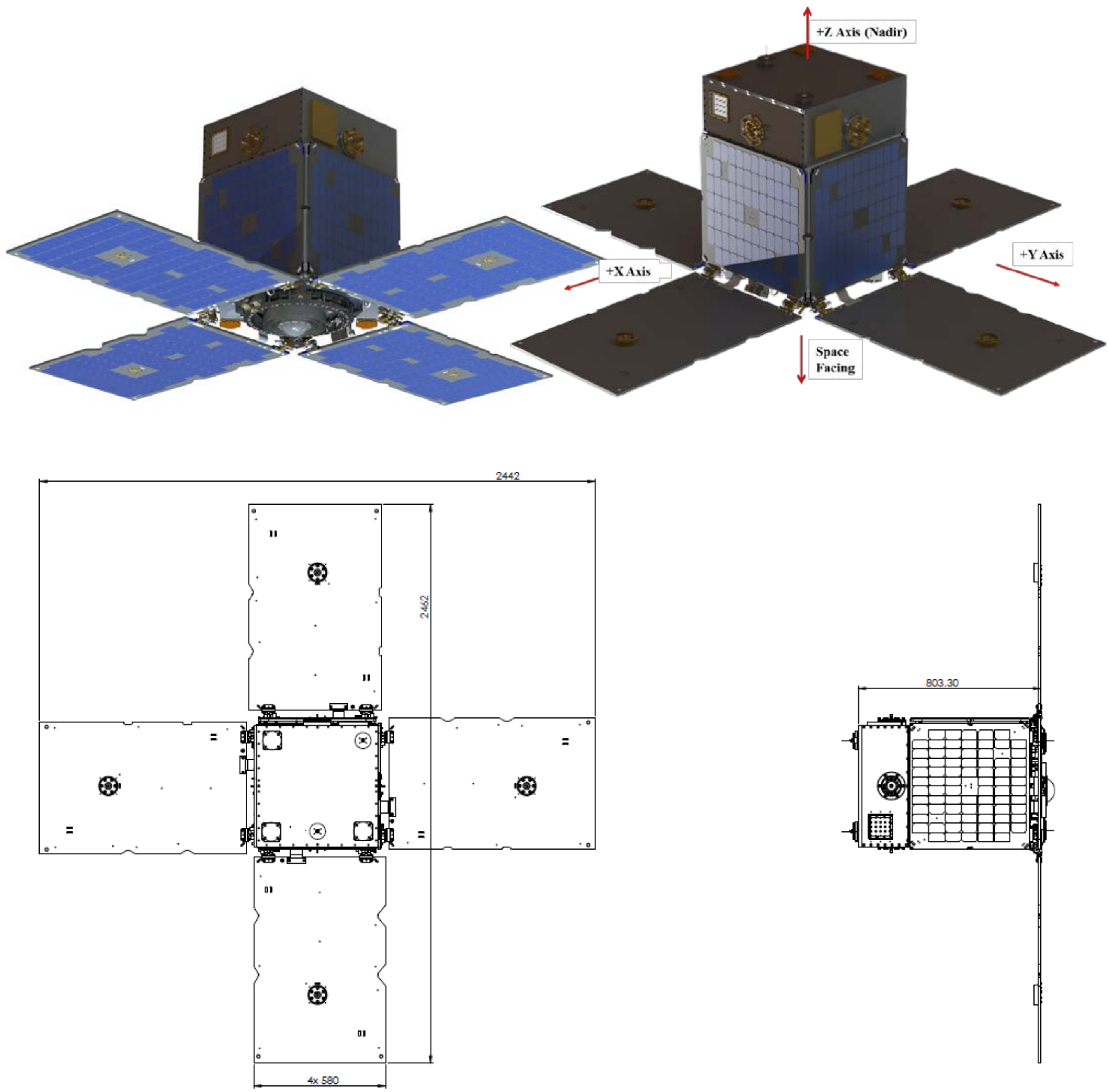


Figure 2-2 OTB physical configuration (units in mm)

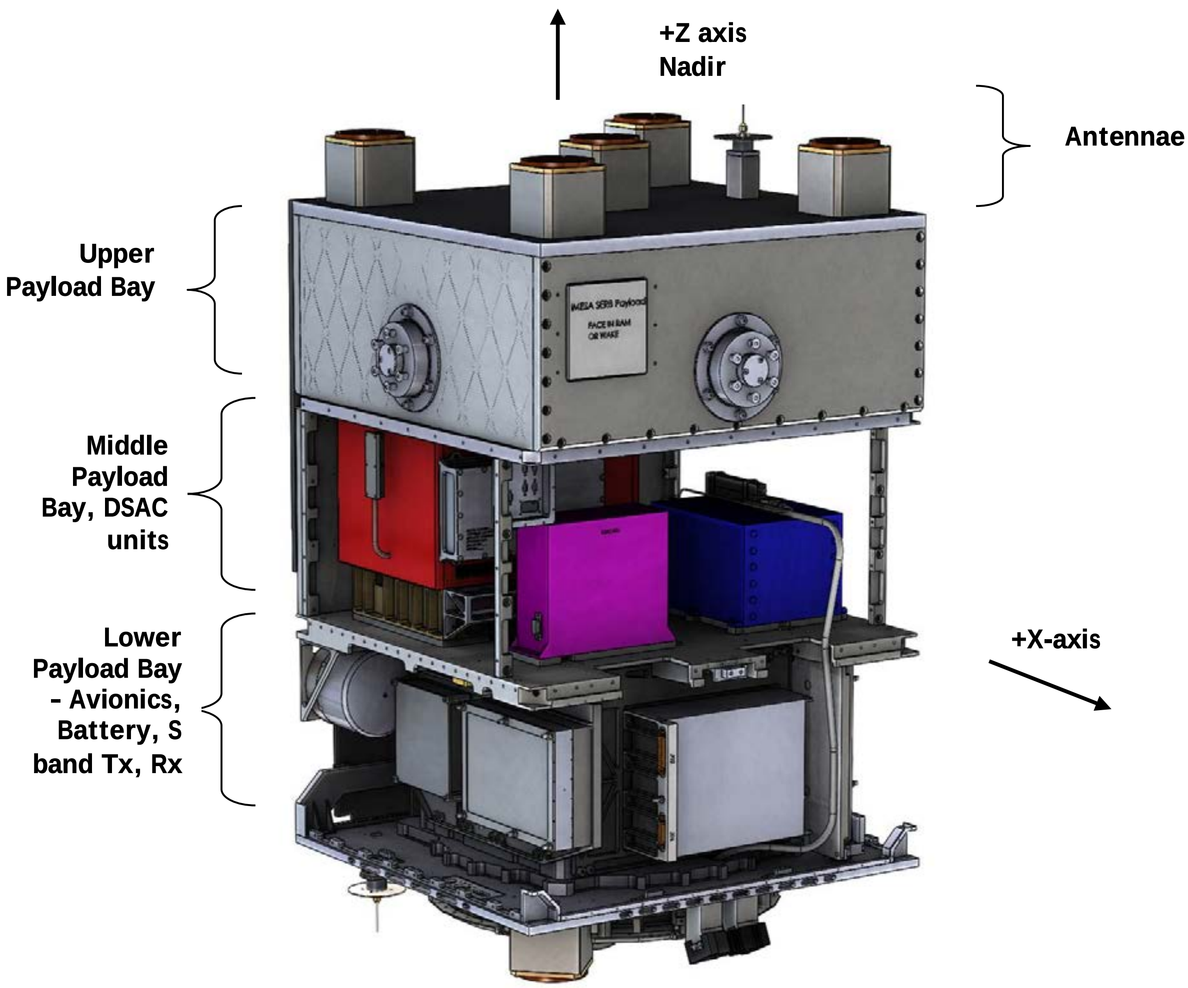


Figure 2-3 Outline of OTB satellite configuration (solar panels removed).

2.1.3 Total spacecraft mass at launch, including all propellants and fluids.

The total spacecraft mass of the OTB at launch is 180kg (maximum).

2.1.4 Dry mass of spacecraft at launch, excluding solid rocket motor propellants.

The total dry mass of the OTB at launch is 180kg maximum (there is no propulsion system).

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

None.

2.1.6 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. Description of all fluid systems including size, type and qualifications of fluid containers such as propellant and pressurization tanks including pressurized batteries.

There are no propellant or pressurization tanks within OTB. Consequently a fluid loading plan / strategy is not required.

OTB will fly the flight proven ABSL 8s10p Lithium-ion battery that employs the commercial SONY 18650HC cell. The contents of this cell are held at 1 bar with all cells having a pressure release device that provides a safe rupture to vent ratio according to recommended NASA safety standards.

2.1.7 Description of all active and/or passive attitude control systems with an indication of the normal attitude of the spacecraft with respect to the velocity vector.

The co-ordinate system of the OTB is indicated in figure 2-2, with the earth pointing on the Z-axis, the velocity vector along the X-axis and the orbital normal along the Y-axis.

The OTB satellite utilizes three Surrey designed and built heritage reaction wheels for attitude control, together with three Surrey heritage magnetorquers for de-saturation of the reaction wheels. In addition, sun sensors, gyros and magnetometers also form part of the Attitude & Orbit Control System as shown in the block diagram, Figure 2-1.

2.1.8 Description of any range safety or other pyrotechnic devices.

There are no pyrotechnic devices within the OTB satellite.

2.1.9 Description of the electrical generation and storage system.

The OTB bus has four deployable solar panels and four body-mounted panels, of which two are experimental, see Figure 2-2. The power from the solar panels is used to charge a single flight proven ABSL 8s10p Lithium-Ion battery manufactured by ABSL which provides an unregulated power supply to downstream subsystems.
http://www.abslspaceproducts.com/Default.aspx?pid=5&subid=19
Power is supplied from the battery to the Power Distribution Module (PDM) units. The PDM controls the switching of the 28V unregulated battery supply to spacecraft subsystems.

2.1.10 Identification of any other sources of stored energy not noted above.

The deployable solar panels are deployed using the SSTL hold down and release system (HDRS, see section 3). No debris is produced during solar panel deployment.

2.1.11 Identification of any radioactive materials on board or make a positive statement that there are no radioactive materials onboard.

There are no radioactive materials onboard the OTB satellite.

3 ASSESSMENT OF SPACECRAFT DEBRIS RELEASED DURING NORMAL OPERATIONS

3.1.1 Identification of any object (>1 mm) expected to be released from the spacecraft any time after launch, including object dimensions, mass, and material.

None - there are no intentional releases from OTB; all deployment systems are self-contained entities.

The deployment systems are:

1) <u>SSTL Hold Down and Release System</u>.

The Hold Down and Release System (HDRS) for the deployable solar panels is a Surrey in-house design. This system utilises captive devices on both sides of the interface (retention of bolt and springs) and as such does not generate debris.

2) <u>Planetary Systems Corporation Separation System ('Lightband')</u>

Planetary Systems Corporation states within their '2000785 Rev C User's Manual for Mark II Lightband, 2nd April 2013 (section 3, point 5) '*Non-pyrotechnic. The Lightband generates no debris on or after separation'*. *http://www.planetarysystemscorp.com/#!__products/mark-ii-motorized-lightband*

3) <u>Tethers Unlimited NanoSat Terminator Tape (nTT)</u>

The Tethers Unlimited NanoSat Terminator Tape (nTT) design utilizes a 'Frangibolt', a non-pyrotechnic release system to deploy the de-orbit tether device. The nTT is designed to remain attached to the spacecraft for the duration of de-orbit and does not generate debris during deployment or operation.

3.1.2 Rationale/necessity for release of each object.

N/A – no objects are released.

3.1.3 Time of release of each object, relative to launch time.

N/A – no objects are released.

3.1.4 Release velocity of each object with respect to spacecraft.

N/A – no objects are released.

3.1.5 Expected orbital parameters (apogee, perigee, and inclination) of each object after release.

N/A – no objects are released.

3.1.6 Calculated orbital lifetime of each object, including time spent in Low Earth Orbit (LEO).

N/A – no objects are released.

3.1.7 Assessment of spacecraft compliance with Requirements 4.3-1 and 4.3-2.

Compliant – no debris released.

Requirement 4.3-1: *Debris passing through LEO – released debris with diameters of 1mm or larger:*

a. Requirement 4.3-1a: All debris released during the deployment, operation, and disposal phases shall be limited to a maximum orbital lifetime of 25 years from date of release (Requirement 56398).

Compliant – no debris released.

b. Requirement 4.3-1b: The total object-time product shall be no larger than 100 object-years per mission (Requirement 56399). The object-time product is the sum of all debris of the total time spent below 2,000 km altitude during the orbital lifetime of each object. (See section 4.3.4.2 for methods to calculate the object-time product.)

Compliant – no debris released.

Requirement 4.3-2: *Debris passing near GEO: For missions leaving debris in orbits with the potential of traversing GEO (GEO altitude +/- 200 km and +/- 15 degrees latitude), released debris with diameters of 5 cm or greater shall be left in orbits which will ensure that within 25 years after release the apogee will no longer exceed GEO - 200 km (Requirement 56400).*

DAS will be used to assess compliance against these requirements.

Compliant – no debris released.

4. ASSESSMENT OF SPACECRAFT INTENTIONAL BREAKUPS AND POTENTIAL FOR EXPLOSIONS

4.1.1 Identification of all potential causes of spacecraft breakup during deployment and mission operations.

The spacecraft is a heritage design and has undergone rigorous structural acceptance testing during qualification. There are no pressurized systems on board and no propulsion system.

OTB will fly the flight proven ABSL 8s10p Lithium-ion battery that employs the commercial SONY 18650HC cell. The contents of this cell are held at 1 bar with all cells having a pressure release device that provides a safe rupture to vent ratio according to recommended NASA safety standards.

No credible potential causes of spacecraft breakup during deployment or mission operations are foreseen.

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

The only device that stores a sufficient amount of energy to cause an accidental explosion is the flight proven, heritage ABSL 8s10p battery. This unit has flown on 31 spacecraft to date and the SONY 18650HC cell that it employs has accrued more than 59,000 cell years in orbit without any safety events in space. Before launch, the battery is charged and then disconnected from the spacecraft. It is only connected to the spacecraft power system upon separation from the launch vehicle so it presents no credible risk during the launch phase of the mission.

Upon separation and during operations, the battery will be cycled at a benign depth of discharge of less than 15% with an end of charge voltage of 32.8V. The power system is a heritage design and has battery charge and discharge safety functionality that has been proven on numerous other Surrey Satellite Technology spacecraft including RapidEye, UK-DMC-2, Deimos and exactView-1.

There are three possible failure modes for the battery:

1. **Overcharge of Lithium-ion batteries above the recommended maximum end of charge voltage of 33.6V could result in thermal runaway. To prevent this, the battery voltage is constantly monitored by the power subsystem and charging is halted if this voltage is exceeded. In the event of the failure of this safety circuitry, the ABSL 8s10p cells contain internal protection devices that result in open circuit shutting down the entire battery. This functionality has been demonstrated via a number of ground tests.**

2. **Short circuit of Lithium-ion batteries can result in very high current draw that lead to heating and could invoke thermal runaway. To prevent this, the spacecraft has fused or switched power lines to all components so that high current draw effects are halted before the battery can be affected. In addition, in the event of fuse failure, the ABSL 8s10p cells carry short circuit protection devices that detect a rise in temperature and increase the internal resistance reducing current flow mitigating a rise in temperature.**

3. **Over discharge of the ABSL 8s10p, where the battery was taken below the minimum recommended operating voltage of 20V, has been proven by test to degrade battery performance but not pose a safety risk. Overcharge tests where ABSL 8s10p cells have been driven to negative voltage have been shown to result in a safe failure with cells effectively becoming resistors. In addition, the power system of the satellite will switch off below approx. 20V to limit the discharge of the battery below this point.**

In summary, there are no credible failure modes which would cause an accidental explosion.

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

N/A – there are no intentional breakups; explosions and intentional collisions planned.

4.1.4 List of components which are passivated at EOM. List includes method of passivation and amount which cannot be passivated.

At End of Mission (EOM), all units except the power system and the RF receivers will be turned off. The battery will continue to charge and discharge at a very low depth of discharge to the nominal end of charge level set via telecommand. The design of the heritage power system is such that the battery cannot be disconnected from the power system at EOM.

Reaction wheels are stopped in a controlled manner as part of EOM operations. An end of charge voltage of 31V will be selected (the minimum possible) that will result in the battery being at a state of charge <50% and minimize the energy available for any failure event. Ground and in-orbit life test data indicate an expected graceful degradation of the battery with effective battery capacity reducing over time, eventually leading to a safe state through the absence of useful capacity.

4.1.5 Rationale for all items which are required to be passivated, but can not be due to their design.

Please see response to 4.1.4 on the battery. The battery cannot be completely passivated (discharged to 0% state of charge and disconnected from the power system) due to heritage system design.

4.1.6 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).*

Compliant - given the qualitative analysis above, Surrey see no credible risk of spacecraft explosion (caused by the spacecraft itself without external impact) during launch, nominal operations and the time between EOM and Earth re-entry.

The only credible source of energy that could cause an accidental explosion is the Lithium-ion battery which has flown on 31 spacecraft to date without incident and the ABSL 18650HC (the individual cell used to make up the battery) has accrued 59,000 cell years of safe space operation.

With reference to the failure modes analyses and safety features inherent in the heritage design of the spacecraft and battery as detailed in the sections above, there are no credible failure modes which would cause an accidental explosion.

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 and a plan to deplete all onboard sources of stored energy and disconnect all energy generation sources when they are no longer required for mission operations or post mission disposal or control to a level which can not cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft (Requirement 56450)*

Compliant – see section 4.1.4 above.

Requirement 4.4-3. *Limiting the long-term risk to other space systems from planned breakups: Planned explosions or intentional collisions shall:*

a. Be conducted at an altitude such that for orbital debris fragments larger than 10 cm the object-time product does not exceed 100 object-years (Requirement 56453). For example, if the debris fragments greater than 10cm decay in the maximum allowed 1 year, a maximum of 100 such fragments can be generated by the breakup.

b. Not generate debris larger than 1 mm that remains in Earth orbit longer than one year (Requirement 56454).

Not applicable – OTB will not undertake any planned explosions or intentional collisions.

Requirement 4.4-4: *Limiting the short-term risk to other space systems from planned breakups: Immediately before a planned explosion or intentional collision, the probability of debris, orbital or ballistic, larger than 1 mm colliding with any operating spacecraft within 24 hours of the breakup shall be verified to not exceed 10-6 (Requirement 56455).*

Not applicable – OTB will not undertake any planned explosions or intentional collisions.

5. ASSESSMENT OF SPACECRAFT POTENTIAL FOR ON-ORBIT COLLISIONS

5.1.1 Calculation of spacecraft probability of collision with space objects larger than 10 cm in diameter during the orbital lifetime of the spacecraft.

Analysis: **The NASA DAS software [2] was used to assess compliance of the OTB spacecraft with Requirement 4.5-1. The probability of collision with large objects was calculated to be 0.00045 during the orbital lifetime, which is compliant with the requirement.**

5.1.2 Calculation of spacecraft probability of collision with space objects, including orbital debris and meteoroids, of sufficient size to prevent post mission disposal.

Analysis: **The units listed in Table 5-1 are critical to completing post-mission disposal activities. Each unit is listed with its individual Probability of Penetration value, as calculated by the DAS [2]. The OTB spacecraft will enter the EOM phase of operations in the nominal, nadir-pointing attitude, and it will remain nadir-pointing until the de-orbit device is deployed. The critical surface of the units will therefore be in the plane of the direction of motion.**

During the EOM phase, the flight computer will receive the de-orbit command from the ground through the S-band patch antennas and the receiver. The onboard computer will then command the de-orbit device to deploy, which will begin to de-orbit the spacecraft. For these actions to occur, the power system must also be active, along with the harness required for interface between the individual components.

An extra level of protection to the critical units is provided by Surrey's standard dual-redundant design approach. Each of the units listed in Table 5-1, aside from the de-orbit device, are redundant. In the unlikely event of a unit being damaged during the operational phase, the de-orbit device could still be deployed by the redundant components.

Critical Surface	Probability of Penetration
De-orbit device	0.001185
Patch antenna	0.000268
On Board Computer	0.000001
S-band Receiver	0.000000
Power System	0.000000

Table 5-1: Critical units/surfaces

The total probability of post-mission disposal failure is 0.001454, which is compliant with the requirement.

5.1.3 Assessment of spacecraft compliance with Requirements 4.5-1 and 4.5-2.

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).

> **Compliant - the probability of collision with large objects was calculated by DAS [2] to be 0.00045 during the orbital lifetime, which is compliant with the requirement, figure 5-1.**

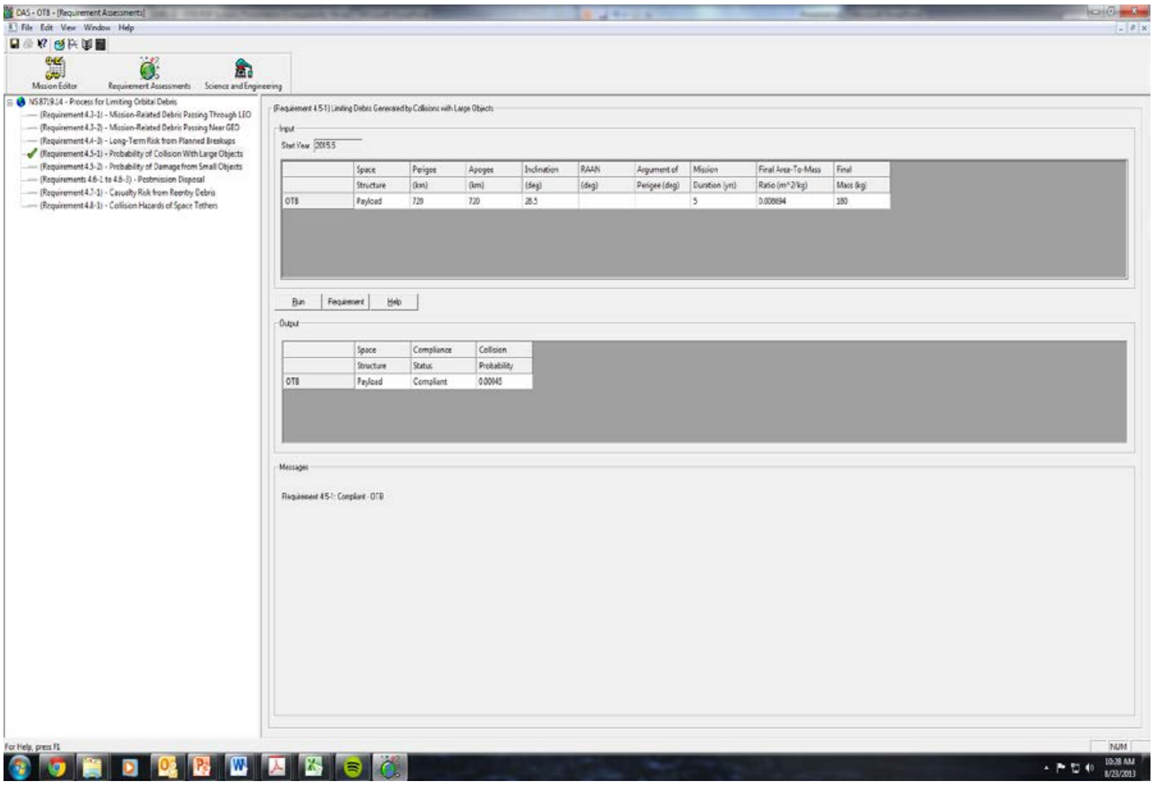


Figure 5-1 DAS output for requirement 4.5-1

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 post mission disposal requirements is less than 0.01 (Requirement 56507).

> **Compliant - the probability of accidental collision with orbital debris and meteoroids sufficient to interfere with post-mission disposal was calculated by DAS [2] to be less than 0.001454, which is compliant with the requirement, figure 5-2.**

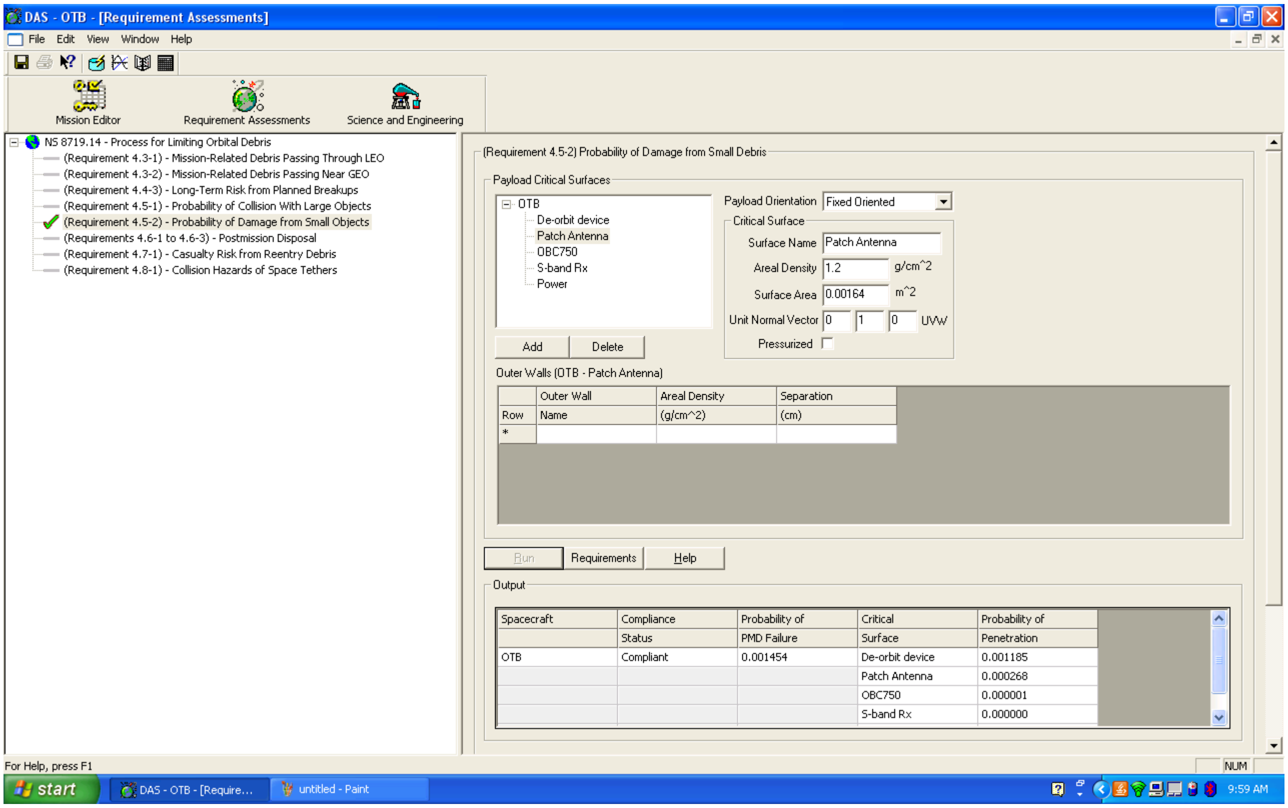


Figure 5-2 DAS output for requirement 4.5-2

Summary: **The OTB spacecraft was found to be compliant by DAS [2] with both Requirement 4.5-1 and 4.5-2.**

Requirement	DAS Calculated Probability [2]	Compliant?
4.5-1: The probability of accidental collision with space objects larger than 10 cm in diameter is less than 0.001	0.00045	Yes
4.5-2: The probability of accidental collision with orbital debris and meteoroids sufficient to interfere with post-mission disposal is less than 0.01	0.001454	Yes

Table 5-2: Compliance Summary

6. ASSESSMENT OF SPACECRAFT POSTMISSION DISPOSAL PLANS AND PROCEDURES

6.1.1 Description of spacecraft disposal option selected.

The spacecraft will de-orbit naturally by atmospheric re-entry following the deployment of the Tethers Unlimited NanoSat Terminator Tape (nTT). The nTT device uses two mechanisms to de-orbit the spacecraft – 1) the increased area to mass ratio increases the atmospheric drag and 2) the tape utilizes passive electromagnetic drag. There is no propulsion system.

6.1.2 Identification of all systems or components required to accomplish any post mission disposal operation, including passivation and maneuvering.

The Tethers Unlimited nTT tape requires the spacecraft command system to issue a command to "deploy" the nTT by activating a power switch. Upon the application of power to the nTT, a Frangibolt breaks and the tape deploys. A redundant firing circuit is integrated in the Frangibolt to insure proper deployment and is connected to a second power switch that can be activated if the primary circuit fails.

Section 4.1.4 details those devices passivated at EOM. The OTB satellite cannot be maneuvered.

6.1.3 Plan for any spacecraft maneuvers required to accomplish post mission disposal.

No maneuvers are required for the proper deployment of the nTT. Following deployment, gravity gradient forces will align the tape with the local vertical direction. This will orient the OTB spacecraft so that it is in the proper orientation for de-orbit.

6.1.4 Calculation of area-to-mass ratio after post mission disposal, if the controlled reentry option is not selected.

Spacecraft Mass: 180kg (Maximum)
Cross-sectional Area: 1.92m^2 (OTB) plus 10.64m^2 (deployed tape) = 12.56m^2
Area to mass ratio: 0.07m^2/kg

6.1.5 If appropriate, preliminary plan for spacecraft controlled reentry. **N/A**

6.1.6 Assessment of spacecraft compliance with Requirements 4.6-1 through 4.6-4.

Requirement 4.6-1. *Disposal for space structures in or passing through LEO: A spacecraft or orbital stage with a perigee altitude below 2,000 km shall be disposed of by one of the following three methods: (Requirement 56557)*

a. Atmospheric reentry option:
- *Leave the space structure in an orbit in which natural forces will lead to atmospheric 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.

Analysis: The OTB satellite reentry is compliant using reentry option "a". At mission completion, the OTB satellite will deploy the nTT device to begin reentry. Following the deployment of the nTT device, the OTB satellite will reenter after approximately 9.5 years. This reentry timeline is less than the 30 year EOM requirement (inc. mission duration of 5 years), figure 6-1. Figure 6-1 also

shows the effect on de-orbit time of the tape being severed at half its length, causing de-orbit time to increase to approximately 13 years.

Requirements 4-6-1(b) and 4-6-1(c) are not applicable.

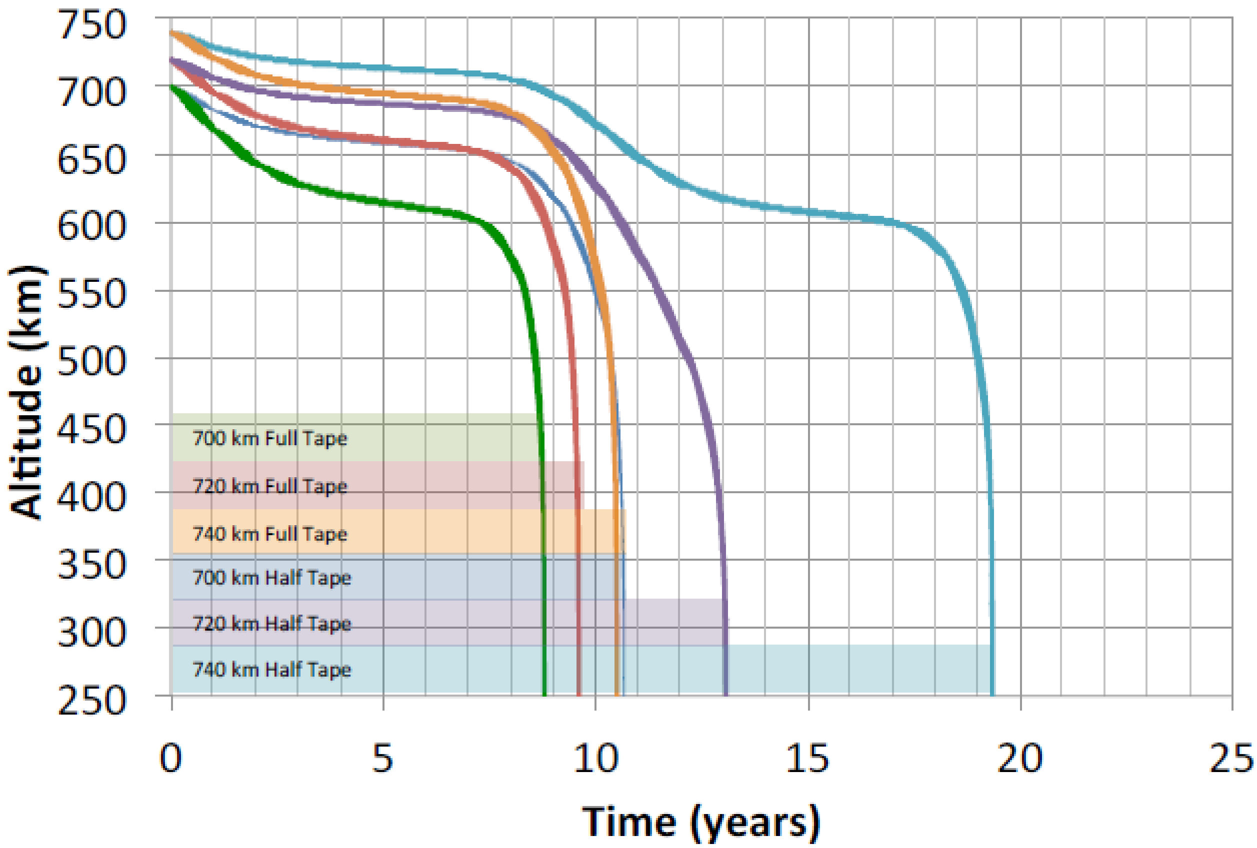


Figure 6-1 OTB re-entry prediction for the full tape length and an illustration of the effect of severing the tape to half length

Requirement 4.6-2. *Disposal for space structures near GEO: A spacecraft or orbital stage in an orbit near GEO shall be maneuvered at EOM to a disposal orbit above GEO with a predicted minimum perigee of GEO +200 km (35,986 km) or below GEO with an apogee of GEO – 200 km (35,586 km) for a period of at least 100 years after disposal (Requirement 56563).*

Analysis: Not applicable. OTB will be in LEO.

Requirement 4.6-3. *Disposal for space structures between LEO and GEO:*
a. A spacecraft or orbital stage shall be left in an orbit with a perigee greater than 2000 km above the Earth's surface and apogee less than 500 km below GEO (Requirement 56565).
b. A spacecraft or orbital stage shall not use nearly circular disposal orbits near regions of high value operational space structures, such as between 19,200 km and 20,700 km (Requirement 56566).

Analysis: Not applicable. OTB will be in LEO.

Requirement 4.6-4. *Reliability of post mission disposal operations in Earth orbit: NASA space programs and projects shall ensure that all post mission disposal operations to meet Requirements 4.6-1, 4.6-2, and/or 4.6-3 are designed for a probability of success as follows: (Requirement 56567)*
a. Be no less than 0.90 at EOM.
b. For controlled reentry, the probability of success at the time of reentry burn must be sufficiently high so as not to cause a violation of Requirement 4.7-1 pertaining to limiting the risk of human casualty.

4.6.4a Analysis: Tethers Unlimited CSTT products have performed repeated deployment reliability testing sufficient to establish a deployment reliability rating of 0.95 with a 96.5% confidence at EOM. These deployment tests will be repeated for the OTB nTT configuration.

4.6.4b N/A – OTB does not have a controlled re-entry.

7. ASSESSMENT OF SPACECRAFT REENTRY HAZARDS

7.1.1 Detailed description of spacecraft components by size, mass, material, shape, and original location on the space vehicle, if the atmospheric re-entry option is selected.

The following table summarizes the major components of the spacecraft which were input into the DAS software [2]. According to the DAS user's guide, the main structure of a spacecraft is assumed to break apart at an altitude of 78 km, exposing the first level of "child" objects to atmospheric forces. All of the objects in the table below are of this first level, and make up the remaining mass of the spacecraft which enters the atmosphere.

No. – refer to figures	Object Name	Qty	Material	Shape	Mass (kg)	Dimensions (m) Box: W x L x H Plate: W x L Cylinder: Dia x L
1	Deployed Solar Panel	4	Aluminum	Flat Plate	3.64	0.580 x 0.934
2	Body Solar Panel	3	Aluminum	Flat Plate	1.08	0.55 x 0.55
3	Deorbit Device	1	Aluminum	Box	0.35	0.135 x 0.157 x 0.015
4	DSAC Ion Clock	1	Aluminum	Box	18.00	0.260 x 0.285 x 0.229
5	DSAC USO	1	Aluminum	Box	2.50	0.20 x 0.24 x 0.11
6	DSAC GPS Receiver	1	Aluminum	Box	6.40	0.18 x 0.25 x 0.12
7	DSAC GPS Antenna	1	Aluminum	Cylinder	1.10	0.242 x 0.090
8	Top Bay Structural Panels	5	Aluminum	Flat Plate	3.00	0.230 x 0.580
9	CUSP (CU-Surrey Payload)	1	Aluminum	Box	2.00	0.30 x 0.30 x 0.15
10	iMESA-R (SERB Payload)	1	Aluminum	Box	0.70	0.105 x 0.118 x 0.035
11	Stack Structural Panels	6	Aluminum	Flat Plate	0.50	0.280 x 0.358
12	Radiator Panels	2	Aluminum	Flat Plate	2.95	0.580 x 0.700
13	Earth Facing Panel	1	Aluminum	Flat Plate	1.60	0.58 x 0.58
14	DSAC Bay Structure Panels	3	Aluminum	Flat Plate	3.00	0.236 x 0.543
15	Antennas	7	Aluminum	Box	0.50	0.082 x 0.082 x 0.067
16	AOCS Actuators	6	Aluminum	Box	1.20	0.2 x 0.2 x 0.2
17	Battery	1	Aluminum	Box	4.00	0.159 x 0.221 0.068
18	AOCS Sensors	8	Aluminum	Box	0.35	0.15 x 0.15 x 0.15
19	Harness	1	Copper	Box	10.00	0.4 x 0.4 x 0.4
20	Nanotray	1	Aluminum	Box	3.00	0.135 x 0.190 x 0.055
21	Top Bay Floor Plate	1	Aluminum	Flat Plate	3.00	0.574 x 0.574
22	AIM (Custom Tray)	1	Al 7075-T6	Box	8.00	0.515 x 0.547 x 0.037
23	S-Band Tx/Rx	1	Aluminum	Box	3.20	0.286 x 0.314 x 0.047
24	OBC 750 0/1	1	Aluminum	Box	2.00	0.286 x 0.314 x 0.032
25	F7 PDM	1	Aluminum	Box	2.00	0.286 x 0.314 x 0.041
26	PCM/PDM	1	Aluminum	Box	1.66	0.286 x 0.314 x 0.032
27	BCM 80 1	1	Aluminum	Box	1.14	0.286 x 0.314 x 0.035
28	BCM 80 0 (Custom Tray)	1	Al 7075-T6	Box	5.02	0.420 x 0.421 x 0.060

Table 7-1 Modelled components of the spacecraft using the DAS software[2]

Please refer to figures 7-1 and 7-2 for indication of the object positions on the OTB satellite (objects 22 – 28 not shown).

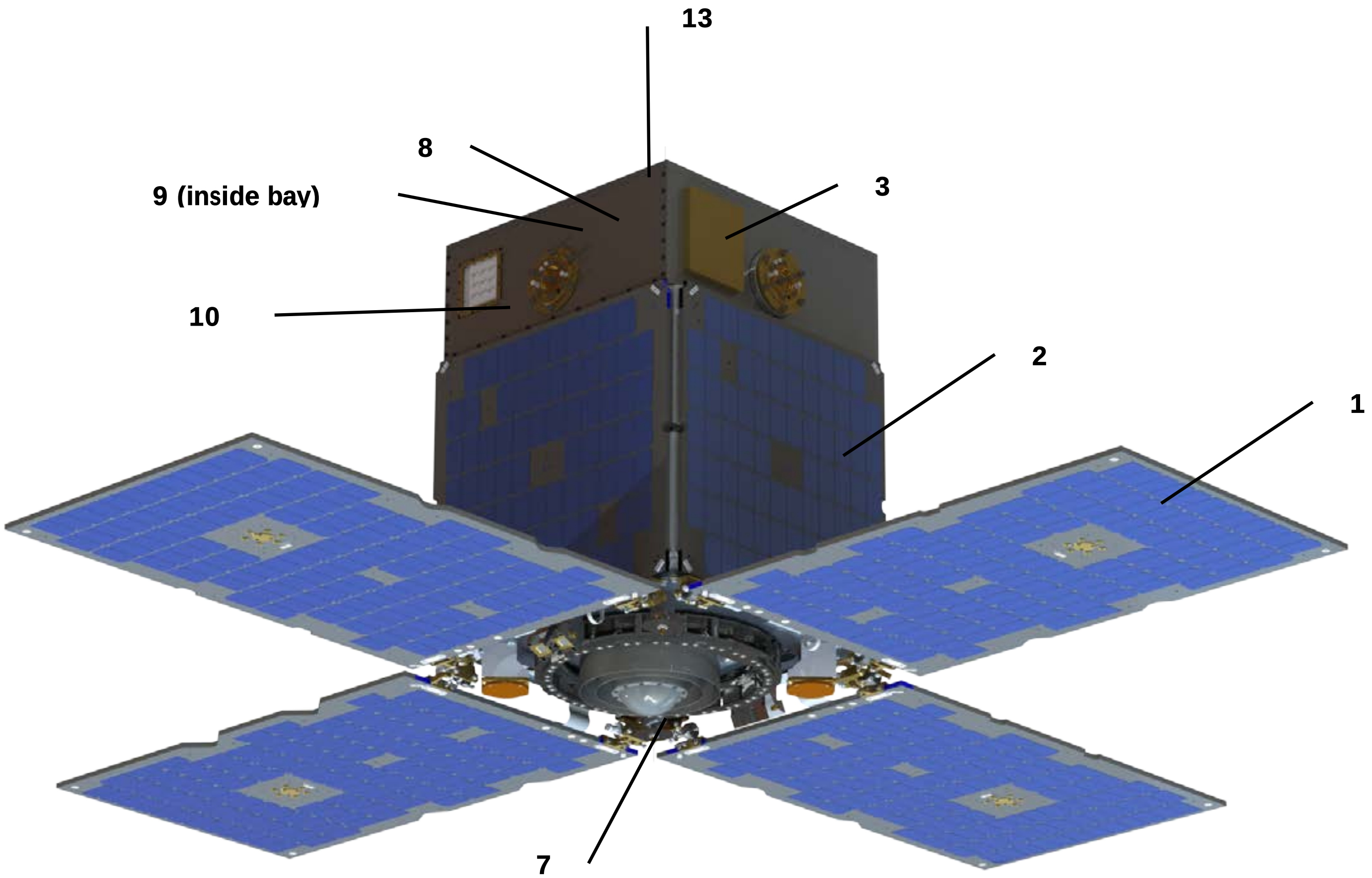


Figure 7.1 An overall CAD representation of the satellite, with callouts of the objects used in the DAS simulation, table 7-1(objects 22 – 28 not shown).

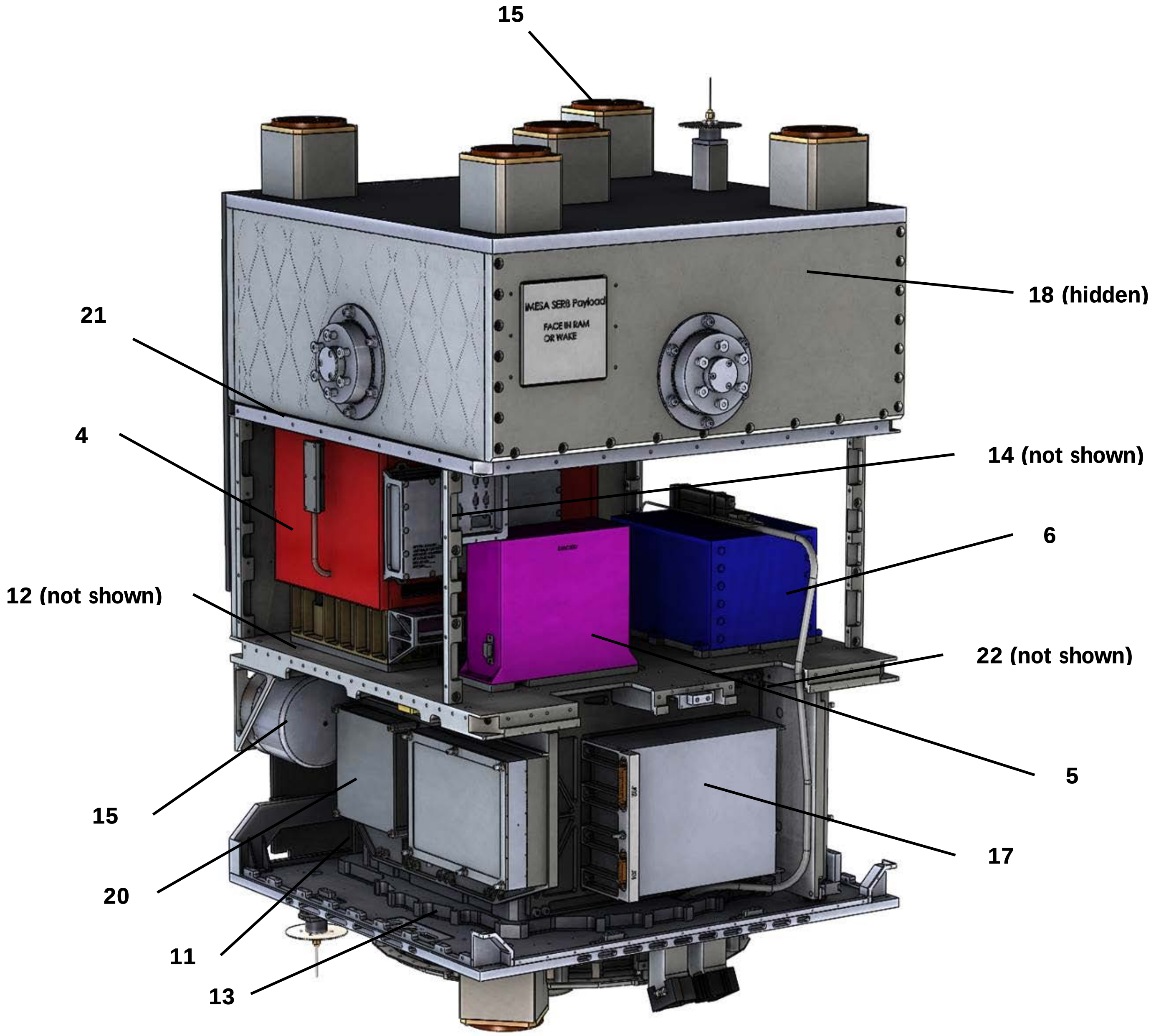


Figure 7-2 A cutaway view of the OTB spacecraft with callouts of the objects used in the DAS simulation, table 7-1. Solar panels and some of the closing panels are removed for clarity (objects 22 – 28 not shown).

7.1.2 Summary of objects expected to survive an uncontrolled reentry, using NASA Debris Assessment Software (DAS), NASA Object Reentry Survival Analysis Tool (ORSAT), or comparable software.

The table below summarizes the objects predicted to survive re-entry using DAS software [2]. Objects that do not survive are not included in the table 7-2 below.

Object Name	Total Debris Casualty Area (m^2)	Kinetic Energy (J)
DSAC ion clock unit	0.75	38811
Harness	1.00	4713
Total	1.75	

Table 7-2 details of objects surviving re-entry

Ref [3] footnote 9, requests further information on objects that are predicted to survive re-entry.

The DSAC clock unit is part of a contracted experimental payload that is modelled as a single aluminium box (due to the characteristics of the DAS software); however it is constructed of several smaller discrete modules that will be more susceptible to destruction on re-entry once its overall enclosure is breached.

The harness is modelled as a simple copper box (due to the characteristics of the DAS software); however in reality it is a more complex, distributed, fragile structure that will be more susceptible to destruction on re-entry. It is not constructed of high melting point materials.

As these components are predicted to survive re-entry, ref [3] footnote 9, recommends insurance arrangements.

Surrey carries third-party liability insurance as part of normal satellite operating procedures.

7.1.3 Calculation of probability of human casualty for the expected year of uncontrolled re-entry and the spacecraft orbital inclination.

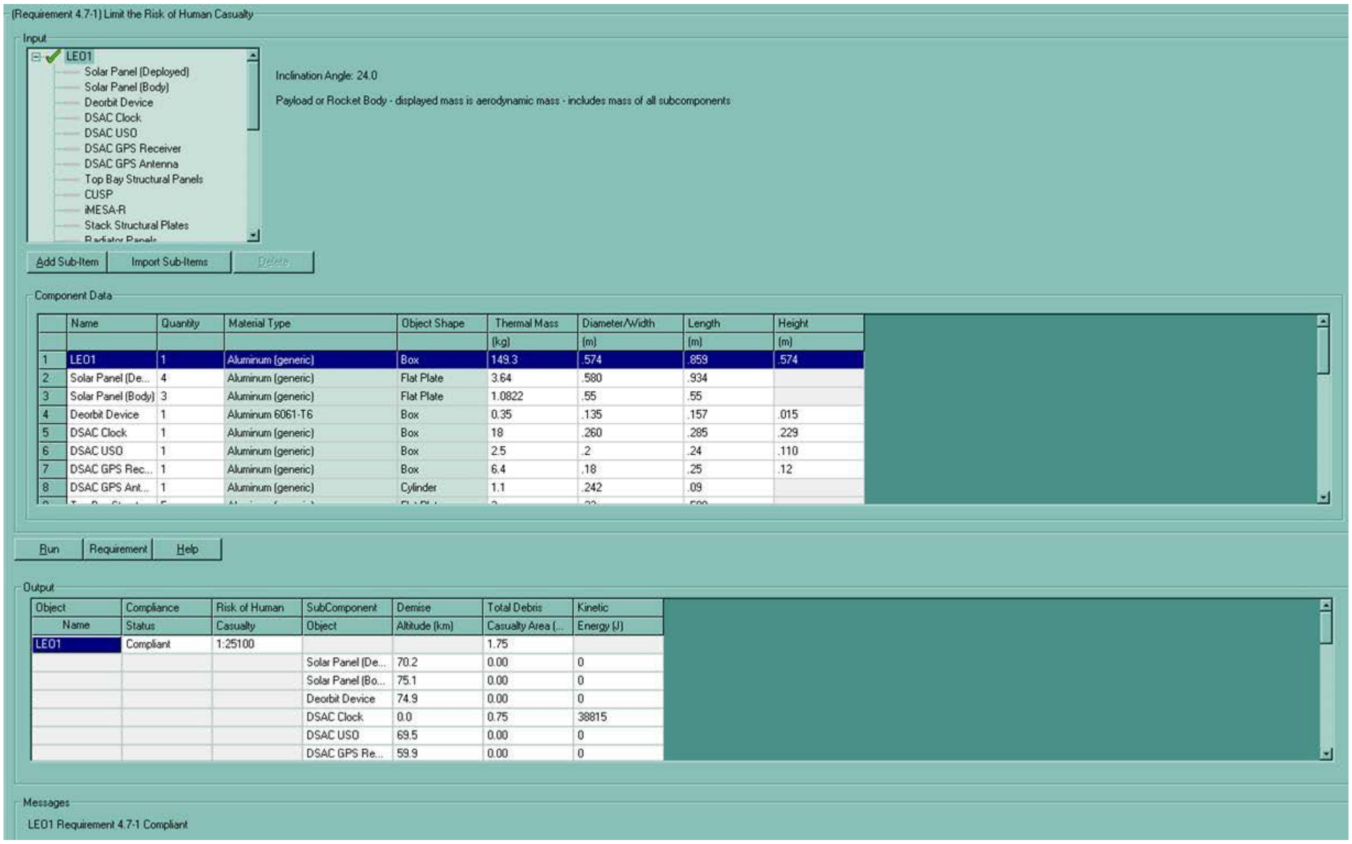
Using the DAS [2] calculated results in the above table; total probability of human casualty is 1:25100, or 0.0000398 which is compliant to the specification, figure 7-3.

7.1.4 Assessment of spacecraft compliance with Requirement 4.7-1.

Using the DAS software [2], OTB is compliant to requirement 4.7-1, as the probability for human casualty does not exceed 1:10000 or 0.0001.

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).

Using the DAS software [2], OTB is compliant to requirement 4.7-1, as the potential for human casualty does not exceed 1:10000 or 0.0001, figure 7-3.



	Name	Quantity	Material Type	Object Shape	Thermal Mass (kg)	Diameter/Width (m)	Length (m)	Height (m)
1	LEO1	1	Aluminum (generic)	Box	149.3	.574	.859	.574
2	Solar Panel (De...	4	Aluminum (generic)	Flat Plate	3.64	.580	.934	
3	Solar Panel (Body)	3	Aluminum (generic)	Flat Plate	1.0822	.55	.55	
4	Deorbit Device	1	Aluminum 6061-T6	Box	0.35	.135	.157	.015
5	DSAC Clock	1	Aluminum (generic)	Box	18	.260	.285	.229
6	DSAC USO	1	Aluminum (generic)	Box	2.5	.2	.24	.110
7	DSAC GPS Rec...	1	Aluminum (generic)	Box	6.4	.18	.25	.12
8	DSAC GPS Ant...	1	Aluminum (generic)	Cylinder	1.1	.242	.09	

Object Name	Compliance Status	Risk of Human Casualty	SubComponent Object	Demise Altitude (km)	Total Debris Casualty Area (...	Kinetic Energy (J)
LEO1	Compliant	1:25100			1.75	
			Solar Panel (De...	70.2	0.00	0
			Solar Panel (Bo...	75.1	0.00	0
			Deorbit Device	74.9	0.00	0
			DSAC Clock	0.0	0.75	38815
			DSAC USO	69.5	0.00	0
			DSAC GPS Re...	59.9	0.00	0

Figure 7-3 DAS output for requirement 4.7-1

b. 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).

N/A

c. 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).

N/A

7A ASSESSMENT OF SPACECRAFT HAZARDOUS MATERIALS

7A.1.1 Summary of the hazardous materials contained on the spacecraft using all columns and the format in paragraph 4.7.5.

Reporting will be done in a table using the below format containing the columns listed in Appendices A and B.
• Column A: Chemical and commercial name of the material
• Column B: Very brief description of how material is a hazard to humans (aka: explosive, carcinogen, toxic, radioactive)
• Column C: Estimated material state (gas/liquid/solid/powder), amount/quantity/activity/pressure at launch
• Column D: Estimated state/quantity/pressure of the material onboard when the space structure reaches operational orbit (Columns D-G use the same format as in Column C).
• Column E: Estimated state/quantity/pressure of the material onboard at expected EOM.
• Column F: Estimated state/quantity/pressure of the material onboard at expected end of passivation.
• Column G: Estimated state/quantity/pressure of the material expected to survive reentry and strike the Earth's surface (Enter NONE if the space structure is not expected to reenter Earth).

7A.1.2 Lithium exists within the flight proven ABSL 8s10p lithium-ion battery which employs the commercial SONY 18650HC cell. The quantity and state of the lithium is shown in table 7A-1.

7A.1.3 Trace amounts of mercury exist within the Deep Space Atomic Clock Ion Clock unit which is part of the DSAC experiment. The quantity and state of the mercury is shown in table 7A-1

Material Description	Lithium	Mercury
Material Hazard presented	Ignition when in contact with water, corrosive	Toxic in liquid and gas form
State, Quantity, Pressure at Launch	Solid, 24g, Ambient	Gas, 100µg, 10e-8 Torr
State, Quantity, Pressure on Orbit	Solid, 24g, Ambient	Gas, 100µg, 10e-8 Torr
State, Quantity, Pressure at EOM	Solid, 24g, Ambient	Gas, 100µg, 10e-8 Torr
State, Quantity, Pressure at Passivation	Solid, 24g, Ambient	Gas, 100µg, 10e-8 Torr
State, Quantity, Pressure Expected to Survive Reentry	None	Gas, 100µg, 10e-8 Torr

Table 7A-1 Hazardous materials data

8. ASSESSMENT FOR TETHER MISSIONS

8.4.1 Type of tether; e.g., momentum or electrodynamics.

The NanoSat Terminator Tape (nTT) device is an electrodynamic, 'Hoytether' type tape and will utilize both aerodynamic and passive electrodynamic drag to deorbit the spacecraft at EOM. No maneuvers are required for the proper deployment of the nTT. Following deployment, gravity gradient forces will align the tape with the local vertical direction. This will orient the OTB spacecraft so that it is in the proper orientation for de-orbit.

8.4.2 Description of tether system, including (1) tether length, diameter, materials, and design (single strand, ribbon, multi-strand mesh), at a minimum and (2) end-mass size and mass.

The nTT module has the stowed dimensions of 18cm x 18cm x 1.8cm.

It is comprised of a 70m long aluminized Kapton tape that is 0.17m wide and 0.5mm thick.

The total mass of the system is 800gm comprising of lower end mass is 440gm and the other end of the tape will remain attached to the spacecraft.

8.4.3 Determination of minimum size of object that will cause the tether to be severed.

The tape is 17cm wide. Due to the way it is folded for packaging, when deployed it has a longitudinal crease that results in it having a "v" shaped cross section. Tethers Unlimited estimates that an object of the order of 5cm in diameter would be required to completely sever the tape. This was verified using the DAS software tool [2].

8.4.4 Tether mission plan, including duration and post mission disposal.

The nTT will be deployed upon the completion of the mission life of 5 years on orbit. At this time a command will be sent to the switches connecting the nTT to the power system and the Frangibolt will release the tape. Once the tape is fully deployed, the system will remain deployed for the duration of deorbit. It is expected that the system will deorbit within 9.5 years after tape deployment, figure 6-1.

8.4.5 Probability of tether colliding with large space objects.

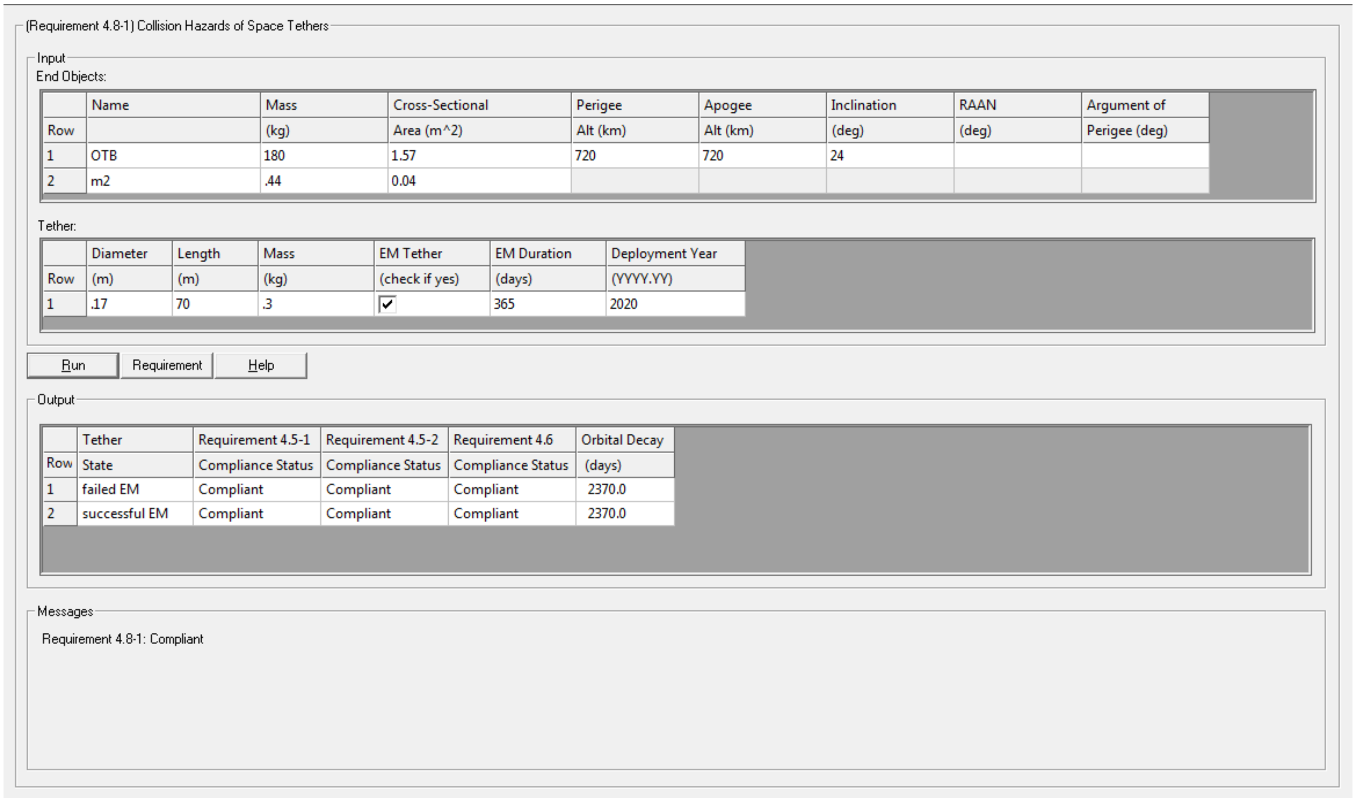
The probability of collision of a deployed tether with space objects larger than 10 cm is less than 0.001. This was verified using the DAS software tool [2].

8.4.6 Probability of tether being severed during mission or after post mission disposal.

The probability of a disabling collision of a deployed tether with small objects is less than 0.01. This was verified using the DAS software tool [2].

8.4.7 Maximum orbital lifetime of a severed tether fragment.

A severed half-length tape fragment will de-orbit within 6.5 years, as calculated by DAS [2], figure 8-1.



(Requirement 4.8-1) Collision Hazards of Space Tethers

Input

End Objects:

Row	Name	Mass (kg)	Cross-Sectional Area (m^2)	Perigee Alt (km)	Apogee Alt (km)	Inclination (deg)	RAAN (deg)	Argument of Perigee (deg)
1	OTB	180	1.57	720	720	24		
2	m2	.44	0.04					

Tether:

Row	Diameter (m)	Length (m)	Mass (kg)	EM Tether (check if yes)	EM Duration (days)	Deployment Year (YYYY.YY)
1	.17	70	.3	✔	365	2020

Run Requirement Help

Output

Row	Tether State	Requirement 4.5-1 Compliance Status	Requirement 4.5-2 Compliance Status	Requirement 4.6 Compliance Status	Orbital Decay (days)
1	failed EM	Compliant	Compliant	Compliant	2370.0
2	successful EM	Compliant	Compliant	Compliant	2370.0

Messages

Requirement 4.8-1: Compliant

Figure 8-1 DAS output showing a severed half length tape fragment will de-orbit in 6.5 years

8.4.8 Assessment of compliance with Requirement 4.8-1.

<u>Requirement 4.8-1.</u> *Mitigate the collision hazards of space tethers in Earth or Lunar orbits: Intact and remnants of severed tether systems in Earth and lunar orbit shall meet the requirements limiting the generation of orbital debris from on-orbit collisions (Requirements 4.5-1 and 4.5-2) and the requirements governing post mission disposal (Requirements 4.6-1 through 4.6-4) to the limits specified in those paragraphs (Requirement 56652).*

The OTB spacecraft and the Tethers Unlimited nTT are compliant with Requirement 4.8-1 as verified by the DAS software tool [2]. A screenshot of the DAS software tool output window can be seen in figure 8-1.