Low-Latitude Ionosphere/Thermosphere Enhancements in Density (LLITED)

Orbital Debris Assessment Report (ODAR)

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Prepared for NASA in compliance with NPR 8715.6A by The Aerospace Corporation.

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Software used in this analysis: NASA DAS v3.2.3

Revision	Date	Pages	Description	Author
1.0	29 June 2021	11	Initial Release	J. Wilson
1.1	15 July 2021	11	Updated software to DAS 3.1.2	J. Wilson
1.2	28 July 2021	11	Minor corrections	J. Wilson
2.0	28 Feb 2022	11	New Orbit	J. Wilson
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VERSION APPROVAL and FINAL APPROVAL*:

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** Signatures required only for Final ODAR

Self-Assessment of Requirements per NASA-STD 8719.14A

Requirement		Compliance Assessment	Comments
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.	Compliant	LLITED will release no debris.
4.3-1b	The total object-time product shall be no larger than 100 object-years per mission.	Compliant	LLITED will release no debris.
4.3-2	For missions leaving debris in orbits with the potential of traversing GEO, 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.	Compliant	LLITED will not operate in or near GEO.
4.4-1	For each spacecraft employed for a mission, the program or project shall demonstrate…that the integrated probability of explosion for all credible failure modes of each spacecraft is less than 0.001.	Compliant	
4.4-2	Design of all spacecraft shall include the ability and a plan to deplete all onboard sources of stored energy and disconnect all energy generation sources when they are no longer required for mission operations or post-mission disposal or control to a level which cannot cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft.	Compliant	
4.4-3	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, and b) not generate debris larger than 1 mm that remains in Earth orbit longer than one year.	Compliant	LLITED has no planned explosions or intentional collisions.
4.4-4	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 10e-6.	Compliant	LLITED has no planned explosions or intentional collisions.
4.5-1	For each spacecraft in or passing through LEO, the program shall demonstrate that, during the orbital lifetime of each spacecraft, the probability of accidental collision with space objects larger than 10 cm in diameter is less an 0.001.	Compliant	
4.5-2	For each spacecraft, the program 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.	Compliant	
4.6-1	A spacecraft with a perigee altitude below 2000 km shall be disposed of by one of the following three methods: a) leave the space structure in an orbit in which natural forces will lead to atmospheric reentry within 25 years, b) maneuver the space structure into a controlled de-orbit trajectory, c) maneuver the space structure into an orbit with perigee altitude above 2000 km and apogee less than GEO-500 km.	Compliant	LLITED will use natural orbit decay.
4.6-2	A spacecraft or orbital stage in an orbit near GEO shall be maneuvered at EOM to a disposal orbit above GEO.	Compliant	LLITED will not operate in or near GEO.
4.6-3	For space structures between LEO and GEO, a spacecraft 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, and a spacecraft shall not use nearly circular disposal orbits near regions of high-value operational space structures.	Compliant	LLITED will not operate in or near MEO.

4.6-4	NASA space programs shall ensure that all post-mission disposal operations to meet the above requirements are designed for a probability of success of no less than 0.90 at EOM.	Compliant	
4.7-1	For uncontrolled reentry, the risk of human casualty from surviving debris shall not exceed 0.0001.	Compliant	
4.8-1	Intact and remnants of severed tether systems in Earth orbit shall meet the requirements limiting the generation of orbital debris from on-orbit collisions and the requirements governing post-mission disposal.	Compliant	LLITED has no tether system.

NOTE: LLITED is currently manifested to fly as a secondary payload. Compliance with requirements levied by NASA-STD 8719.14A on the launch vehicle will be the responsibility of the primary payload and/or launch provider.

Section 1: Program Management and Mission Overview

Mission Directorate: The Aerospace Corporation, Space Science Applications Laboratory
Program Executive: Dr. Rebecca Bishop

System Engineer: Darren Rowen, The Aerospace Corporation
Project Manager: William Chavez, The Aerospace Corporation

Foreign government or space agency participation: none

Nominal Schedule of Mission Design and Development:

Event	Date
Project initiation	18 Oct 2017
System Requirements Review (SRR)	16 Mar 2018
Bus Design Review	21 Jun 2019
Test Readiness Review (TRR)	5 Apr 2021
Pre-Ship Review	18 May 2021
Delivery	1 Dec 2022
Target launch date	15 Feb 2023

Brief Description of the Mission: The Low-Latitude Ionosphere/Thermosphere Enhancements in Density (LLITED) program consists of two nearly identical spacecraft, LLITED-A and LLITED-B, that will provide coincident measurements of Earth's ionosphere and thermosphere layers to characterize the Equatorial Temperature Wind Anomaly (ETWA) and the Equatorial Ionization Anomaly (EIA).

Identification of the anticipated launch vehicle and launch site: LLITED is manifested as part of the upcoming Momentus Vigoride OSV that is manifested on the SpaceX Falcon 9 Transporter-7. The mission orbit will have an apogee of 495 km and a perigee of 495 km and will be inclined about 96.4°.

Identification of the proposed launch date and mission duration: The LLITED mission anticipates a launch in February 2023. The main mission phase is approximately 12 months.

Description of the launch and deployment profile: The LLITED spacecraft will be deployed from the launch vehicle from a CubeSat dispenser. Typically, the launch vehicle will optimize separation timing to reduce the likelihood of collision between CubeSats. Both LLITED spacecraft combined will fill a single 3U slot in a flight qualified spacecraft dispenser.

Reason for selection of operational orbit: As a secondary payload, LLITED has no control over the selection of operational orbit. LLITED can perform its mission in any LEO orbit, although the altitude must be low enough to ensure natural decay and reentry within the timeframe specified by NPR8751.6A. The altitude to which the deployment vehicle and its payloads will be delivered (including LLITED) satisfies that requirement.

Identification of any interaction or potential physical interference with other operational spacecraft: As one of many CubeSats deployed on the mission, there is a small risk of contact between LLITED and another CubeSat. The timing of satellite deployments from the dispenser is intended to mitigate this risk as much as possible. Debris mitigation for the deployment process is the responsibility of the launch vehicle. In the event of contact shortly after deployment, the relative velocities between CubeSats is on the order of centimeters per second, which would not provide enough force to cause catastrophic breakup of the satellites or generate significant amounts of debris (the glass coverings of solar cells may crack). The launch vehicle trajectory and mission plan is designed to ensure there is no risk to the primary payload. There is no anticipated risk to any other operational spacecraft.

Section 2: Spacecraft Description

Physical Description: The LLITED spacecraft are 1.5U CubeSats with outer dimensions of 17 cm x 11 cm x 11 cm. Deployable solar panels extend off the long axis of the spacecraft with dimensions 17 cm x 10 cm. The exterior bus is made from 6061-T6 aluminum and houses all payload and electronics components.

Total spacecraft mass at launch: The LLITED spacecraft, will weigh about 1.97 kg at launch.

Dry mass of spacecraft at launch: The LLITED spacecraft have no propulsion system; dry mass is 1.97 kg.

Description of all propulsion systems: Neither LLITED-A nor LLITED-B has a propulsion system.

Identification of all fluids planned to be on board: No fluids will be carried on board either spacecraft.

Description of all active and/or passive attitude control systems with an indication of the normal attitude of the spacecraft with respect to the velocity vector: LLITED has 3-axis attitude control via three torque rods and three “pico” reaction wheels. The torque rods are a mutually orthogonal triad of coiled wire, wrapped around a high magnetic permeability alloy that can generate a magnetic dipole of 0.15-0.2 A-m^2 when the satellite passes current through the wire. The rods generate negligible magnetic field when powered off. The torque rods are made from 0.8 cm-diameter mu-metal rods that are 8 cm long. The pico reaction wheels have flight heritage from The Aerospace Corporation's AeroCube-7 and AeroCube-10 spacecraft. Attitude sensors include Earth nadir sensors, two-axis Sun sensors on various spacecraft surfaces, a 3-axis magnetometer, and two star trackers. A high-accuracy 3-axis rate gyro will be used to provide an inertial attitude reference when 0.7° or better pointing accuracy is required and the Sun and Earth are not simultaneously visible by an appropriate sensor, and a medium-resolution 3-axis rate gyro and 3-axis magnetometer will serve as a backup.

Description of any range safety or other pyrotechnic devices: LLITED has no pyrotechnic devices.

Description of the electrical generation and storage system: Power for the LLITED spacecraft is generated by solar cells mounted onto panels that will be deployed from both sides of the bus, as well as cells affixed to the spacecraft bus. These cells are capable of producing up to 15 W of power. Power is stored on-board with lithium-ion batteries. Each satellite has 2 batteries mounted in an aluminum 6061-T6 structure as a unit and are shock and thermally isolated by a thermoplastic mount. Each battery is composed of two cells and are rated at 10.5 W-hr for a total of 42 W-hr on the spacecraft. Specific details of the batteries' manufacture appear in Section 4.

Identification of any other sources of stored energy: There are no other sources of stored energy on LLITED.

Identification of any radioactive materials on board: LLITED carries no radioactive materials.

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: LLITED will release no objects into space during normal operations.

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

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

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

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

Calculated orbital lifetime of each object, including time spent in LEO: N/A

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

Requirement 4.3-1a: COMPLIANT
Requirement 4.3-1b: COMPLIANT
Requirement 4.3-2: COMPLIANT

Section 4: Assessment of Spacecraft Intentional Breakups and Potential for Explosion

Identification of all potential causes of spacecraft breakup during deployment and mission operations: There is no credible scenario that would result in spacecraft breakup during normal deployment and operations.

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

Battery risk: A possible malfunction of the lithium ion or lithium polymer batteries or of the control circuit has been identified as a potential, but low probability, cause of accidental breakup or explosion. Natural degradation of the solar cells and batteries will occur over the post-mission period and poses an increased chance of undesired battery-energy release. The battery capacity for storage will degrade over time, possibly leading to changes in the acceptable charge rate for the cells. Individual cells may also change properties at different rates due to time degradation and temperature changes. The control circuit may also malfunction due to exposure over long periods of time. The cell pressure relief vents could be blocked by small contaminants. Any of these individual or combined effects may theoretically cause an electro-chemical reaction that results in rapid energy release in the form of combustion.

Notwithstanding these potential sources of energy release, LLITED still meets Requirement 4.4-2 as the on-board batteries cannot “cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft.” Underwriters Laboratories (UL) certifies the batteries used on LLITED. In general, these batteries are similar in size and power to cell phone batteries.

Model Number (UL Listing)	Manufacturer	Number of Cells	Energy Stored
ICR18650M	Molicel	2	<=10.5 W-hr per cell (2 batteries total)

The batteries are consumer-oriented devices. The batteries have been recognized as UL tested and approved. UL recognition has been determined through the UL Online Certifications Directory, which clearly shows that these cell batteries have undergone and passed UL Standards. Furthermore, safety devices incorporated in these batteries include pressure release valves, over-current charge protection, and over-current discharge protection.

The fact that the LLITED batteries are UL recognized indicates that they have passed the UL standard testing procedures that characterize their explosive potential. Of particular concern to NASA is UL Standard 1642, which specifically deals with the testing of lithium batteries. Section 20 Projectile Test of UL 1642 subjects the test battery to heat by flame while within an aluminum- and steel-wire-mesh octagonal box, "[where the test battery] shall remain on the screen until it explodes or the cell or battery has ignited and burned out" (UL 1642 20.5). To pass the test, "no part of an exploding cell or battery shall penetrate the wire screen such that some or all of the cell or battery protrudes through the screen" (UL 1642 20.1).

It is reasonable to expect the batteries on LLITED to experience similar conditions during their orbital life span. While the sources of failure would not be external heat on orbit, analysis of the expected mission thermal environment shows that given the low power dissipation for CubeSats, the batteries will be exposed to a maximum temperature well below their 212° F (100° C) safe operation limit. Continual charging with 2 to 6 W average power from the solar panels over an orbital life span greater than 15 years may expose the batteries to overcharging, which could cause similar heat to be generated internally. Through the UL recognition and testing, it has been shown that these batteries do not cause an explosion that would cause a fragmentation of the spacecraft.

In addition to the aforementioned certification of the LLITED batteries against explosion, ten potential failure modes for lithium batteries and their applicability or mitigation in LLITED are addressed in the following table:

	Failure Mode	**Applicability or Mitigation**
1	Internal short circuit	The LLITED body and internal design prevents deformation or crushing of the batteries that could lead to internal short circuit.
2	Internal thermal rise due to high load discharge rate	See Failure Mode #4.
3	Overcharging and excessive charge rate	The battery cells on LLITED have charge interrupt devices that activate during cell internal pressure buildup (due to cell internal chemical that forms a gas) that occurs during overcharging conditions.
4	Excessive discharge rate or short circuit due to external device failure	The bus batteries have an internal positive temperature coefficient (PTC) device that acts as a resettable fuse during external short circuit that limits the cell output current during such an event.
5	Inoperable vents	Vents have access through the structure that holds them and into the larger satellite volume. Venting will not be inhibited by physical obstructions.
6	Crushing	Satellite body and internal design prevent loads on battery cases.
7	Low level current leakage or short circuit through battery pack case or due to moisture-based degradation of insulators	Satellites are stored in a controlled environment.
8	Excess temperatures due to orbital environment and high discharge combined	Thermal sensors on the batteries provide telemetry on battery temperature. There is no cutoff for overheating batteries except whatever is inherent in the cell itself. However, as noted earlier in this section of the ODAR, the batteries on LLITED are UL-certified as non-explosive in over-heating scenarios.

9	Polarity reversal due to over-discharge	A 2.7 V discharge cutoff threshold circuit in LLITED has been verified in acceptance tests for the electric power system.
10	Excess battery temperatures due to post-mission orbital environment and constant overcharging	The circuit that charges the batteries cannot exceed 4.1 V and therefore will never overcharge the batteries.

Through a combination of UL certification, compliance with AFSPCMAN 91-710 V3 requirements, and an understanding of the general behavior of the failure modes associated with these types of batteries, it is possible to conclude that the batteries meet Requirement 4.4-2.

Detailed plan for any designed breakup, including explosions and intentional collisions: LLITED has no plans for intentional breakups, explosions, or collisions.

List of components, which are passivated at EOM: No systems on the LLITED spacecraft require passivation at EOM.

Rationale for all items which are required to be passivated, but cannot due to their design: As described above, the batteries do not present a debris-generation hazard per Requirement 4.4-2, and in the interest of not increasing the complexity of the LLITED power system, it was decided not to passivate the batteries at EOM.

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

Requirement 4.4-1: COMPLIANT
Requirement 4.4-2: COMPLIANT
Requirement 4.4-3: COMPLIANT
Requirement 4.4-4: COMPLIANT

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

Collision probabilities have been calculated using DAS v3.2.3 with the assumptions: 495 km x 495 km altitude orbit, 96.4° inclination; 1.97 kg mass, and 0.02363 m^2/kg area-to-mass ratio (the average area-to-mass configuration of the spacecraft post-mission).

Calculation of spacecraft probability of collision with space objects larger than 10 cm in diameter during the orbital lifetime of the spacecraft: Probability = 1.91×10^{-7}, per DAS v3.2.3.

Calculation of spacecraft probability of collision with space objects, including orbital debris and meteoroids, of sufficient size to prevent post-mission disposal: Because the mission has selected natural de-orbit (see Section 6) for disposal and no systems will be passivated at EOM (see Section 4), small debris do not pose a threat to post-mission disposal.

Assessment of spacecraft compliance with Requirements 4.5-1 and 4.5-2:

Requirement 4.5-1: COMPLIANT
Requirement 4.5-2: COMPLIANT

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

Description of spacecraft disposal option selected: The LLITED mission has selected atmospheric reentry for disposal. The vehicles use a 17 x 11 x 11 cm bus and weigh 1.97 kg each. The minimum cross-sectional area for LLITED will be approximately 100 cm^2, though the spacecraft will spend most of its time in a tumble state, with an average cross-sectional area of about 425 cm^2. DAS evaluates a lifetime of about 1.5 year, using the orbit assumptions listed at the beginning of Section 5. This lifetime is compliant with ODAR requirements.

Identification of all systems or components required to accomplish any post-mission disposal operation, including passivation and maneuvering: As discussed in Section 4, no disposal or passivation is planned for LLITED. Natural orbit decay is sufficient to deorbit the spacecraft.

Plan for any spacecraft maneuvers required to accomplish post-mission disposal: None

Calculation of area-to-mass ratio after post-mission disposal, if the controlled reentry option is not selected: N/A

Preliminary plan for spacecraft controlled reentry: N/A

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

Requirement 4.6-1: COMPLIANT
Requirement 4.6-2: COMPLIANT
Requirement 4.6-3: COMPLIANT
Requirement 4.6-4: COMPLIANT

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: The LLITED vehicles are primarily constructed of aluminum and PCB electronic board material. The only components with a higher density or resistance to melting are found in the battery (stainless steel), the torque rods (HyMu-80), and the reaction wheels (HyMu-80). However, since these parts are smalls, these parts are not expected to survive reentry.

Requirement 4.7-1 requires that all surviving debris from an uncontrolled spacecraft reentry have a risk of human casualty of less than 1:10,000. Human casualty is defined as an impact from an object with an energy of at least 15 J. As calculated by DAS, no part of the LLITED spacecraft is expected to survive reentry. The LLITED mission is fully compliant with Requirement 4.7-1.

Summary of objects expected to survive an uncontrolled reentry: None

Calculation of probability of human casualty for the expected year of uncontrolled reentry and the spacecraft orbital inclination: 1:0

Assessment of spacecraft compliance with Requirement 4.7-1:

Requirement 4.7-1: COMPLIANT

Section 8: Assessment for Tether Missions

The LLITED mission has no tether. All requirements are COMPLIANT.

Sections 9–14: Assessment of Launch Vehicle Debris

LLITED will fly as a secondary payload. Assessment of launch-vehicle debris is the responsibility of the primary payload. These sections are N/A for LLITED.