ORBITAL TEST-BED 3 (OTB-3), ADVANCED DATA COLLECTION SYSTEM (A-DCS) HOSTING SERVICES

ORBITAL DEBRIS ASSESSMENT REPORT (ODAR)

Revision A

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Prepared in compliance with NASA-STD-8719.14B

NASA Debris Assessment Software (DAS) version 3.1.0 used in preparing this report.

REVISION HISTORY

Revision	Date	Description of Change
A	2020/11/24	Initial Release; ECN-000000

AUTHORIZATION

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

Acronym	Definition
A-DCS	Advanced Data Collection System
AOCS	Attitude & Orbit Control System
ASM	Active Safety Module
BCM	Battery Control Module
BCR	Battery Charge Regulator
CAD	Computer Aided Design
CAN	Controller Area Network
CNES	Centre National d'Etudes Spatiales
COM	Wireless Communications System
DAS	Debris Assessment Software
DC	Direct Current
EELV	Evolved Expendable Launch Vehicle
EFF	Earth Facing Facet
EGSE	Electrical Ground Support Equipment
EMS	Electromagnetic Systems
EOM	End of Mission
EPS	Electrical Power System
ESPA	EELV Secondary Payload Adapter
g	Grams
GA	General Atomics
Gyro	Gyroscope
HDRM	Hold Down Release Mechanism
HDRS	Hold Down Release System
HoPS	Hosted Payload Solutions
IDIQ	Indefinite-Delivery/Indefinite-Quantity
kg	kilogram
LEO	Low Earth Orbit
Li	Lithium
LTAN	Local Time of Ascending Node
LV	Launch Vehicle
m	Meter
m^2	Meters squared
mk	Mark
MLB	Motorized Lightband
MtM	Magnetometer
MTQ	Magnetorquer
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration

Acronym	Definition
OBC	On-Board Computer
ODAR	Orbital Debris Assessment Report
OTB	Orbital Test-Bed
OSMA	Office of Safety and Mission Assurance
PDM	Power Distribution Module
PIU	Payload Interface Unit
PSC	Planetary Sciences Corporation
PTT	Platform Terminal Transmitters
RadMon	Radiation Monitor
RPU	Receiving Processing Unit
RSDO	Rapid Spacecraft Development Office
RW	Reaction Wheel
SA	Solar Array
SMA	SubMiniature version A
SMC	Space and Missile Systems Center
SS	Sun Sensor
TMR	Triple Mode Redundant
TRL	Technology Readiness Level
TTC	Telemetry, tracking Commanding
Tx	Transmitter
TXU	Transmitting Unit
UHF	Ultra High Frequency

SELF-ASSESSMENT OF THE ODAR USING THE FORMAT IN APPENDIX A.2 OF NASA-STD-8719.14B

A self-assessment is provided below in accordance with the assessment format provided in Appendix 2.1 of NASA-STD-8719.14. In the final ODAR document, this assessment will reflect any inputs received from NASA's Office of Safety and Mission Assurance (OSMA).

Table 1: Orbital Debris Self-Assessment Report Evaluation: OTB-3

Requirement #	Spacecraft				Comments
	Compliant	N/A	Not Compliant	Incomplete	***For all incompletes, include risk assessment (low, medium, or high risk) of non-compliance & Project Risk Tracking #***
4.3-1.a 25 year limit	☑	☐	☐	☐	No debris released in LEO.
4.3-1.b <100 object x year limit	☑	☐	☐	☐	No debris released in LEO.
4.3-2 GEO ± 200km	☐	☑	☐	☐	LEO Mission
4.4-1 <0.001 Explosion Risk	☑	☐	☐	☐	
4.4-2 Passivate Energy Sources	☑	☐	☐	☐	
4.4-3 Limit BU Long term Risk	☑	☐	☐	☐	No planned breakups.
4.4-4 Limit BU Short term Risk	☑	☐	☐	☐	No planned breakups.
4.5-1 <0.001 10cm Impact Risk	☑	☐	☐	☐	
4.5-2 Postmission Disposal Risk	☑	☐	☐	☐	
4.6-1a-c Disposal Method	☑	☐	☐	☐	
4.6-2 GEO Disposal	☐	☑	☐	☐	LEO Mission
4.6-3 MEO Disposal	☐	☑	☐	☐	LEO Mission
4.7-1 Ground Population Risk	☑	☐	☐	☐	
4.8-1 Tether Risk	☐	☑	☐	☐	No tethers used.

ASSESSMENT REPORT FORMAT

ODAR Technical Sections Format Requirements:

This ODAR follows the format in NASA-STD-8719.14B, Appendix A.1 and includes content required per the NASA-STD in sections 2 through 8 below for the OTB-3 space vehicle (SV).

Sections 9 to 14 apply to the launch vehicle ODAR and are therefore omitted from this report.

ODAR SECTION 1: PROGRAM MANAGEMENT AND MISSION OVERVIEW

Mission Owner & Operator

General Atomics (GA) is headquartered in San Diego, at 3550 General Atomics Court, San Diego, CA 92121. GA is the owner and operator of the Orbital Test-Bed 3 (OTB-3) spacecraft. Operations will be led out of the GA-EMS Englewood facility at 7304 South Joliet Street, Suite 200, Englewood, Colorado 80112.

Foreign Government or Space Agency Participation & NASA Agreement(s)

The U.S. Air Force Space and Missile Systems Center (SMC) is the Hosted Payload Solutions (HoPS) contracting office under contract number FA8814-14-D-0005. The A-DCS payload provider is the French Centre National d'Etudes Spatiales (CNES). All GA personnel working on OTB-3 are United States citizens.

OTB-3 is not covered by any NASA contracts or agreements.

Mission Schedule & Milestones

Table 2: OTB-3 Milestones and projected/completion dates

Milestone	Date
Kickoff	08 January 2019 (completed)
Preliminary Design Review (PDR)	05 May 2019 (completed)
Critical Design Review (CDR)	10 December 2019 (completed)
Test Readiness Review (TRR)	01 April 2021
Pre-Launch Review	02 September 2021
Proposed Launch	02 December 2021

Mission Description

OTB-3 is a GA-owned and operated Low Earth Orbit (LEO) small satellite. OTB-3 is a heritage bus design that will provide an on-orbit test bed for the demonstration of scientific, research and prototype payloads as well as a platform for hosted payload services. The list of payloads includes:

1. The Radiation Monitor (RadMon) is an internally funded radiation measurement experiment. RadMon measures radiation exposure both in real-time and as cumulative Total Ionizing Dose throughout the mission duration.
2. Argos-4 is a hosted payload program for the National Oceanic and Atmospheric Administration (NOAA) with oversight from Space Missile Center (SMC). The Argos Hosted Payload provides geolocation of ground mobile Platform Terminal Transmitters (PTT).

Mission Characteristics

Table 3: Summary of significant mission characteristics (LV, Orbit, mission duration etc.)

Characteristic	**Note / Description**
Launch Vehicle (LV)	Rocket Lab Electron
Launch Site	Mahia, New Zealand
Mission Duration	5 years
Orbital Altitude	750 kilometers
Inclination	98.3±0.05 degrees
Local Time of Ascending Node (LTAN)	17:30 (±1 hour)
Orbit parking, maneuvers or transfers	None, OTB-3 will remain in the specified orbit for the mission life

Maneuver, Attitude & Orbit Control Capabilities

OTB-3 is a three axis controlled spacecraft with the capability, and requirement, to maintain nadir pointing for the mission duration to within a 2.5 degree half-angle (can be visualized as a 5 degree cone).

OTB-3 does not have a propulsion system and cannot change orbit beyond natural orbital altitude decline from initial injection.

OTB-3 employs a deployable drag augmentation device to accelerate orbit decay at End of Mission (EOM). For more information, see ODAR Section 6.

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

The OTB-3 operational orbit was selected based on requirements from the hosted payload (Argos-4) combined with launch vehicle capabilities and system mass. In particular, the hosted payload requires that OTB-3 operate in a polar sun-synchronous orbit with the characteristic described in Table 3.

Identification of any interaction or potential physical interference with other operational spacecraft

ODAR Section 5 details the analysis for OTB-3 using NASA DAS software showing that the probably of collision over the spacecraft lifetime is negligible.

ODAR SECTION 2: SPACECRAFT DESCRIPTION

Physical description of the spacecraft

The OTB-3 satellite design is based on the SSTL-150 spacecraft bus, first flown in 2007. The SSTL-150 is listed in the Rapid III spacecraft catalog offered by the National Aeronautics and Space Administration (NASA) Rapid Spacecraft Development Office (RSDO). The OTB-3 avionics bus largely consists of heritage components with minor updates to address obsolescence and mission specific requirements. The majority of the OTB-3 bus is redundant, see Figure 2.

Supporting the Argos-4 payload required a new design, the Payload Interface Unit (PIU) that acts as an electrical interface adapter. The PIU interfaces discrete and analog signals with Argos-4 and an L-band transmitter to satisfy Argos-4 mission requirements. Payload instrumentation is not required for the RadMon payload as it interfaces directly with the spacecraft bus.

OTB-3 has four significant appendages, two deployable solar panels that are aligned with the "Y" body axis when stowed and the "X" body axis when deployed. Two fixed antennas extend from the nadir-facing panel. See Figure 1.

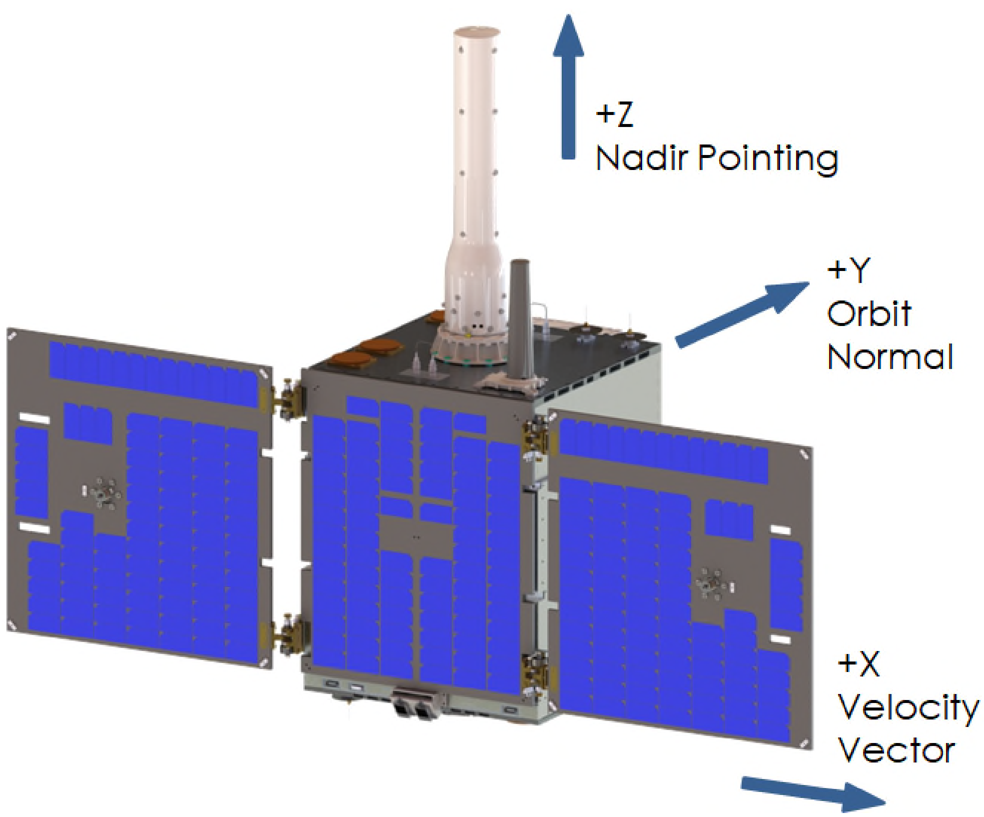

Figure 1: OTB-3 CAD rendering, deployed state

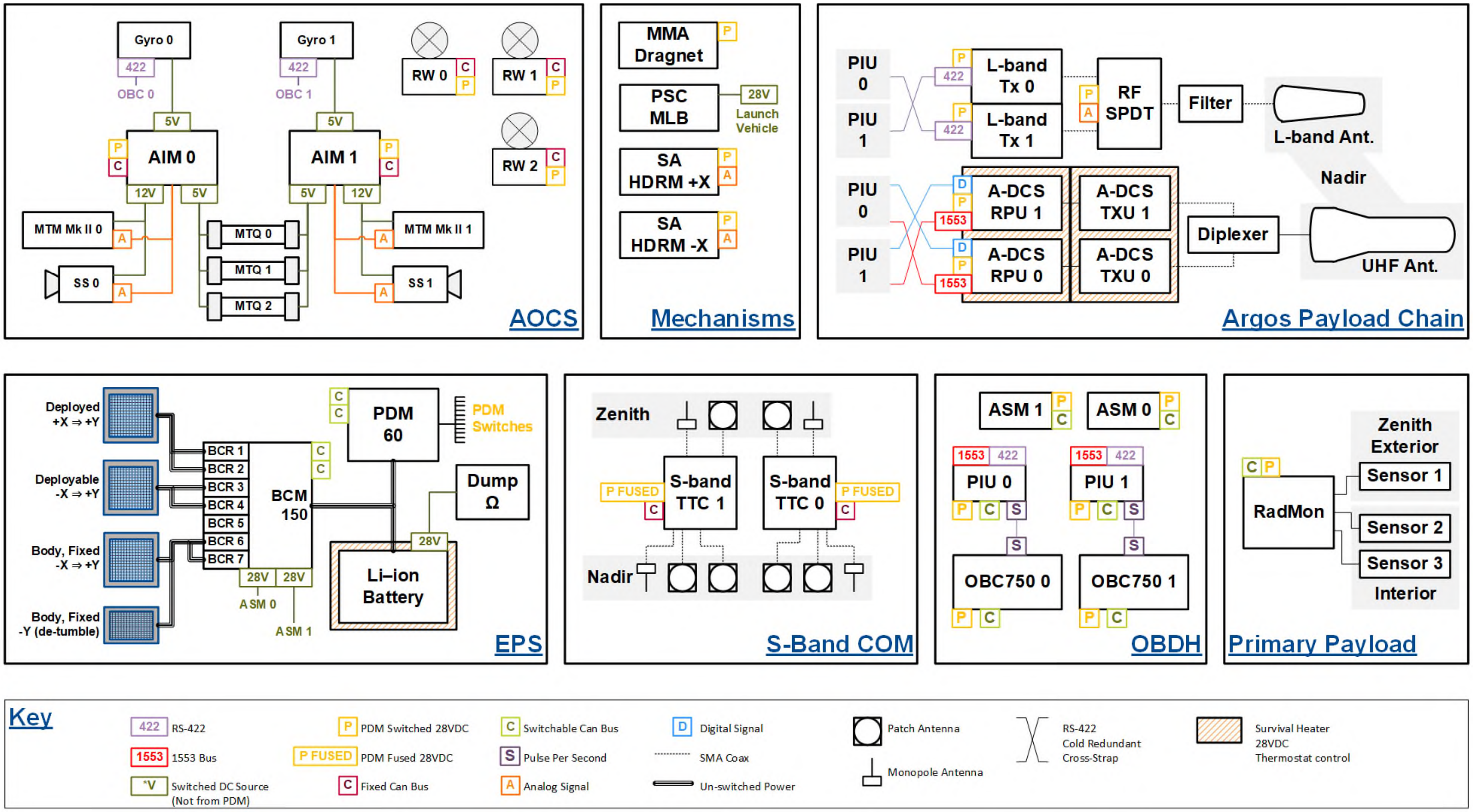

Figure 2: OTB-3 block diagram depicting functional subsystems

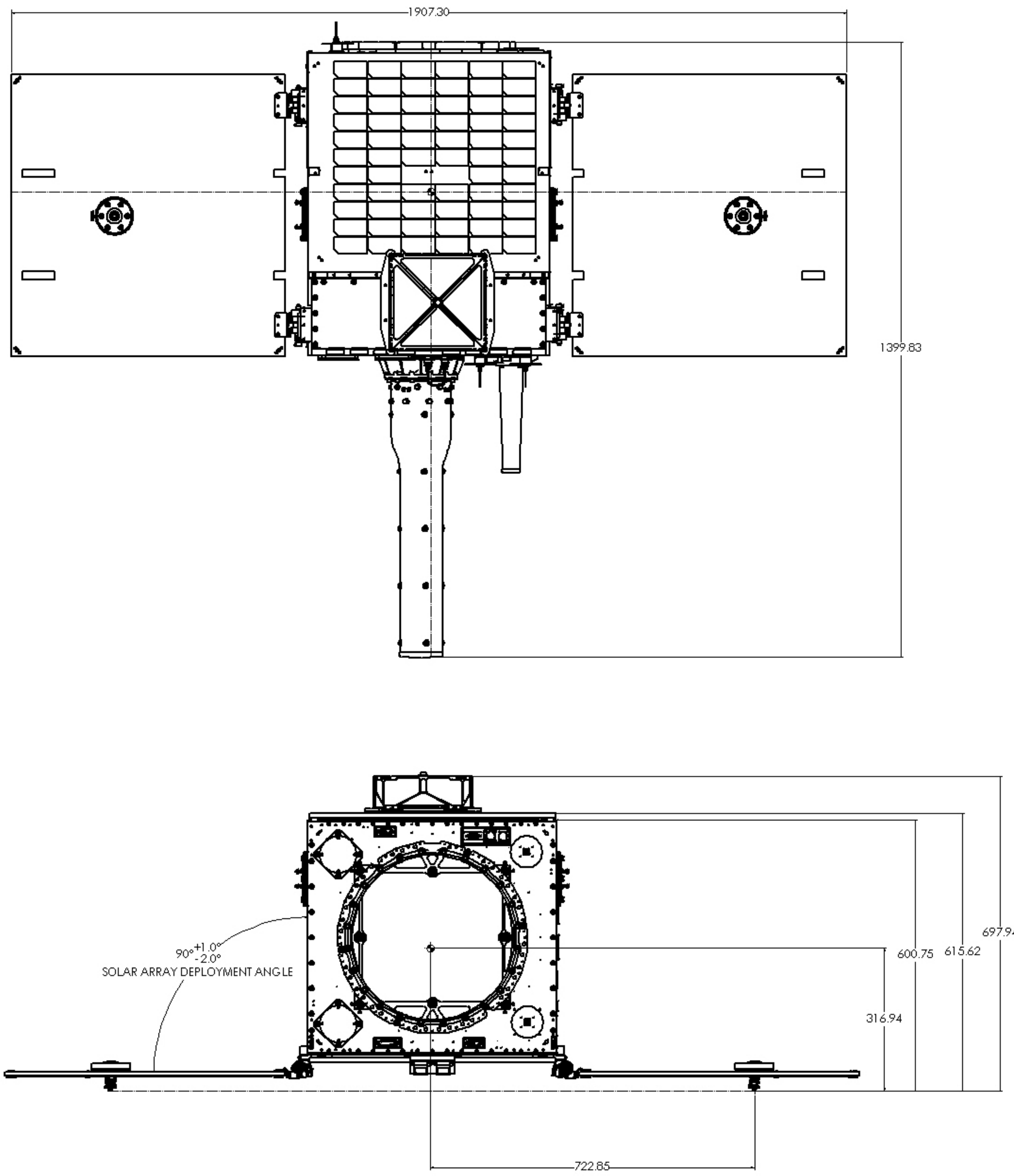

Figure 3: Dimensions of OTB-3 in deployed/operational configuration (dimensions in mm)

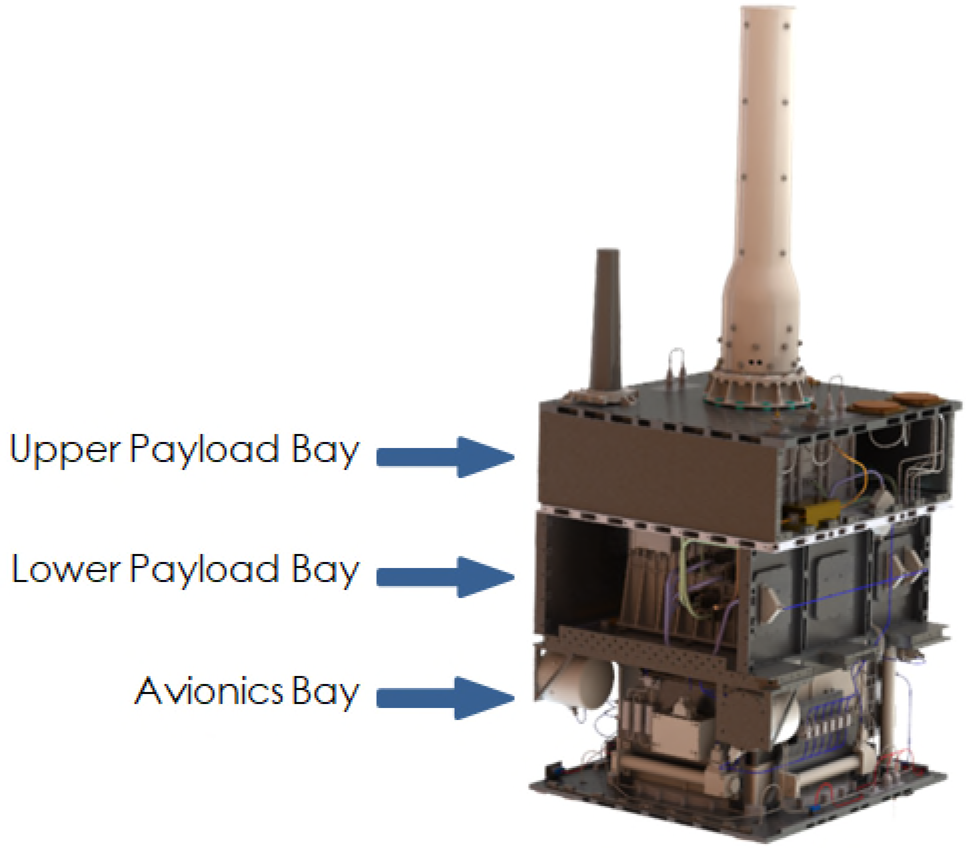

Figure 4: Interior components and layout of OTB-3

Spacecraft mass at launch

The total OTB-3 spacecraft mass at launch is 120 kilograms.

Spacecraft dry mass

OTB-3 does not have a propulsion system or any consumables or deployable mechanisms that would result in added mass.

Spacecraft Propulsion

OTB-3 does not have a propulsion system.

Spacecraft fluids

There are no propellants, sealed heat pipes, or pressurization tanks within OTB-3. Consequently, a fluid loading plan / strategy is not required.

The OTB-3 power system will include one (1) EnerSys/ABSL 8s10p Lithium-ion battery manufactured by ABSL (http://www.enersys.com/). The battery has considerable flight heritage and employs SONY 18650HCM Li-Ion cells with over 150,000 cell years in orbit. All cells within the battery feature three inherent protection measures including a Current Interrupt Device (CID), a controlled cell vent, and a Positive Temperature Coefficient (PTC) Polyswitch. OTB-3 battery fluids are a very low risk due to cell-level protection measures, electrical power system (EPS) safety features, and battery flight heritage.

If a cell is overcharged beyond 4.8 V, the internal CID disk will rupture and physically remove the electrical connection within the cell. This disconnect protection mechanism causes an open-circuit condition within the cell and prevents thermal runaway. Contents of each cell are nominally held at 1 bar but internal cell pressure may increase due to off-nominal operational conditions. Each cell includes a controlled cell vent to facilitate pressure release and to provide a safe rupture to vent ratio in accordance with recommended NASA safety standards. Finally, all cells include a PTC Polyswitch. The PTC switch prevents thermal damage to the cell caused by long-duration high-current discharges, i.e. an unintentional short. During excessive current flow, PTC switch resistance sharply increases therefore reducing current flow. If the high current condition abates, the PTC switch will cool and return the cell to normal operation. If the high current condition remains, the PTC switch acts as a fuse and will permanently terminate cell discharge capability to protecting against an overcurrent induced thermal runaway condition.

Spacecraft Attitude Control System

The co-ordinate system of OTB-3 is indicated in Figure 1, with the Earth pointing on the Z-axis, the velocity vector along the X-axis and the orbital normal along the Y-axis.

OTB-3 utilizes a heritage 3-axis attitude control system. This system consists of three reaction wheels (10sp-m-small-satellite-microwheel) for attitude control, together with three magnetorquers for de-saturation of the reaction wheels. In addition two each of, sun sensors, gyros and magnetometers form part of the Attitude & Orbit Control System (AOCS) as shown in the block diagram, Figure 2.

Range Safety or other Pyrotechnic Devices

There are no pyrotechnic devices within the OTB-3 satellite.

Description of the electrical generation and storage system

The OTB-3 bus has two deployable solar panels and two body-mounted solar panels. When deployed, the two deployable solar panels and one body-mounted solar panel are aligned with the "X" axis "sun-facing" facet of the satellite. The second, smaller, body mounted panel is mounted on the opposite facet. During nominal operations, the satellite orients the +Y facet towards the sun, but all panels contribute to power generation when in tumble. Solar panel power charges the ABSL 8s10p Li-Ion battery, which provides an unregulated power supply to downstream subsystems. The EPS and battery will continue to support satellite operations in the event of a string failure on the battery or the solar arrays, albeit at a reduced mission capability.

Power is supplied from the battery to one Power Distribution Module (PDM). The PDM controls switching of the 28V unregulated solar panel and battery power supply to spacecraft subsystems. The spacecraft is also equipped with an automated overvoltage protection system for the battery. The Battery Charge Module (BCM) will detect an over voltage condition via a Triple Mode Redundant (TMR) majority voting system. If detected, the BCM will enable a pair of series switches, which directly connect the battery to overvoltage shunt resistors. Shunt resistors are sized to dissipate maximum excess power and will prevent an overcharge situation from occurring. The overvoltage protection circuit will only be necessary in the event of at least two sequential failures within the EPS.

Other sources of stored energy

OTB-3 utilizes a SSTL Hold Down and Release System (HDRS) to deploy two solar panels. A MMA drag augmentation device is used to accelerate de-orbit at EOM. Both of these systems use spring-loaded, stored kinetic energy to deploy. See ODAR Sections 3 and 6 for more information. No debris is produced during these deployments.

Radioactive Materials

OTB-3 contains no radioactive materials.

Planned Proximity Operations or Docking

OTB-3 is neither capable of, nor planned to, dock or intentionally come within close proximity of other spacecraft.

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 from OTB-3; all deployment systems are self-contained and do not to release debris into the environment.

OTB-3 deployable mechanisms are:

1) Surrey Satellite Technologies Ltd. Hold Down and Release System

   The Hold Down and Release System (HDRS) for the deployable solar panels utilizes captive devices on both sides of the interface (retention of bolt and springs) and as such does not generate debris. This system has been used successfully on previous SSTL spacecraft and as such is a TRL9 system.

2) Planetary Systems Corporation mkII (PSC) 15” Motorized Lightband (MLB)

   PSC, within their 2000785G MkII MLB User Manual dated July 24, 2018 (section 3, point 6) states: “*Non-pyrotechnic. The Lightband generates no debris on or after separation*” and is a TRL 9 system.

3) MMA dragNET Drag Augmentation Device

   The drag augmentation device is based on flight proven technologies and components. This system is further explained in ODAR Section 6.

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

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

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 during normal operations.

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 during normal operations.

<u>Requirement 4.3-2:</u> 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.

Not applicable — OTB-3 will be injected and operate in LEO.

ODAR SECTION 4: ASSESSMENT OF SPACECRAFT INTENTIONAL BREAKUPS AND POTENTIAL FOR EXPLOSIONS

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

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 over 50 spacecraft to date with no failures. The battery's SONY 18650HCM cells have accrued more than 150,000 cell years in orbit without any safety events. The spacecraft battery is charged via the launch vehicle umbilical that connects to the OTB-3 MLB via a separation connector. This is the only charging method available after integration with the launch vehicle. Prior to launch, the umbilical is disconnected from Electrical Ground Support Equipment (EGSE) and all electrical connections between the spacecraft and launch vehicle are terminated. The battery is only connected to the spacecraft power system upon separation from the launch vehicle, which presents no credible risk during the launch phase of the mission.

Upon separation and throughout operation, the battery will be cycled at a benign depth of discharge between 10% - 20% with a maximum end of charge voltage of 32V. The EPS is a heritage design that includes proven battery charge and discharge safety functionality on numerous spacecraft including CFESat, RapidEye, UK-DMC-2, Deimos and exactView-1. No credible causes of spacecraft breakup during deployment or mission operations are foreseen.

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

Thermal runaway is the primary failure mode of Li-Ion cells that may lead to an accidental explosion. SONY 18650HCM cells, within the ABSL 8s10p battery, have been subjected to extensive thermal runaway testing. Test results show that propagation does not occur in the event of a single cell thermal runaway, assuming all other cells are in healthy condition. As such, thermal runaway of a single cell, which is protected through the mechanisms previously described, has not been shown to cause a cascading thermal runaway failure.

<u>Four possible failure modes have been identified for the battery:</u>

1) Overcharge of Lithium-ion batteries above the manufacturer recommended maximum voltage of 33.6V could result in thermal runaway. To prevent this, the battery voltage is constantly monitored by the EPS, and charging is halted if this voltage is exceeded, as previously described by the overvoltage protection system. This functionality has been tested and verified using the OTB-3 EPS. As a second level of protection, all battery cells contain internal protection devices that disable the battery from charging and result in a

fail-safe open circuit condition. This functionality has been demonstrated via a number of ground tests.

2) A thermal runaway condition could result if internal cell temperature of the ABSL 8s10p rises far beyond the cell manufacturer rated survival temperature. This will be prevented due to the thermal design of the spacecraft. Extensive thermal analysis has been performed during all operational modes of the mission including launch, separation, de-tumble, nominal operations, and safe mode. The battery is mounted inside the spacecraft structure, and will not experience direct thermal transfer from the sun. The battery is also thermally coupled to the spacecraft structure, which enables excellent thermal dissipation of cell heat generation.

3) Short circuit of Lithium-ion batteries can result in very high current draw and quick heating, which 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. At the cell level, each cell includes a PTC switch for short circuit protection. Heat is generated in the PTC switch, which causes its resistance to increase sharply, reducing current flow and preventing the short circuit for occurring.

4) Test results show that over-discharge of the battery, described as bring the battery voltage below the minimum recommended operating voltage of 20V, degrades performance but does not pose a safety risk. Over-discharge tests, which drive cells to negative voltage, have also been performed. These tests result in a safe failure, with cells effectively becoming resistors. In addition, the satellite PDM will switch all loads off when the battery falls below 24V to preserve battery health.

In summary, no credible failure modes at the cell, battery, or EPS level will cause an accidental explosion. The battery design has been sufficiently tested and flown to ensure that thermal runaway propagation does not occur.

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

There are no intentional breakups (explosions or intentional collisions) planned.

List of components which are passivated at EOM.

At End of Mission (EOM), the spacecraft deorbit device, an MMA drag sail, will be deployed and will fully occlude the +Y solar panel. All satellite components will be turned off and disabled with the exception of the EPS and RF receivers, which are fused on. After turning off attitude control, the satellite will eventually degrade into a random tumble throughout the de-orbit period. This would illuminate the –Y panels and resume charging of the battery, albeit at a highly reduced rate.

In this scenario, power analysis shows that the battery will continue to charge and discharge. Ground and in-orbit life test data indicate a continued graceful degradation of the battery with an effective reduction of battery capacity over time. Battery capacity fade analysis shows an EOM capacity of < 50% of the original 15Ah nameplate capacity. An end of charge voltage of 31V (the minimum possible) will also be set via telecommand at EOM, which will further limit charge of the battery to < 50% state of charge (SoC). A combination of the lifetime capacity fade and low maximum SoC will result in a total EOM maximum energy store of < 25% of the original name plate energy. This puts the battery in a benign energy storage state, which will only continue to decrease throughout the duration of de-orbit. The automated overvoltage protection system will continue to remain operational throughout de-orbit and will prevent any overcharge situation from occurring. The overvoltage protection circuit will only be necessary in the event of at least two sequential failures within the EPS.

Thermal analysis has been performed for random tumble scenarios to confirm that the battery will remain within a safe temperature range below its recommended operational temperature. There is negligible risk of failure due to temperature induced thermal runaway. Additionally, each cell features the previously discussed internal protection measures including a CID, a PTC switch, and a controlled cell vent.

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

The battery cannot be completely passivated (discharged to 0% SoC and disconnected from the power system) due to heritage system design and power system which have successfully flown on numerous satellite missions.

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

<u>*Requirement 4.4-1:*</u> *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 — There is 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 (refer to OTB-3 potential causes of spacecraft breakup described above).

<u>*Requirement 4.4-2:*</u> *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 on-board 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 cannot cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft (Requirement 56450)

Compliant – there is a plan in place for OTB-3 after EOM to control on-board sources of stored energy to a level which cannot cause an explosion or deflagration.

<u>Requirement 4.4-3:</u> 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-3 will not undertake any planned explosions or intentional collisions.

<u>Requirement 4.4-4:</u> 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-3 will not undertake any planned explosions or intentional collisions.

ODAR SECTION 5: ASSESSMENT OF SPACECRAFT POTENTIAL FOR ON-ORBIT COLLISIONS

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

NASA DAS software was used to assess compliance of the OTB-3 spacecraft with Requirement 4.5-1. For this analysis, the average area-to-mass ratio was used. This represents the spacecraft following the deployment of the drag augmentation devices and in tumble. The maximum cross-sectional area was identified, and with the two orthogonal areas, the average cross-sectional area was calculated using the accepted NASA formula. (Note that the maximum cross-sectional area, with the drag augmentation device deployed, is not orthogonal to the plane of the deployed solar panels.) The resulting area-to-mass ratio is calculated to be 0.0699 m^2/kg. OTB-3's orbit is not controlled during its 5-year mission lifetime, and is unable to perform any maneuvers. The DAS software takes into account the full orbital lifetime until deorbit.

The probability of collision with large objects was calculated to be 0.00075 during the orbital lifetime (Figure 5), which is compliant with the requirement of 0.001. Additional analysis was performed to confirm that the deployment of the drag augmentation device does not increase the probability of collision to a level greater than if no device was used. Detail below in Section 6.

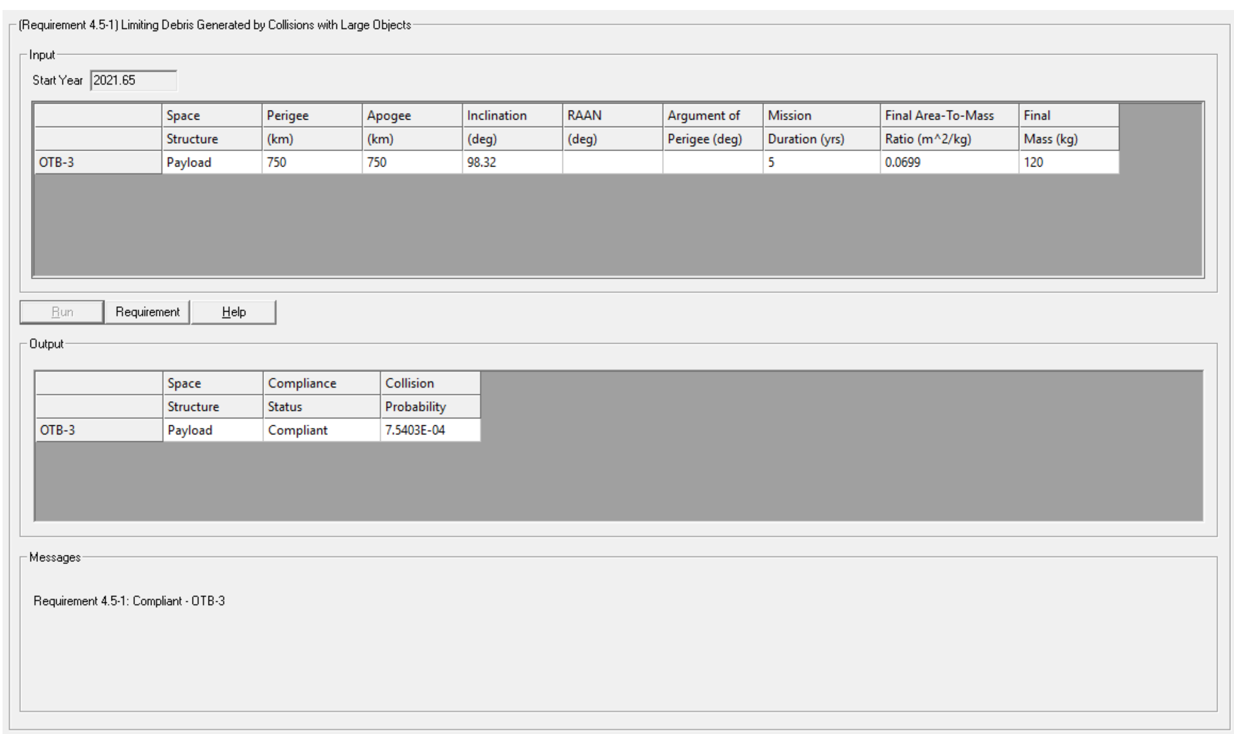

Figure 5: OTB-3 DAS Output for Collisions with Large Objects

Calculation of spacecraft probability of collision with space objects, including orbital debris and meteoroids, of sufficient size to prevent postmission disposal

The units listed in Table 4 are critical to completing post-mission disposal activities. Each unit is listed with its individual Probability of Penetration value, as calculated by DAS. The OTB-3 spacecraft will enter the EOM phase of operations in the nominal, nadir-pointing attitude, and it will remain nadir-pointing until the deorbit 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 deorbit command from the ground through the S-band patch antennas and the receiver. The onboard computer will then command the deorbit device to deploy, which will begin to deorbit the spacecraft. For these actions to occur, the power system must also be active.

Table 4: Probability of penetration for each disposal critical component

Critical Surface	**Probability of Penetration**
Drag Augmentation Device	0.0044
OBC	0.0000081
PDM	0.0000036
Battery	0.000023
S-band RF Tray	0.0000039
S-band Antennas	0.0029
TOTAL PROBABILITY OF PENETRATION	0.0073

The total probability of post-mission disposal failure is 0.0073, which is compliant with the requirement.

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 0.00075 during the orbital lifetime, which is compliant with the requirement, see Figure 5.

<u>Requirement 4.5-2:</u> 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 using DAS to be 0.0073, which is compliant with the requirement, see Table 4.

Detailed description and assessment of the efficacy of any planned debris avoidance capability intended to help in meeting the requirements of requirement 4.5-1, including any plans to move to less congested altitudes, as well as any tracking enhancements (GPS, laser retroreflector, e.g.) that may assist in reducing the covariance of collision estimates. Note that significant risk remains for impact with debris objects less than 10 cm and/or that are otherwise untrackable from the Earth, so such measures are only expected to slightly influence the statistical probability of collision with dangerous objects.

OTB-3 does not have any propulsion systems, avoidance capability, or ability to affect orbit beyond end of life de-orbit sail deployment.

Description of characteristics of the space station's orbit that may present a collision risk, including any planned and/or operation space stations in those orbits, and indicate what steps, if any, have been taken to coordinate with the other spacecraft or system, or what other measures the operator plans to use to avoid collision

Because it is sun-synchronous, OTB-3's orbit will present a theoretical collision risk to all other planned and/or operational spacecraft with a similar orbital altitude of 750 km. The OTB-3 operators will coordinate with the 18th Space Control Squadron to identify any planned or operational space stations in orbits with a 750 km orbital altitude to mitigate potential collision risk. At this stage, no specific steps have been taken to coordinate with other spacecraft or systems.

If at any time during the space station(s)' mission or de-orbit phase the space station(s) will transit through the orbits used by any inhabitable spacecraft, including the International Space Station, describe the design and operational strategies, if any, that will be used to minimize the risk of collision and avoid posing any operational constraints to the inhabitable spacecraft.

During the de-orbit phase, OTB-3 will transit through the orbit used by the International Space Station ("ISS"). The OTB-3 operators will share information with the 18th Space Control Squadron and NASA, as necessary, to mitigate potential collision risk with the ISS. At this stage, OTB-3 will have deployed its drag augmentation device and will not have enough power to perform any orbital avoidance maneuvers. However, the spacecraft will be trackable and its trajectory easily assessed, facilitating risk assessment and mitigation.

Description of the accuracy, if any, with which orbital parameters will be maintained, including apogee, perigee, inclination, and the right ascension of the ascending node(s). In the event that a system will not maintain orbital tolerances, e.g., its propulsion system will not be used for orbital maintenance, that fact should be included in the debris mitigation disclosure. Such systems must also indicate the anticipated evolution over time of the orbit of the proposed satellite or satellites. All systems must describe the extent of satellite maneuverability, whether or not the space station design includes a propulsion system.

OTB-3 does not have a propulsion system, and will not be maintaining its orbit. Considering the expected 3σ distribution of launch vehicle orbit insertion, the anticipated range over the mission of the mean orbital elements is given in Table 5, below. As a sun-synchronous satellite, the right ascension of the ascending node will vary from 0 to 360 degrees throughout the year.

Table 5: The expected range of apogee, perigee, and inclination for OTB-3's orbit.

Apogee Altitude (km)	Perigee Altitude (km)	Inclination (deg)
725 – 768	708 – 750	98.16 – 98.57

Certification that upon receipt of a space situational awareness conjunction warning, the operator will review and take all possible steps to assess the collision risk, and will mitigate the collision risk if necessary.

Upon receipt of a space situational awareness conjunction warning, the OTB-3 operators will review and take all possible steps to assess the collision risk, and will mitigate the collision risk if necessary. The OTB-3 operators will contact the operator of any active spacecraft involved in such a warning and share relevant ephemeris data.

Description of planned method to identify the space station(s) following deployment and whether space station tracking will be active or passive

OTB-3 will be identified using its initial deployment ephemeris provided by the launch vehicle provider to establish the first ground pass windows and make contact during those times. OTB-3 is specifically identified by encrypted commands & telemetry and by a unique satellite identifier built into command and telemetry that differentiate it from other spacecraft. The spacecraft tracking of OTB-3 will be passive, relying solely on ground-based tracking.

Whether, prior to deployment, the space station(s) will be registered with the 18th Space Control Squadron or successor entity. The extent to which the space station operator plans to share information regarding initial deployment, ephemeris, and/or planned maneuvers with the 18th Space Control Squadron or successor entity, other entities that engage in space situational awareness or space traffic management functions, and/or other operators

OTB-3 will be registered with the 18th Space Control Squadron or successor entity prior to launch. OTB-3 will share all information regarding initial deployment and ephemeris with the 18th Space Control Squadron. OTB-3 will not be performing any maneuvers.

ODAR SECTION 6: ASSESSMENT OF SPACECRAFT POSTMISSION DISPOSAL PLANS AND PROCEDURES

Description of spacecraft disposal option selected

The spacecraft will deorbit naturally by atmospheric re-entry following the deployment of a drag augmentation device. This device is described later in this section and has been designed in order to increase the average cross-sectional area of the satellite at the EOM to deorbit OTB-3 while utilizing simple and robust mechanical principles.

The drag augmentation device will be stowed for mission duration on the +Y panel of the spacecraft (in eclipse during nominal operations), as shown in Figure 7. At EOM, the device will be actuated by sending an “Arm” and “Fire” command set. Deployment of the drag augmentation device only requires that a Frangibolt releases; the device’s stored mechanical energy ensures deployment upon release. With the drag device deployed, the spacecraft can then be passivated for final disposal. This sequence is highlighted in Figure 6. The spacecraft does not need to be controlled through re-entry as the system has been designed to deorbit within the required period in a random tumbling orientation.

Note that the end-of-mission operational plan is to deploy the de-orbit device and then passivate the satellite. The commands to passivate can be received by the satellite when it is in any orientation, due to the placement of the receive antennas. This antenna placement is a requirement for spacecraft early operations, when initially separated from the launch vehicle in a tumbling state.

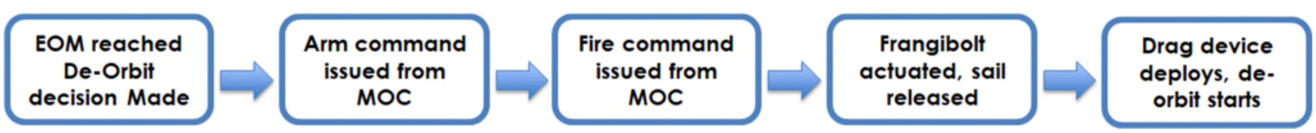

Figure 6: EOM, drag augmentation deployment procedure

Identification of all systems or components required to accomplish any postmission disposal maneuvers. Plan for any spacecraft maneuvers required to accomplish postmission disposal

OTB-3 will utilize the MMA Design LLC dragNET de-orbit device that is based on the following on-orbit demonstrated technologies:

1) Frangibolt actuated release. Frangibolts have been qualified on-orbit numerous times.
2) 14 m^2 of effective deployed area for aerodynamic drag
3) Robust and reliable spring-powered deployment
4) Shaped, deployed membrane to support vehicle passive stability
5) Redundant composite tapes
6) No motors / passive mechanism

MMA's dragNET De-orbit System meets NASA requirements for de-orbiting space assets in low earth orbit (LEO) and has successfully de-orbited the ORS-3 Minotaur I Upper Stage within a 2-year time frame. It features four compactly stowed, thin membranes that release using a single heater-powered actuator. The deployment is powered via the release of stored spring energy acting through articulating booms and, once tensioned, the membranes form a high-drag, aerodynamic shape to passively de-orbit the space asset thereby obviating the need for additional space-propulsion resources.

The drag augmentation system has also been designed with inherit performance redundancy by being designed to deorbit the system well within the required timeline, as described below. This additional margin provides further confidence for uncertainty in atmospheric models.

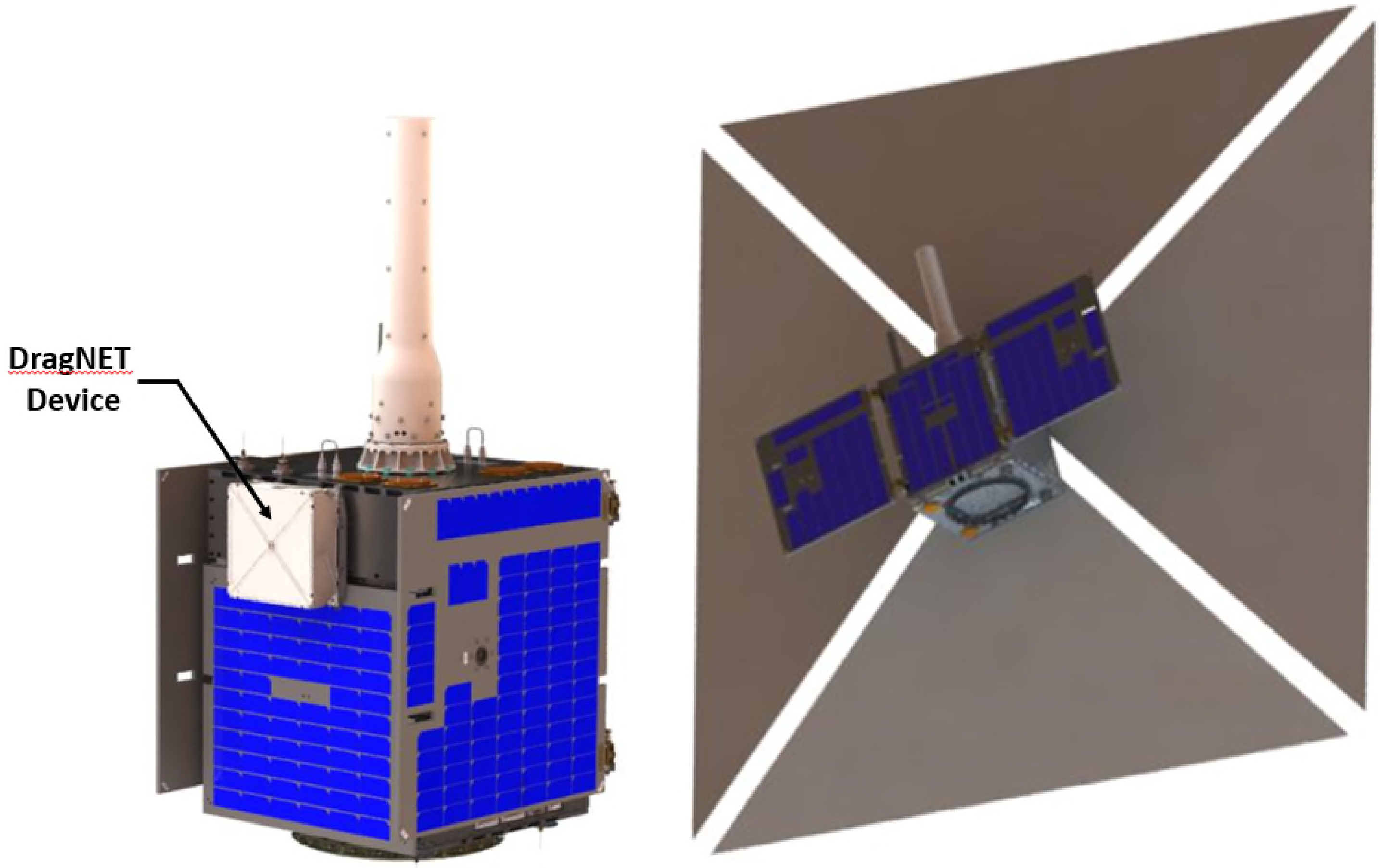

Figure 7: dragNET device (Left) stowed, (Right) deployed

Figure 8 shows the lifetime plot for the OTB-3 satellite after deployment of the drag augmentation device at end of mission. Assuming a launch date in late 2021, nominal orbit insertion at launch, with a 5 year mission lifetime: OTB-3 will de-orbit within 17.1 years from launch. Note this calculation assumes random tumble of the OTB-3 satellite after deployment. If at launch, OTB-3 is inserted to its orbit with the maximum semi-major axis error, the de-orbit time increases to 23.2 years from launch. In the event the drag augmentation device fails, the de-orbit time increases to 156 years from launch. As discussed below, however, the drag augmentation device, Frangibolt based release mechanism, has a minimum reliability of 0.99999 — this is the supplier published reliability for the TiNi Frangibolt and is the industry standard, with 20 years of space heritage.

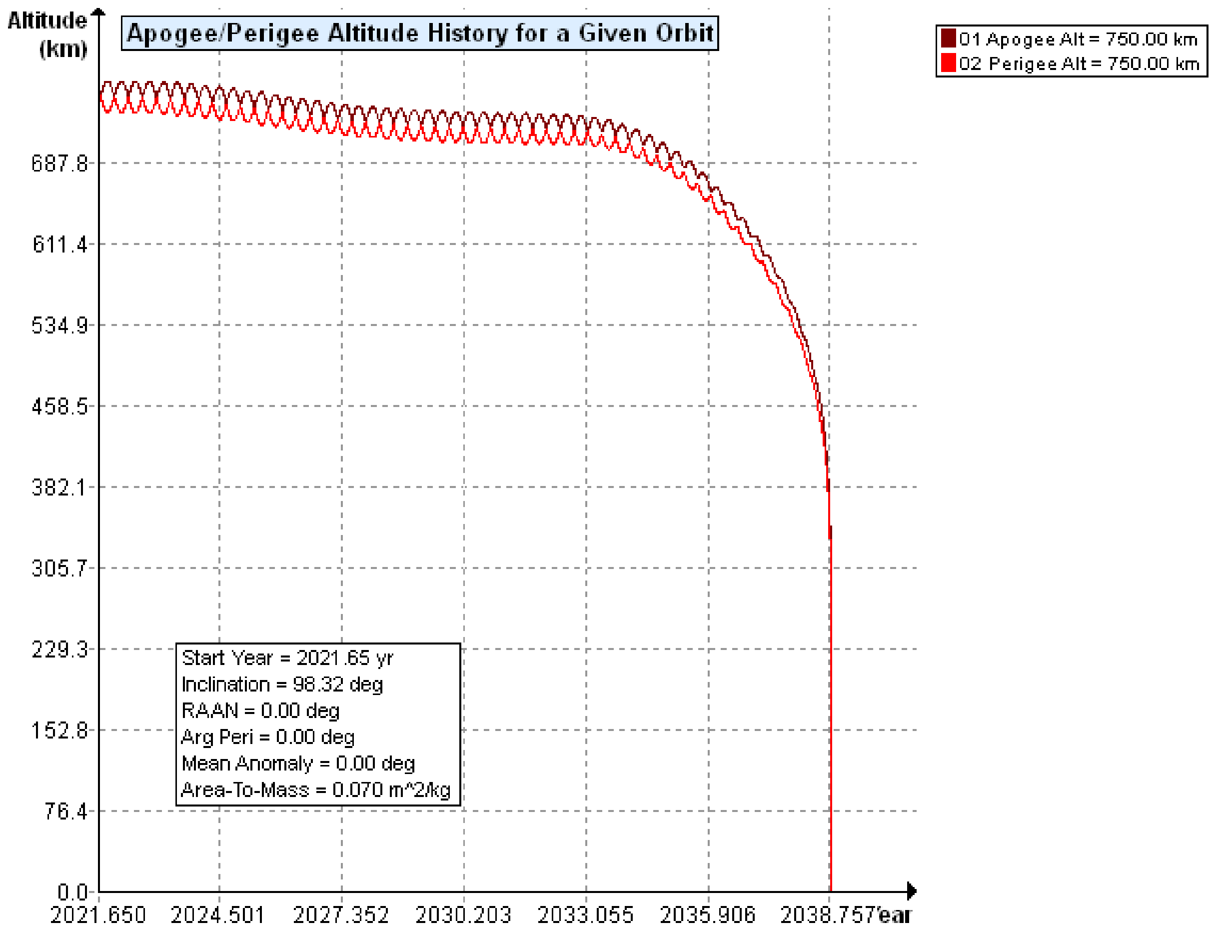

Figure 8: Orbital apogee/perigee altitude de-orbit using drag augmentation device

Calculation of area-to-mass ratio after postmission disposal, if the controlled reentry option is not selected. Effective area-to-mass ratio may change based on changes in attitude control at end-of-mission and end-of-life.

Table 6: Input parameters and outcome for probability of collision using DAS

Critical Surface	Probability of Penetration
Spacecraft Mass	120kg
Cross-Sectional Area	8.388m^2
Area to Mass Ration	0.0699 m^2/kg
<u>TOTAL PROBABILITY OF COLLISION WITH LARGE OBJECTS</u>	<u>0.00075</u>

If appropriate, preliminary plan for spacecraft controlled reentry

As described previously, OTB-3 will reenter the atmosphere naturally using drag, a plan for controlled reentry is not applicable.

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

<u>Requirement 4.6-1:</u> *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:*
  - *1) 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*
  - *2) Maneuver the space structure into a controlled deorbit 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.*

The OTB-3 satellite reentry is compliant using reentry option "a".

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

<u>Requirement 4.6-2:</u> *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).*

Not applicable. OTB-3 will be in LEO.

<u>Requirement 4.6-3:</u> *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).*

Not applicable. OTB-3 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.*

SSTL has a long heritage of successful missions, 49 spacecraft launched to date with over 500 years collectively on orbit, in part due to the multiple points of redundancy built into every mission design with a design life of 5 years or more. The drag augmentation device, Frangibolt based, has a minimum reliability of 0.99999 — this is the supplier published reliability for the TiNi Frangibolt and is the industry standard with 20 years of space heritage. The OTB-3 satellite is an "SSTL-150 ESPA" which is listed in the NASA Rapid III catalogue; it has a Ps of 92%. (Noting that SSTL have not had a mission failure on-orbit in over 15 years, and none with this class of satellite.)This gives us confidence that OTB-3 will be able to complete its 5 year mission and successfully deploy the drag augmentation devices at EOM, with a Ps = 0.91999.

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.*

Not applicable, OTB-3 does not have a controlled re-entry.

ODAR SECTION 7: ASSESSMENT OF SPACECRAFT REENTRY HAZARDS

Detailed description of spacecraft components by size, mass, material, shape, and original location on the space vehicle, if the atmospheric reentry option is selected

Table 7 summarizes the major components of the spacecraft input into the DAS software. The main structure of the spacecraft consists of three major sections, the avionics bay, lower payload bay, and upper payload bay. The avionics stack is contained within the avionics bay. The top-level items are shown in bold to indicate that they are modelled in DAS as "parents" to the items underneath them.

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

The DAS software calculates that there are several components within the main structure that may survive reentry, with a total debris casualty area of 7.5 m^2. These components are the Primary Payload, AOCS Interface Module (AIM), Active Safety Module (ASM), tie rods that support the avionics stack, the Argos Receiving Processing Unit (RPU) in the lower payload bay, and the Argos Transmitting Unit (TXU) in the upper payload bay. According to the DAS user's guide, the model does not simulate pre-heating of the internal objects. As a result, it is expected that the DAS calculation determining when the internal objects break-up is conservative. Additionally, the objects with high kinetic energy are conservatively modelled.

Calculation of probability of human casualty for the expected year of uncontrolled reentry and the spacecraft orbital inclination

The total probability of human casualty is 1:10,100, using DAS calculated results as shown in Figure 9. This is compliant to the requirement.

Table 7: Modelled components of the spacecraft

No.	Object Name	Qty	Material	Shape	Mass (kg)	Dimensions (m) Box: W x L x H Plate: W x L Cylinder: Diameter x L	Demise Altitude (km)	Total Debris Casualty Area (m^2)	Kinetic Energy (J)
1	**OTB-3**	**1**	**Aluminum**	**Box**	**120**	**0.574 x 0.859 x 0.574**		7.5	
2	**MLB**	**1**	**Aluminum**	**Box**	**0.67**	**0.381 x 0.381 x 0.053**	**76.5**	0	0
3	**Avionics Bay**	**1**	**Aluminum**	**Box**	**2.08**	**0.515 x 0.555**	**76.7**	0	0
4	Harness	1	Copper Alloy	Flat Plate	0.76	0.2 x 0.4	74.5	0	0
5	Magnetorquers	3	Aluminum	Cylinder	0.50	0.026 x 0.256	75.4	0	0
6	10SP Reaction Wheel	3	Aluminum	Cylinder	1.00	0.104 x 0.102	69.0	0	0
7	Battery	1	Aluminum	Box	4.40	0.159 x 0.221 x 0.068	61.0	0	0
8	Avionics Bay Fasteners	1	Aluminum	Box	4.00	0.2 x 0.2 x 0.2	66.8	0	0
9	Primary Payload	1	Aluminum	Box	1.00	0.294 x 0.322 x 0.033	70.6	0	0
10	**Avionics Stack**	**1**	**Aluminum**	**Box**	**8.80**	**0.515 x 0.547 x 0.288**	**64.5**	0	0
11	PIU	1	Fiberglass	Box	2.00	0.294 x 0.322 x 0.033	0.0	0.69	197.84
12	AIM	1	Fiberglass	Box	2.00	0.515 x 0.547 x 0.037	0.0	0.98	281.89
13	ASM	1	Fiberglass	Box	2.00	0.515 x 0.547 x 0.037	0.0	0.98	281.89
14	S-Band Tx/Rx	1	Fiberglass	Box	1.75	0.286 x 0.314 x 0.047	65.6	0	0
15	OBC 750	1	Fiberglass	Box	1.99	0.286 x 0.314 x 0.032	64.5	0	0
16	PDM	1	Fiberglass	Box	1.80	0.286 x 0.314 x 0.041	65.3	0	0
17	BCM	1	Fiberglass	Box	2.55	0.286 x 0.314 x 0.035	62.8	0	0
18	Tie Rods	8	Titanium	Cylinder	0.07	0.008 x 0.3	0.0	3.37	20.14
19	**Lower Payload Bay**	**1**	**Aluminum**	**Box**	**8.49**	**0.547 x 0.547 x 0.4**	**73.0**	0	0
20	Argos RPU	1	Aluminum	Box	14.37	0.304 x 0.305 x 0.2	0.0	0.77	21957.61
21	HDRM	2	Aluminum	Cylinder	0.66	0.12 x 0.093	67.7	0	0
22	Magnetometers	2	Aluminum	Box	0.22	0.061 x 0.099 x 0.05	70.4	0	0
23	Lower Payload Bay Fasteners	1	Aluminum	Box	2.00	0.1 x 0.1 x 0.1	57.3	0	0
24	**Upper Payload Bay**	**1**	**Aluminum**	**Box**	**8.15**	**0.547 x 0.58 x 0.2**	**71.9**	0	0
25	L-Band Transmitter	2	Aluminum	Cylinder	1.90	0.06 x 0.25	60.7	0	0

No.	Object Name	Qty	Material	Shape	Mass (kg)	Dimensions (m) Box: W x L x H Plate: W x L Cylinder: Diameter x L	Demise Altitude (km)	Total Debris Casualty Area (m^2)	Kinetic Energy (J)
26	Filter	1	Aluminum	Box	0.40	0.068 x 0.1 x 0.063	67.6	0	0
27	Switch	1	Aluminum	Box	0.10	0.068 x 0.1 x 0.063	70.9	0	0
28	Diplexer	1	Aluminum	Box	0.99	0.127 x 0.152 x 0.051	63.8	0	0
29	Argos TXU	1	Aluminum	Box	8.80	0.284 x 0.31 x 0.121	0.0	0.72	11299
30	Upper Payload Bay Fasteners	1	Aluminum	Box	2.00	0.1 x 0.1 x 0.1	55.6	0	0
31	**Argos UHF Antenna**	**1**	**Aluminum**	**Cylinder**	**2.80**	**0.136 x 0.082 x 0.067**	**73.7**	0	0
32	**S-Band Patch Antennas**	**6**	**Aluminum**	**Box**	**0.08**	**0.082 x 0.082 x 0.067**	**77.1**	0	0
33	**Monopole antenna**	**4**	**Aluminum**	**Cylinder**	**0.06**	**0.06 x 0.15**	**77.4**	0	0
34	**Argos L-Band Antenna**	**1**	**Aluminum**	**Cylinder**	**0.29**	**0.057 x 0.263**	**76.1**	0	0
35	**Radiator Panels**	**2**	**Aluminum**	**Flat Plate**	**1.90**	**0.58 x 0.7**	**75.2**	0	0
36	**Deployed Solar Panel**	**2**	**Aluminum**	**Flat Plate**	**2.90**	**0.58 x 0.934**	**74.6**	0	0
37	**Body Solar Panel**	**2**	**Aluminum**	**Flat Plate**	**1.19**	**0.55 x 0.55**	**75.8**	0	0
38	**Deorbit Sail**	**1**	**Polyamide**	**Flat Plate**	**2.80**	**0.45 x 2.8**	**77.7**	0	0
39	**Sun Sensors**	**2**	**Aluminum**	**Box**	**0.35**	**0.15 x 0.15 x 0.15**	**76.6**	0	0
40	**Sun Sensor Bracket**	**1**	**Aluminum**	**Box**	**0.28**	**0.15 x 0.15 x 0.15**	**76.9**	0	0
41	**External Fasteners**	**1**	**Aluminum**	**Box**	**4.00**	**0.2 x 0.2 x 0.2**	**68.3**	0	0

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).

Using the DAS software, OTB-3 complies with requirement 4.7-1, as the probability for human casualty does not exceed 1:10000 or 0.0001. Please see Figure 9.

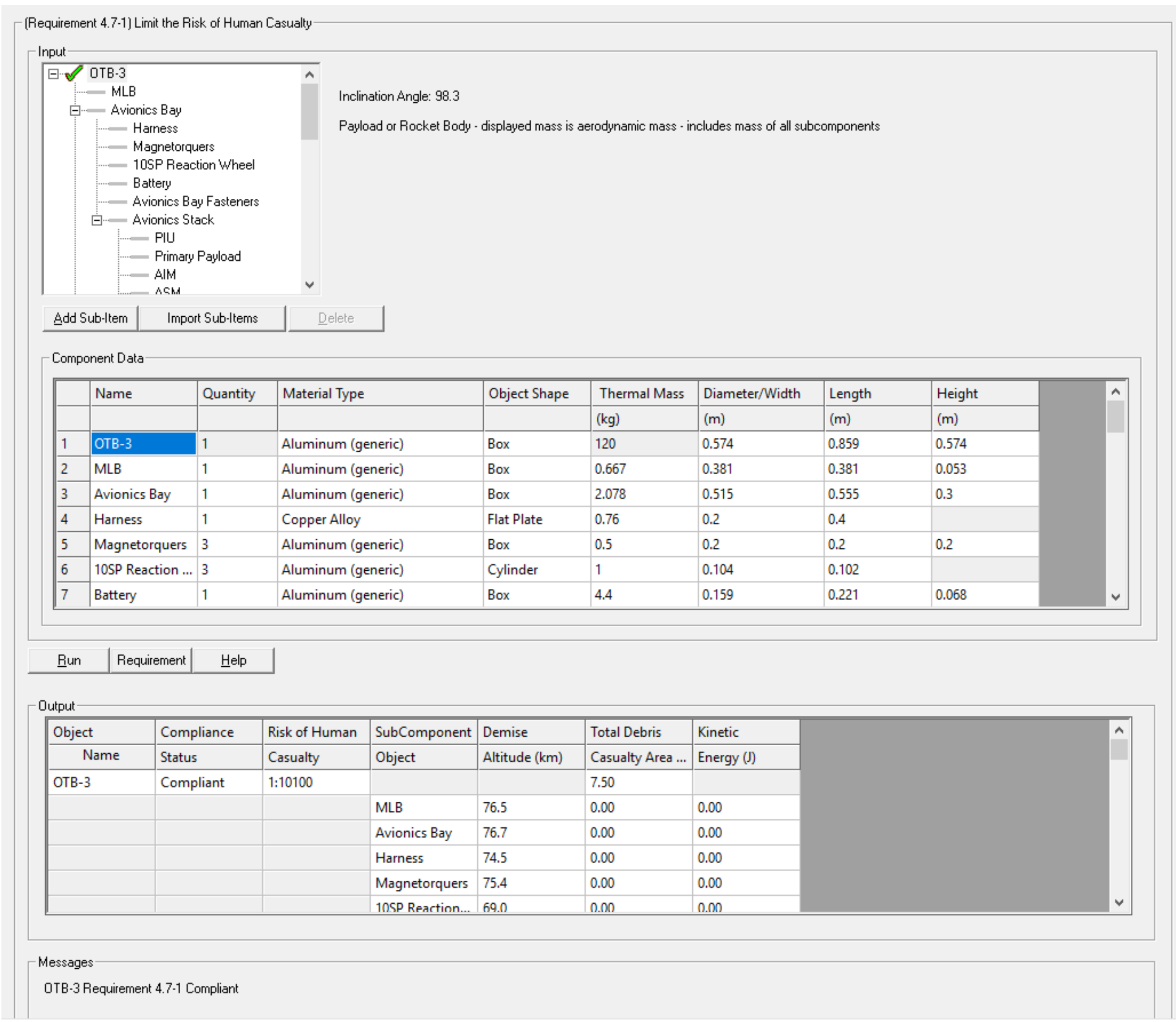

Figure 9: DAS Output for Requirement 4.7-1

ODAR SECTION 7A: ASSESSMENT OF SPACECRAFT HAZARDOUS MATERIALS

Summary of the hazardous materials contained on the spacecraft using all columns and the format in paragraph 4.7.4.10.

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 8.

Table 8: Hazardous Materials Data

Material Description	Material Hazard Presented		Material at Launch	Material During Operations	Material at EOM	Material at Passivation	Material Surviving Re-entry
Lithium	Ignition when in contact with water, corrosive	State	Solid	Solid	Solid	Solid	None
		Mass	24g	24g	24g	24g	
		Pressure	Ambient	Ambient	Ambient	Ambient	

ODAR SECTION 8: ASSESSMENT FOR TETHER MISSIONS

OTB-3 does not employ or carry tethers.