Orbital Debris Mitigation Plan
(Impulse – Impulse-4)

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I. Background

This orbital debris mitigation plan[1] is for the Impulse-4 spacecraft. Table 1 and Table 2 provide the input parameters for the various calculations in this document.

Table 1 captures the deployed spacecraft's mission, mass, area-to-mass ratio, and projected start date information.

Table 1: Deployed Spacecraft Information[2]

Mission Phase	Max Mass (kg)	Max Area to Mass (m^2/kg)	Projected Start Date
Post-Launch Vehicle Deployment	351	0.0235	July 31, 2026
Post-Mission Disposal	202	0.041	July 31, 2028

Table 2 summarizes the spacecraft launch vehicle, altitudes, and inclinations.

Table 2: Orbital Parameters

Satellite Name	Impulse-4
Launch Date	July 31, 2026
Launch Vehicle	SpaceX Falcon 9
Operational Perigee Altitude (km)	175-850
Operational Apogee Altitude (km)	325-1600
Operational Inclination (deg)	88.0 ± 2.0

[1] This orbital debris mitigation plan uses National Aeronautics and Space Administration (NASA) Debris Assessment Software (DAS) version 3.2.6, Object Reentry Survival Analysis Tool (ORSAT) version 7.1, and Micrometeoroid and Debris Risk Assessment BUMPER3-SAT-3.24.0410.0.

[2] The stowed satellite's maximum mass is 351 kg and area-to-mass ratio is 0.0078 (m^2/kg).

II. 47 C.F.R. § 25.114(d)(14) Compliance Showing

(14) A description of the design and operational strategies that will be used to mitigate orbital debris, including the following information:

(i) A statement that the space station operator has assessed and limited the amount of debris released in a planned manner during normal operations. Where applicable, this statement must include an orbital debris mitigation disclosure for any separate deployment devices, distinct from the space station launch vehicle, that may become a source of orbital debris;

Impulse has assessed and limited the amount of debris released in a planned manner during normal operations. There are no intentional releases.

(ii) A statement indicating whether the space station operator has assessed and limited the probability that the space station(s) will become a source of debris by collision with small debris or meteoroids that would cause loss of control and prevent disposal. The statement must indicate whether this probability for an individual space station is 0.01 (1 in 100) or less, as calculated using the NASA Debris Assessment Software or a higher fidelity assessment tool;

Impulse has assessed and limited the probability that Impulse-4 will become a source of debris by collision with small debris or meteoroids that would cause loss of control and prevent disposal. Table 3 summarizes the small object collision risk, and Table 4 summarizes the maximum time that Impulse-4 may operate in any orbital shell to ensure that Impulse-4's accidental collision with small debris and meteoroids (MMOD) remains below 0.01.[3]

Impulse-4's primary pointing mode includes a sun-relative attitude constraint for power generation, and as a result, the spacecraft face exposed to the highest MMOD flux will change over the orbit as a function of the solar beta angle. At low beta angles, the spacecraft +X face will be aligned with the velocity vector (+XVV) and will experience the highest MMOD flux. At high absolute beta angles, the +Y or –Y faces will be aligned with the velocity vector (+YVV, -YVV). At mid-beta angles, a blend of +X and +Y or –Y faces will be exposed to the highest MMOD flux over the course of the orbit. Bumper code is not able to explicitly simulate sun-relative attitudes, so a blend of runs with varying attitudes was performed consistent with NASA JSC recommended practice. For a high-inclination mission, which is expected to experience the full range of solar beta angles, a simple blend of 50% $+X_{VV}$, 25% $+Y_{VV}$, and 25% $-Y_{VV}$ was performed to determine total mission MMOD risk.

[3] MMOD risk is calculated at the altitude where the MMOD risk is the highest within the range provided.

Table 3: Small Object Collision Risk

Apogee Orbit (km)	Perigee Orbit (km)	Total MMOD Penetrations (per year)			
		+Xvv	+Yvv	-Yvv	Mission Attitude Blend
350 ± 25	200 ± 25	5.46E-04	5.26E-04	7.68E-04	5.96E-04
450 ± 25	450 ± 25	3.58E-03	2.07E-03	2.34E-03	2.89E-03
500 ± 50	500 ± 50	1.01E-02	5.17E-03	5.44E-03	7.70E-03
600 ± 50	600 ± 50	2.00E-02	1.10E-02	1.13E-02	1.56E-02
800 ± 50	800 ± 50	4.15E-02	2.70E-02	2.73E-02	3.43E-02
1150 ± 150	450 ± 25	2.75E-02	1.81E-02	1.84E-02	2.29E-02
1450 ± 150	450±25	1.65E-02	1.06E-02	1.08E-02	1.36E-02

Table 4: Small Object Allowable Mission Duration

Apogee Orbit (km)	Perigee Orbit (km)	Total MMOD Penetrations (#/year)	Probability Exceedance Duration > 0.01 (Months)
350 ± 25	200 ± 25	5.96E-04	202
450 ± 25	450 ± 25	2.89E-03	42
500 ± 50	500 ± 50	7.70E-03	16
600 ± 50	600 ± 50	1.56E-02	8
800 ± 50	800 ± 50	3.43E-02	4
1150 ± 150	450 ± 25	2.29E-02	5
1450 ± 150	450 ± 25	1.36E-02	9

(iii) A statement that the space station operator has assessed and limited the probability, during and after completion of mission operations, of accidental explosions or of release of liquids that will persist in droplet form. This statement must include a demonstration that debris generation will not result from the conversion of energy sources on board the spacecraft into energy that fragments the spacecraft. Energy sources include chemical, pressure, and kinetic energy. This demonstration should address whether stored energy will be removed at the spacecraft's end of life, by depleting residual fuel and leaving all fuel line valves open, venting any pressurized system, leaving all batteries in a permanent discharge state, and removing any remaining source of stored energy, or through other equivalent procedures specifically disclosed in the application;

Impulse has assessed and limited the probability, during and after completion of mission operations, of accidental explosions or release of liquids that will persist in droplet form. All credible spacecraft failure modes that would result in accidental debris generation are detailed below, along with the probability of occurrence and mitigation strategy. Stored energy will be removed at the spacecraft's end of life as covered below.

<u>Saiph Thruster Explosion</u>:

- **Effect**: An off-nominal ignition event that could cause debris to be generated.

- **Probability**: Extremely low, estimated to be orders of magnitude less than 0.001.
- **Mitigation**: Current testing of the Saiph thrusters demonstrates that there have been over 100,000 pulses of the Saiph thruster to date without an uncontained failure.

Pressure Vessel Explosion:

- **Effect**: A rupture of a propellant tank would release ethane or nitrous oxide gas. The leak would induce a body rate on the spacecraft, but no additional material would be generated. Neither nitrous oxide nor ethane will create persistent droplets that would cause debris concerns through leaks or intentional release.
- **Probability**: Extremely low, estimated to be orders of magnitude less than 0.001.
- **Mitigation**: Tanks are expected to leak before bursting.[4]
    - Nitrous Oxide Tank: The tank design minimum burst pressure is 2452 psi, which is greater than 2x maximum expected operating pressure (MEOP) psi. Tank burst testing demonstrated leak-before-burst occurred at over 3000 psi. Additionally, the tank implements a burst disk and relief valve protection set to relieve at 1139 psi. Nominal tank pressure is 750 psi, which is the fluid-saturated condition at 70 degrees F. Thermal environments are not expected to increase tank pressure up to the relief pressure.
    - Ethane Tank: The tank design minimum burst pressure is 2452 psi, which is greater than 2x MEOP psi. Tank burst testing demonstrated leak-before-burst occurred at over 3000 psi. Additionally, the tank implements a burst disk and relief valve protection set to relieve at 1139 psi. Nominal tank pressure is 560 psi, which is the fluid-saturated condition at 70 degrees F. Thermal environments are not expected to increase tank pressure up to the relief pressure.

Accumulator Explosion:

- **Effect**: A rupture of an accumulator would release ethane or nitrous oxide. The leak would induce a tumble on the spacecraft, but no additional material would be generated.
- **Probability**: Extremely low, estimated to be orders of magnitude less than 0.001.
- **Mitigation**:
    - Accumulators leak before bursting and thus do not present any risk of debris generation.
    - Both accumulators have a design burst pressure of 2849 psi whereas nominal operation is at 400 psi.
    - Orbital thermal environments are not expected to increase accumulator pressure to the design burst pressure. Telemetry from current spacecraft shows that the pressures in the manifold stay in the saturated region.

[4] The ethane gas is stored in one tank with a volume of 90 L. The nitrous oxide gas is stored in two tanks with a total volume of 180 L. A total of 27.9 kg of ethane and 121.5 kg of nitrous oxide is self-pressurized to 560 and 750 psi, respectively, before launch.

Battery Explosion:

- **Effect**: A rupture of a battery cell would release hot gases and possibly other debris. The gas and debris would be contained inside the aluminum enclosure, and the gas would vent in a controlled manner through vents on the sides of the enclosure.
- **Probability**: Extremely low, estimated to be orders of magnitude less than 0.001.
- **Mitigation**:
    - o The battery cells used in the construction of the packs are commercially available Lithium-Ion cells certified to UL 1642. UL1642 requires that a cell overcharge, short circuit, or forced discharge shall not result in an explosion, and requires that if venting occurs to mitigate pressure build-up, the battery case will prevent dimensional expansion.
    - o The battery pack includes external overvoltage, undervoltage, overcurrent, and short-circuit protection circuits that prevent the cells from operating under adverse circumstances.
    - o The battery cells are contained inside a vented aluminum enclosure that prevents crushing and contains any gas or debris that might be produced in the unlikely event of a runaway cell.
    - o The expected operating temperature range is well within the temperature rating of the cells.
    - o The battery cells, protection circuits, enclosure, and external loads are all environmentally acceptance-tested prior to spacecraft installation.

(iv) A statement that the space station operator has assessed and limited the probability of the space station(s) becoming a source of debris by collisions with large debris or other operational space stations.

Impulse-4 has assessed and limited the probability of the spacecraft becoming a source of debris by collisions with large debris or other operational space stations. See the following responses.

(A) Where the application is for an NGSO space station or system, the following information must also be included:

(1) A demonstration that the space station operator has assessed and limited the probability of collision between any space station of the system and other large objects (10 cm or larger in diameter) during the total orbital lifetime of the space station, including any de-orbit phases, to less than 0.001 (1 in 1,000). The probability shall be calculated using the NASA Debris Assessment Software or a higher fidelity assessment tool. The collision risk may be assumed zero for a space station during any period in which the space station will be maneuvered effectively to avoid colliding with large objects.

Impulse-4 may operate in a broad altitude and inclination range. Table 5 summarizes the maximum time that Impulse-4 may operate in any orbital altitude shell to ensure that Impulse-4's accidental collision with large objects remains below 0.001. Impulse-4 will maneuver to avoid large object collisions, so this allowable duration is applicable only once the vehicle is passivated at end of mission.

Table 5: Large Object Collision Risk

Apogee Orbit (km)	Perigee Orbit (km)	Collision Risk Probability	Probability Exceedance Duration > 0.001 (Months)
350 ± 25	200 ± 25	1.5405E-06	7792
450 ± 25	450 ± 25	1.6173E-05	741
500 ± 50	500 ± 50	2.9031E-05	414
600 ± 50	600 ± 50	3.3285E-04	36
800 ± 50	800 ± 50	3.2173E-03	4
1150 ± 150	450 ± 25	3.6190E-04	33
1450 ± 150	450 ± 25	3.4805E-04	34

(2) The statement must identify characteristics of the space station(s)' orbits that may present a collision risk, including any planned and/or operational 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.

Other spacecraft operators are authorized at or below the proposed altitude range (as published in the FCC Approved Space Station List and ITU SpaceExplorer Database). Impulse will coordinate with these operators as required to minimize collision risk. Further, Impulse is working with Kayhan Space for conjunction notification and analyses supported by high-fidelity ephemeris and its advanced collision analysis software, Pathfinder. Impulse is also working with SpaceX's Starlink Collision Avoidance Team to proactively share ephemeris data for its automated avoidance maneuvering system.

(3) 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, the statement must 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.

Impulse is committed to being a responsible space steward. Impulse-4's orbit plan includes operations at altitudes near the International Space Station (ISS) and the Tiangong Space Station. Impulse-4 will maintain an inclination of 88.0 ± 2 degrees to allow separation from inhabitable spacecraft (ISS at ~51.6 deg; Tiangong at ~41.6 deg). In addition, Impulse will coordinate with operators and the 18th Space Defense Squadron to minimize the probability of a collision occurring between respective spacecraft prior to disposal. This, in combination with the low collision probabilities calculated above, eliminates any collision risk with inhabitable space stations.

(4) The statement must disclose 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 is not able to maintain orbital tolerances, **e.g.,** ***its propulsion system will not be used for orbital maintenance, that fact must 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.

Impulse-4 is expected to maintain an orbital tolerance of ±50 km altitude and ±2.0 degrees inclination but is capable of being more precise as required. Maneuvering is possible using the propulsion or the attitude control system as described below.

Propulsion

Impulse-4 uses four pods of three cold gas thrusters. These cold gas thrusters can provide a small delta-v amount to perform collision avoidance maneuvers with other spacecraft or debris.
Impulse-4 uses the main Saiph thrusters in "cold flow mode" for attitude control (RCS), including nitrous oxide gas as the propellant. Impulse-4's Saiph thrusters support large delta-v maneuvers.

Attitude Control System

The Guidance, Navigation, and Control (GNC) system consists of star trackers, inertial measurement units (IMUs) (each containing accelerometers and gyroscopes), reaction wheels, 3-axis cold gas thruster clusters, sun sensors, and Global Positioning System (GPS) receivers, including GPS antennas. This system will maintain a pointing accuracy of <10 arcsec (1σ) and a GPS accuracy of better than 10 meters (1σ) but can be more precise as required.

The GNC subsystem has several operational modes that enable the spacecraft to execute its mission:

- A series of states comprises *safe mode*, which is entered after flight-computer boot or autonomously by the flight software when it detects a critical vehicle fault.
    - A *rate null mode* slows body rates toward zero and transitions to safe-spins or safe-pointing.
    - A *safe spin mode* is entered if there is not a valid attitude solution, but body rates are low. The spacecraft will begin a lighthouse maneuver and roll until it acquires the sun.
    - A *safe-pointing mode (standby mode)* is used to maximize solar power generation when the sun-to-body vector is known. In this mode, the spacecraft will maintain its solar panels pointing towards the Sun using solar panel illumination measurements.

- A *mission pointing mode* is used to maximize solar power generation while allowing for slewing and orienting the spacecraft's body frame in relation to a variety of inertial and rotating frames using star trackers and IMUs. This mode is used for slewing to and tracking ground stations, payload deployments, collision avoidance, and attitude maneuvers.

During nominal operations, the reaction wheels provide 3-axis attitude control. The nominal vehicle attitude is nadir pointing (with the +X axis of the vehicle aligned with the center of the Earth), and the solar arrays are angled toward the Sun vector.

(5) The space station operator must certify 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. As appropriate, steps to assess and mitigate

the collision risk should include, but are not limited to: Contacting the operator of any active spacecraft involved in such a warning; sharing ephemeris data and other appropriate operational information with any such operator; and modifying space station attitude and/or operations.

Impulse certifies that upon receipt of an SSA conjunction warning, its Mission Operations team will review and take all possible steps to assess the collision risk and will mitigate the collision risk if necessary. As appropriate, steps to assess and mitigate the collision risk will include, but are not limited to, contacting the operator of any active spacecraft involved in such a warning; sharing ephemeris data and other appropriate operational information with any such operator; and modifying spacecraft attitude and/or operations.

Collision avoidance planning will occur if a conjunction prediction falls into the Emergency Criteria specified in the SDS' Spaceflight Safety Handbook for Satellite Operators (*i.e.*, time of closest approach ≤ 3 days, overall miss ≤ 1 km, and probability of collision ("Pc") ≥ 1E-4). If the Pc is greater than 1E-4, Impulse plans to initiate coordination, as applicable, with the operator of the other on-orbit asset for collision avoidance. Following best practices, when a conjunction's Pc exceeds 1E-4, the pursued mitigation action will reduce the Pc by at least 1.5 orders of magnitude from the threshold.

(B) Where a space station requests the assignment of a geostationary orbit location, it must assess whether there are any known satellites located at, or reasonably expected to be located at, the requested orbital location, or assigned in the vicinity of that location, such that the station keeping volumes of the respective satellites might overlap or touch. If so, the statement must include a statement as to the identities of those satellites and the measures that will be taken to prevent collisions;

Not applicable.

(v) A statement addressing the trackability of the space station(s). Space station(s) operating in low-Earth orbit will be presumed trackable if each individual space station is 10 cm or larger in its smallest dimension, excluding deployable components.

The spacecraft is presumed trackable given its smallest dimension is 35 cm.

Where the application is for an NGSO space station or system, the statement shall also disclose the following:

(A) How the operator plans to identify the space station(s) following deployment and whether space station tracking will be active or passive;

Impulse-4 will be passively tracked via Space Force radar. Impulse-4 will also be actively tracked using GPS telemetry and a unique command-and-telemetry protocol that guarantees the correct spacecraft is identified from the ground.

(B) Whether, prior to deployment, the space station(s) will be registered with the 18th Space Control Squadron or successor entity; and

Impulse will register Impulse-4 with the 18th Space Defense Squadron (or successor entity) before deployment via its Satellite Registration Form and Space Situational Awareness Sharing Agreement.

(C) 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.

Impulse will routinely share deployment plans, ephemeris data, and planned maneuvers of the spacecraft with the 18th Space Defense Squadron (or successor entity) as available or as requested.

(vi) A statement disclosing planned proximity operations, if any, and addressing debris generation that will or may result from the proposed operations, including any planned release of debris, the risk of accidental explosions, the risk of accidental collision, and measures taken to mitigate those risks.

Not applicable. No proximity operations are planned.

(vii) A statement detailing the disposal plans for the space station, including the quantity of fuel—if any—that will be reserved for disposal maneuvers.

Impulse-4 will be disposed of via uncontrolled atmospheric reentry. Prior to atmospheric reentry, Impulse-4 will passivate the reaction wheels, propulsion system, and batteries. Identification of all systems or components required to accomplish any post-mission disposal operation, including passivation, is included below by subsystem.

Reaction Wheels

- Momentum will be dumped from the wheels for a final time at end of mission via the cold gas RCS system.
- Required systems:
  - Flight computer
  - Battery management system (BMS)
  - Actuator controllers (1-fault-tolerant peripheral boards that command solenoids and reads sensors for the thrusters and reaction wheels)
  - Reaction wheel motors

Propellant

- All remaining propellant will be vented through the thruster system at end of mission. Without active control through RCS, the vehicle will tumble.
- Required systems:
  - Flight computer
  - BMS

- Actuator controllers (1-fault-tolerant peripheral boards which command solenoids and reads sensors relating to the thrusters and reaction wheels)
- Solenoid valves

Batteries

- Batteries will be commanded to permanently disconnect from solar panels. Residual battery charge will be discharged with a slow bleed-off circuit.
- Required systems:
    - Flight computer
    - BMS

In addition, the following specific provisions apply:
(A) For geostationary orbit space stations, the statement must disclose the altitude selected for a disposal orbit and the calculations that are used in deriving the disposal altitude.

Not applicable.

(B) For space stations terminating operations in an orbit in or passing through the low-Earth orbit region below 2,000 km altitude, the statement must disclose whether the spacecraft will be disposed of through atmospheric re-entry, specifying if direct retrieval of the spacecraft will be used. The statement must also disclose the expected time in orbit for the space station following the completion of the mission.

Impulse-4 will be disposed of via uncontrolled atmospheric reentry (with no direct spacecraft retrieval). The final disposal orbit will be 450 x 450 km and result in an orbital lifetime of 0.717 years. Section III.C includes the supporting inputs and calculations.[5]

(C) For space stations not covered by either paragraph (d)(14)(vii)(A) or (B) of this section, the statement must indicate whether disposal will involve use of a storage orbit or long-term atmospheric re-entry and rationale for the selected disposal plan.

Not applicable.

(D) For all space stations under paragraph (d)(14)(vii)(B) or (C) of this section, the following additional specific provisions apply:

(1) The statement must include a demonstration that the probability of success of the chosen disposal method will be 0.9 or greater for any individual space station. For space station systems consisting of multiple space stations, the demonstration should include additional information regarding efforts to achieve a higher probability of success, with a goal, for large systems, of a probability of success for any individual space station of 0.99 or better. For space stations under paragraph (d)(14)(vii)(B) of this section ending their mission in or passing through the low-Earth orbit region below 2000 km altitude, successful disposal is defined, for the purposes of

[5] In the scenario where Mira does not deploy solar arrays and dies at the drop off altitude of 500 km circular, then the estimated orbital lifetime is 7.5 years.

this demonstration, as atmospheric re-entry of the spacecraft as soon as practicable, but no later than five years following completion of the mission. For all other space stations under paragraph (d)(14)(vii)(B) and paragraph (d)(14)(vii)(C) of this section, successful disposal will be assessed on a case-by-case basis.

Impulse has a multipronged approach to ensuring a 0.9 or greater probability of achieving the planned end-of-life disposal orbit.

<u>Fault-Tolerant System Design</u>: Wherever possible, Impulse has designed for fault tolerance in critical systems and components.

- 8 flight-proven bi-propellant main thrusters (Saiphs) with a control system that is tolerant to any one thruster failing to ignite
- 12 flight-proven cold gas RCS thrusters, supplemented by qty. 4 Saiph thrusters in "cold gas" mode, to allow for tolerance of any single thruster failing to actuate while maintaining 3-axis control.
- The electronics architecture and GNC sensor suite are tolerant to a failure of any single electronic component while retaining the ability to execute end-of-life operations:
  - 2 flight computers in a primary/backup configuration
  - 5 star trackers
  - 4 reaction wheels (tolerant to one faulting with RCS system as a further backup)
  - 2 GPS receivers
  - 2 IMUs
  - 4 sun sensor elements (safe mode still tolerant to one broken sensor element)
- The power system's architecture is also tolerant of a failure of a single major component.
  - 2 battery packs (tolerant to either pack ceasing function)
  - 2 solar array drive assemblies (units to ensure at least one solar array remains sun-pointing)
- The fluids system architecture is tolerant to many common component-level failures while retaining the ability to execute end-of-life operations.
  - Critical control sensors are redundant.
  - Propellant accumulator pressurization valves are redundant to protect against a single valve failing to open. Valves are sized such that two of the three valves can control accumulator pressure.
  - 2 valve seats exist between bulk-stored propellant and space to protect against a single, very leaky valve draining propellant.
- The radio frequency communications system has redundant paths for uplink and downlink.
  - 2 radios (primary and backup), each capable of both uplink and downlink.

In addition to these redundancy features, Impulse-4 is designed with robust dead-bus recovery capability, which will allow the bus to recover from any unforeseen circumstances that lead to a loss of power.

Impulse also designs all critical electronics to derating standards like NASA EEE-INST-002's derating standards. These derating standards greatly reduce the stresses to which individual parts are subjected. By following these derating standards, the components will use considerably less of their "cycle range" and prolong their lifetimes.

Component-Level Testing: All critical components (including those without prior flight heritage) are planned to be tested to SMC-S-016 (Air Force Space Command, Space & Missile Systems Center Standard, 'Test Requirements for Launch, Upper-Stage, and Space Vehicles') with tailoring. Test plans for proto-qualification and qualification include inspection, performance, and vibration as well as combinations of thermal cycling, thermal vacuum testing, and shock. For unit acceptance testing, the tests required are inspection, performance, vibration, and thermal cycling. SMC-S-016's testing plan was designed to screen components past "infant mortality" to significantly reduce the likelihood of component failure on orbit.

Radiation Testing: All internally designed critical electronics have radiation testing planned, with some testing already complete. This testing is done with either heavy ions, high-energy protons, or both under conditions replicating the worst-case circuit-loading conditions to maximize electric field stress in devices under test. Additionally, the spacecraft's critical processors have flown on Impulse-1 and Impulse-2 in similar orbits with demonstrated good radiation performance.

Functional Assembly Testing: The full spacecraft will undergo a full testing suite after assembly, including –

- performance and functional testing;
- sensor end-to-end and polarity testing;
- electromagnetic self-compatibility testing;
- random vibration testing;
- quasi-static load testing; and
- pressure system testing.

Verification & Validation Approach: In addition to the full environmental testing suite the spacecraft will undergo, Impulse utilizes both a hardware-in-the-loop (HITL) testbed and a "flatsat" testbed. On these testbeds, continuous integration/continuous deployment (CI/CD) pipelines push software and perform automated verification and validation test cases. CI/CD ensures no regressions in software capability while developers improve software. The HITL testbed consists of all core avionics components with simulated sensor inputs and actuator outputs, connected to a 6-degree-of-freedom physics simulator for closed-loop functionality. The test suite demonstrates that the software is operating correctly in the presence of sensor data and performing as expected. Test cases include full first boot, simulated orbital maneuvers, and ground-contact testing using radio hardware.

The flatsat testbed consists of all flight-like hardware installed on the spacecraft, including all actual sensors (instead of simulated on the HITL testbed). This testbed allows Impulse to fully test all spacecraft interfaces and ensure full compatibility of hardware/software interactions.

(2) If planned disposal is by atmospheric re-entry, the statement must also include:

(i) A disclosure indicating whether the atmospheric re-entry will be an uncontrolled re-entry or a controlled targeted reentry.

Atmospheric reentry will be uncontrolled.

(ii) An assessment as to whether portions of any individual spacecraft will survive atmospheric reentry and impact the surface of the Earth with a kinetic energy in excess of 15 joules, and demonstration that the calculated casualty risk for an individual spacecraft using the NASA Debris Assessment Software or a higher fidelity assessment tool is less than 0.0001 (1 in 10,000).

Using ORSAT, the human casualty risk is 1 in 16,777.

The ORSAT model does not include mission-specific antennas and commercial-off-the-shelf star tracker added to Impulse-4. Evaluation with DAS confirmed that these components fully demise and do not contribute to casualty risk.

(E) Applicants for space stations to be used only for commercial remote sensing may, in lieu of submitting detailed post-mission disposal plans to the Commission, certify that they have submitted such plans to the National Oceanic and Atmospheric Administration for review.

Not applicable.

(viii) For non-U.S.-licensed space stations, the requirement to describe the design and operational strategies to minimize orbital debris risk can be satisfied by demonstrating that debris mitigation plans for the space station(s) for which U.S. market access is requested are subject to direct and effective regulatory oversight by the national licensing authority.

Not applicable.

III. Debris Assessment Software Activity Logs

A. Small Object Collision Risk

Impulse-defined orbits in (1) ORDEM to determine the orbital debris environment (see Figure 6) and (2) General Mission Analysis Tool to determine orbital velocities, which are then input into MEM to define the micrometeoroid environment (see Figure 7).

Figure 6: Sample ORDEM Screenshot

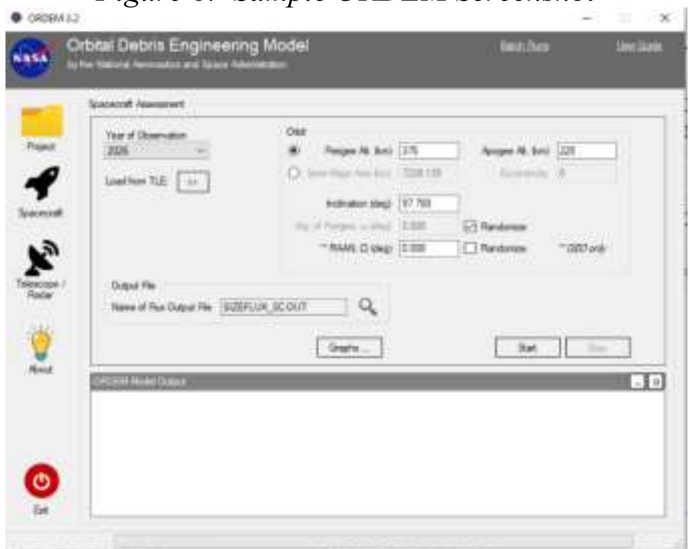
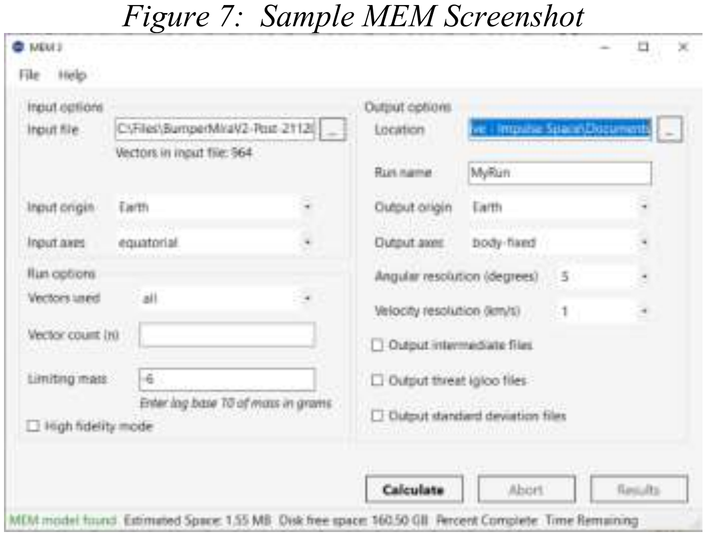


Figure 7: Sample MEM Screenshot



The logs are available in the folder below and attached to the Impule-4 application.

Impulse - Impulse-4 - ODMP Small Object Collision Risk Logs - 03-04-26 (final).zip

B. Large Object Collision Risk

INPUT

Space Structure Name = Orbit 1
Space Structure Type = Payload
Perigee Altitude = 200.000 (km)
Apogee Altitude = 350.000 (km)
Inclination = 88.000 (deg)
RAAN = 0.000 (deg)
Argument of Perigee = 0.000 (deg)
Mean Anomaly = 0.000 (deg)
Final Area-To-Mass Ratio = 0.0410 (m^2/kg)
Start Year = 2026.600 (yr)
Initial Mass = 351.000 (kg)
Final Mass = 202.000 (kg)
Duration = 1.000 (yr)
Station-Kept = True
Abandoned = True
Long-Term Reentry = False

OUTPUT

Collision Probability = 1.5405E-06
Returned Message: Normal Processing
Date Range Message: Normal Date Range
Status = Pass

INPUT

Space Structure Name = Orbit 2
Space Structure Type = Payload
Perigee Altitude = 450.000 (km)
Apogee Altitude = 450.000 (km)
Inclination = 88.000 (deg)
RAAN = 0.000 (deg)
Argument of Perigee = 0.000 (deg)
Mean Anomaly = 0.000 (deg)
Final Area-To-Mass Ratio = 0.0410 (m^2/kg)
Start Year = 2026.600 (yr)
Initial Mass = 351.000 (kg)
Final Mass = 202.000 (kg)
Duration = 1.000 (yr)
Station-Kept = True
Abandoned = True
Long-Term Reentry = False

OUTPUT

Collision Probability = 1.6173E-05
Returned Message: Normal Processing
Date Range Message: Normal Date Range
Status = Pass

INPUT

Space Structure Name = Orbit 3
Space Structure Type = Payload
Perigee Altitude = 500.000 (km)
Apogee Altitude = 500.000 (km)
Inclination = 88.000 (deg)
RAAN = 0.000 (deg)
Argument of Perigee = 0.000 (deg)
Mean Anomaly = 0.000 (deg)
Final Area-To-Mass Ratio = 0.0410 (m^2/kg)
Start Year = 2026.600 (yr)
Initial Mass = 351.000 (kg)
Final Mass = 202.000 (kg)
Duration = 1.000 (yr)
Station-Kept = True
Abandoned = True
Long-Term Reentry = False

OUTPUT

Collision Probability = 2.9031E-05
Returned Message: Normal Processing
Date Range Message: Normal Date Range
Status = Pass

INPUT

Space Structure Name = Orbit 4
Space Structure Type = Payload
Perigee Altitude = 600.000 (km)
Apogee Altitude = 600.000 (km)
Inclination = 88.000 (deg)
RAAN = 0.000 (deg)
Argument of Perigee = 0.000 (deg)
Mean Anomaly = 0.000 (deg)
Final Area-To-Mass Ratio = 0.0410 (m^2/kg)
Start Year = 2026.600 (yr)

Initial Mass = 351.000 (kg)
Final Mass = 202.000 (kg)
Duration = 1.000 (yr)
Station-Kept = True
Abandoned = True
Long-Term Reentry = False

OUTPUT

Collision Probability = 3.3285E-04
Returned Message: Normal Processing
Date Range Message: Normal Date Range
Status = Pass

INPUT

Space Structure Name = Orbit 5
Space Structure Type = Payload
Perigee Altitude = 800.000 (km)
Apogee Altitude = 800.000 (km)
Inclination = 88.000 (deg)
RAAN = 0.000 (deg)
Argument of Perigee = 0.000 (deg)
Mean Anomaly = 0.000 (deg)
Final Area-To-Mass Ratio = 0.0410 (m^2/kg)
Start Year = 2026.600 (yr)
Initial Mass = 351.000 (kg)
Final Mass = 202.000 (kg)
Duration = 1.000 (yr)
Station-Kept = True
Abandoned = True
Long-Term Reentry = False

OUTPUT

Collision Probability = 3.2173E-03
Returned Message: Normal Processing
Date Range Message: Normal Date Range
Status = Fail

INPUT

Space Structure Name = Orbit 6
Space Structure Type = Payload
Perigee Altitude = 450.000 (km)
Apogee Altitude = 1150.000 (km)

Inclination = 88.000 (deg)
RAAN = 0.000 (deg)
Argument of Perigee = 0.000 (deg)
Mean Anomaly = 0.000 (deg)
Final Area-To-Mass Ratio = 0.0410 (m^2/kg)
Start Year = 2026.600 (yr)
Initial Mass = 351.000 (kg)
Final Mass = 202.000 (kg)
Duration = 1.000 (yr)
Station-Kept = True
Abandoned = True
Long-Term Reentry = False

OUTPUT

Collision Probability = 3.6190E-04
Returned Message: Normal Processing
Date Range Message: Normal Date Range
Status = Pass

INPUT

Space Structure Name = Orbit 7
Space Structure Type = Payload
Perigee Altitude = 450.000 (km)
Apogee Altitude = 1450.000 (km)
Inclination = 88.000 (deg)
RAAN = 0.000 (deg)
Argument of Perigee = 0.000 (deg)
Mean Anomaly = 0.000 (deg)
Final Area-To-Mass Ratio = 0.0410 (m^2/kg)
Start Year = 2026.600 (yr)
Initial Mass = 351.000 (kg)
Final Mass = 202.000 (kg)
Duration = 1.000 (yr)
Station-Kept = True
Abandoned = True
Long-Term Reentry = False

OUTPUT

Collision Probability = 3.4805E-04
Returned Message: Normal Processing
Date Range Message: Normal Date Range
Status = Pass

C. Orbital Lifetime[6]

INPUT

Start Year = 2028.750000 (yr)
Perigee Altitude = 450.000000 (km)
Apogee Altitude = 450.000000 (km)
Inclination = 97.500000 (deg)
RAAN = 0.000000 (deg)
Argument of Perigee = 0.000000 (deg)
Area-To-Mass Ratio = 0.041000 (m^2/kg)

OUTPUT

Orbital Lifetime from Startyr = 0.717317 (yr)
Time Spent in LEO during Lifetime = 0.717317 (yr)
Last year of Propagation = 2029 (yr)
Returned Error Message: Object reentered

INPUT

Start Year = 2026.750000 (yr)
Perigee Altitude = 500.000000 (km)
Apogee Altitude = 500.000000 (km)
Inclination = 97.500000 (deg)
RAAN = 0.000000 (deg)
Argument of Perigee = 0.000000 (deg)
Area-To-Mass Ratio = 0.007830 (m^2/kg)

OUTPUT

Orbital Lifetime from Startyr = 7.509925 (yr)
Time Spent in LEO during Lifetime = 7.509925 (yr)
Last year of Propagation = 2034 (yr)
Returned Error Message: Object reentered

[6] The runs were done at 97.5 deg. For orbital lifetime, the results change negligibly for 88 deg.

D. Human Casualty Risk

As mentioned above, Impulse ran ORSAT and DAS. The ORSAT inputs and results are available in the file below and attached to the Impulse-4 application.

Impulse - Impulse-4 - ODMP Human Casualty Risk ORSAT Logs - 03-04-26 (final).xlsx

The DAS inputs and results are reproduced below.

Return Status : Passed

***********INPUT****
Item Number = 1

name = IMPULSE 4
quantity = 1
parent = 0
materialID = 8
type = Box
Aero Mass = 200.000000
Thermal Mass = 200.000000
Diameter/Width = 0.900000
Length = 1.100000
Height = 0.400000

name = ANTENNA HYDRA
quantity = 2
parent = 1
materialID = 23
type = Box
Aero Mass = 0.490000
Thermal Mass = 0.260000
Diameter/Width = 0.180000
Length = 0.180000
Height = 0.020000

name = BRACKET ANTENNA S BAND
quantity = 2
parent = 2
materialID = 8
type = Box
Aero Mass = 0.230000
Thermal Mass = 0.230000
Diameter/Width = 0.180000

Length = 0.180000
Height = 0.020000

name = PCBA ANTENNA TITAN
quantity = 2
parent = 1
materialID = 23
type = Box
Aero Mass = 2.340000
Thermal Mass = 0.660000
Diameter/Width = 0.418000
Length = 0.418000
Height = 0.004000

name = ANTENNA ADAPTER TITAN MIRA V2
quantity = 2
parent = 4
materialID = 8
type = Box
Aero Mass = 1.360000
Thermal Mass = 1.360000
Diameter/Width = 0.432000
Length = 0.432000
Height = 0.003000

name = #10 SPACER .070L X 1.0625OF TITAN
quantity = 8
parent = 4
materialID = 58
type = Box
Aero Mass = 0.080000
Thermal Mass = 0.080000
Diameter/Width = 0.027000
Length = 0.027000
Height = 0.018000

name = ANTENNA ATLAS S BAND LOW GAIN
quantity = 4
parent = 1
materialID = 23
type = Box
Aero Mass = 0.200000
Thermal Mass = 0.120000
Diameter/Width = 0.083000
Length = 0.083000
Height = 0.020000

name = BUSHING ANTENNA MOUNTING ATLAS
quantity = 16
parent = 7
materialID = 58
type = Cylinder
Aero Mass = 0.020000
Thermal Mass = 0.020000
Diameter/Width = 0.010000
Length = 0.036000

name = ANTENNA EUROPA V2 PCBA
quantity = 4
parent = 1
materialID = 23
type = Flat Plate
Aero Mass = 0.013600
Thermal Mass = 0.002800
Diameter/Width = 0.034000
Length = 0.034000

name = BUSHING ANTENNA MOUNTING EUROPA
quantity = 16
parent = 9
materialID = 58
type = Cylinder
Aero Mass = 0.002700
Thermal Mass = 0.002700
Diameter/Width = 0.008000
Length = 0.020000

name = Assembly Multi Payload Interface Board
quantity = 1
parent = 1
materialID = 8
type = Box
Aero Mass = 2.560000
Thermal Mass = 2.190000
Diameter/Width = 0.214000
Length = 0.373000
Height = 0.020000

name = PCBA Multi payload interface board
quantity = 1
parent = 11
materialID = 23

type = Box
Aero Mass = 0.370000
Thermal Mass = 0.370000
Diameter/Width = 0.198000
Length = 0.356000
Height = 0.010000

name = The rest of the spacecraft
quantity = 1
parent = 1
materialID = 8
type = Box
Aero Mass = 190.000000
Thermal Mass = 190.000000
Diameter/Width = 0.500000
Length = 0.500000
Height = 0.300000

**************OUTPUT****
Item Number = 1

name = IMPULSE 4
Demise Altitude = 77.997277
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = ANTENNA HYDRA
Demise Altitude = 77.118373
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = BRACKET ANTENNA S BAND
Demise Altitude = 76.775693
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = PCBA ANTENNA TITAN
Demise Altitude = 77.283041
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = ANTENNA ADAPTER TITAN MIRA V2

Demise Altitude = 76.638968
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = #10 SPACER .070L X 1.0625OF TITAN
Demise Altitude = 71.063821
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = ANTENNA ATLAS S BAND LOW GAIN
Demise Altitude = 76.831290
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = BUSHING ANTENNA MOUNTING ATLAS
Demise Altitude = 73.531674
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = ANTENNA EUROPA V2 PCBA
Demise Altitude = 77.842246
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = BUSHING ANTENNA MOUNTING EUROPA
Demise Altitude = 76.980385
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = Assembly Multi Payload Interface Board
Demise Altitude = 76.629287
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = PCBA Multi payload interface board
Demise Altitude = 75.859791
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****
name = The rest of the spacecraft
Demise Altitude = 53.514435
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

****