Integrated Solar Array and Reflectarray Antenna (ISARA) 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 v2.0.2

Revision	Date	Pages	Description	Author
1.0	2 April 2015	15+ Appendices	First version, requires signatures	J. Wilson, Astrodynamics Dept.

VERSION APPROVAL and FINAL APPROVAL*:

The Aerospace Corporation	NASA Concurrence**
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* Approval signatures indicate acceptance of the ODAR-defined risk.

** 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	ISARA will release no debris.
4.3-1b	The total object-time product shall be no larger than 100 object-years per mission.	Compliant	ISARA 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	ISARA 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	ISARA 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 10-6.	Compliant	ISARA 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	ISARA will use natural orbit decay.
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	ISARA 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	ISARA 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	ISARA 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.	In Progress	Evaluation of deployable system is in progress
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	ISARA has no tether system.

NOTE: ISARA 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 Materials Laboratory

Program Executive: Dr. James Nokes

Principal Investigator: Dr. Richard Hodges, Jet Propulsion Laboratory

Program Manager: Darren Rowen, The Aerospace Corporation

Foreign government or space agency participation: none

Nominal Schedule of Mission Design and Development:

Event	Date
Project initiation	9 Aug 2012
System Requirements Review (SRR)	23 Apr 2013
Preliminary Design Review (PDR)	12 Nov 2013
Critical Design Review (CDR)	15 Apr 2015
Flight Readiness Review (FRR)	15 Dec 2015
Delivery	15 Jan 2016
Target launch date	1 Mar 2016

Brief Description of the Mission: The Integrated Solar Array and Reflectarray Antenna (ISARA) mission will demonstrate a high bandwidth Ka-band antenna for satellite communications in the CubeSat form factor. The primary payload, a reflectarray antenna, is designed to provide up to 100 Mbps data rate with minimal impact to satellite mass, volume, or power. The reflectarray is integrated to the underside of a deployable solar array panel, which provides power for Ka-band transmission and nominal mission operations. Currently, NASA rates the reflectarray as a TRL 5 technology. ISARA will perform direct, on-orbit measurements of the antenna gain to mature the reflectarray to a TRL 7.

The reflectarray is printed to the underside of the solar panels, which is 30 cm x 70 cm, and will provide at least 35 dB of gain at 26 GHz. The reflectarray is complemented by a 1 cm by 2 cm patch antenna etched into the solar array that acts as a feed to obtain good taper and spillover efficiency. By maturing the TRL, it is expected that this reflectarray design could become a practical high gain antenna option for 3U (30 cm x 10 cm x 10 cm) and larger CubeSats.

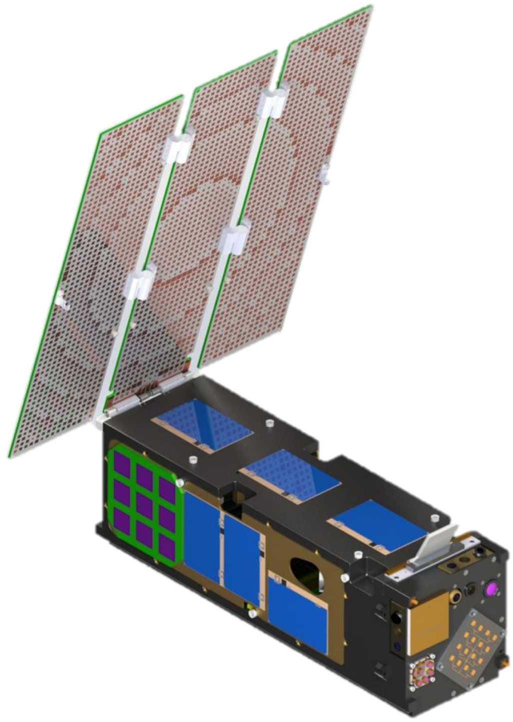

Figure 1. The ISARA spacecraft with reflectarray/solar cells deployed.

Identification of the anticipated launch vehicle and launch site: ISARA has been manifested as a secondary payload with FORMOSAT-5, which will fly on a Falcon 9 launch scheduled for March 2016. ISARA will be deployed using the SHERPA deployment system along with 83 other CubeSats. SHERPA, which is manufactured by Andrews Space, is designed from an EELV Secondary Payload Adapter (ESPA) ring to fit on U.S. Medium and Intermediate launch vehicles (e.g. EELV, Falcon 9, Antares). SHERPA contains an avionics system that controls the release of its payloads such that no release will interfere with the primary payload deployment. SHERPA has an independent flight computer, propulsion system, power system, and orbit determination capability, which allows for the release of the secondary payloads into an orbit that ensures atmospheric reentry for the released payloads. SHERPA will deploy ISARA to a roughly 425 km x 720 km altitude orbit inclined 97.4°.

Identification of the proposed launch date and mission duration: The ISARA mission anticipates a launch as a secondary payload in March 2016. The main mission phase is approximately 5 months. The stretch mission will extend the operational lifetime to at least 2 years.

Description of the launch and deployment profile: As a secondary payload, the ISARA spacecraft will be deployed from the launch vehicle to minimize risk to the primary payload and upper-stage space structures. Secondary payload deployment will occur after deployment of the primary payload. Typically, after deploying the primary payload, the upper stage performs a small burn to alter the orbit (eliminating the risk of collision with the primary) before releasing any secondary payloads.

Reason for selection of operational orbit: As a secondary payload, ISARA has no control over the selection of operational orbit. ISARA 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 SHERPA deployment vehicle and its payloads will be delivered (including ISARA) satisfies that requirement.

Identification of any interaction or potential physical interference with other operational spacecraft: As one of several dozen CubeSats deployed by SHERPA, there is a small risk of contact between ISARA and another CubeSat. The timing of satellite deployments from SHERPA is intended to mitigate this risk as much as possible. Debris mitigation for the deployment process is the responsibility of SHERPA. 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 ISARA mission consists of a three unit (3U) CubeSat with dimensions 30 x 10 x 10 cm. The satellite contains a Sun sensor and Earth sensor, RF communications antennae, GPS receiver, a medium-field camera, and narrow-field camera. The 30 cm x 70 cm solar panels will extend off the anti-nadir side of ISARA.

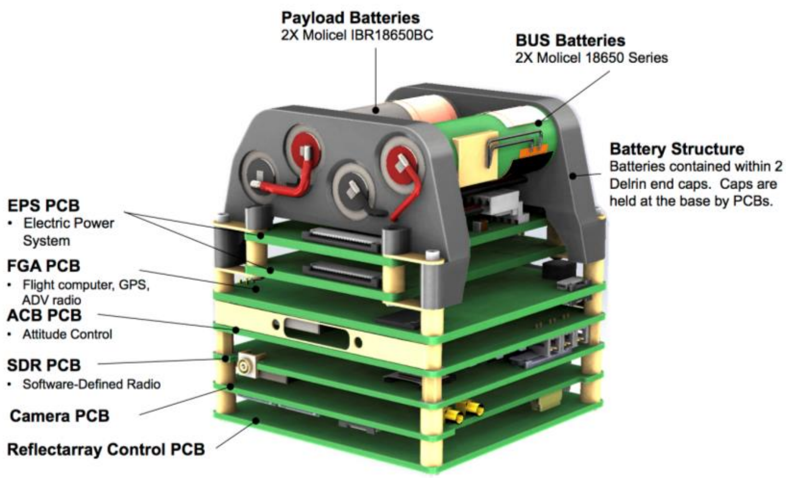

Figure 2. Internal layout of ISARA.

Total spacecraft mass at launch: < 5 kg

Dry mass of spacecraft at launch: < 5 kg

Description of all propulsion systems: ISARA has no propulsion system.

Identification of all fluids planned to be on board: ISARA carries no fluids on board.

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: ISARA 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 to 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 35.5 cm-diameter mu-metal rods that are 5.5 cm long. The pico reaction wheels have flight heritage on three AeroCube-4 and two AeroCube-5 spacecraft. Attitude sensors include Earth nadir sensors, two-axis Sun sensors on various spacecraft surfaces, a 3-axis magnetometer, and two star trackers of the same type and model that will fly on AeroCube-7. 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: ISARA has no pyrotechnic devices.

Description of the electrical generation and storage system: Power for ISARA is generated by solar cells mounted onto panels that will be deployed from the anti-nadir side of the bus, as well as cells affixed to the spacecraft bus. These cells are capable of producing up to 22 W of power. Power is stored on-board with lithium-ion batteries. The satellite has 4 batteries mounted in an aluminum 6061-T6 structure as a unit and are shock and thermally isolated by a low-outgassing rubber grommet. Each battery is composed of two cells. Two batteries are rated at 9 W-hr while the other two are rated at 6 W-hr, for a total of 30 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 ISARA.

Identification of any radioactive materials on board: ISARA 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: ISARA 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 as a result of 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, ISARA 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 ISARA. In general, these batteries are similar in size and power to cell- phone batteries.

Model Number (UL Listing)	Manufacturer	Number of Cells	Energy Stored per Cell
ICR18650H	Molicel	2	<9 W-hr
IBR18650BC	Molicel	2	<6 W-hr

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 ISARA 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 ISARA 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 12 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 ISARA batteries against explosion, ten potential failure modes for lithium batteries and their applicability or mitigation in ISARA are addressed in the following table:

	Failure Mode	**Applicability or Mitigation**
1	Internal short circuit	The ISARA 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 ISARA 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 ISARA 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 ISARA 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: ISARA has no plans for intentional breakups, explosions, or collisions.

List of components, which are passivated at EOM: No systems on ISARA will be passivated 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 ISARA 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 v2.0.2 with the assumptions: 425 km x 720 km altitude orbit, 97.7° inclination, 5 kg mass (initial and final), and 0.0154 m^2/kg area-to-mass ratio (the maximum-area configuration).

In addition to the DAS analysis, The Aerospace Corporation has performed additional analysis looking at the collision probability of ISARA with 0^{th}-, 1^{st}-, and 2^{nd}-generation debris objects with 95^{th}-, 50^{th}-, and 5^{th}-percentile solar cycle assumptions. The probability of collision for all cases considered is below the 0.001 requirement. A summary of the Aerospace analysis is appended to this ODAR.

Calculation of spacecraft probability of collision with space objects larger than 10 cm in diameter during the orbital lifetime of the spacecraft: Probability = 0.00000, per DAS v2.0.2

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 prevent 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 ISARA mission has selected atmospheric reentry for disposal. The vehicle is a 30 x 10 x 10 cm bus. The vehicle's mass is approximately 5 kg. The longest possible orbital lifetime occurs if the vehicle were permanently aligned nadir with the smallest face pointing in the direction of motion, with a cross-sectional area of 310 cm^2. Although in practice after EOM the vehicle will tumble with a higher "average" cross-sectional area of 770 cm^2, the analysis in DAS assumed the worst-case low-drag configuration for lifetime. DAS evaluates a lifetime of 9.057 years, using the orbit assumptions listed at the beginning of Section 5 (except for using a lower area-to-mass ratio of 0.0062 m^2/kg). This lifetime is compliant with ODAR requirements. Assuming the predicted nominal post-mission cross-sectional area of 770 cm^2, DAS predicts a lifetime of 6.412 years.

This lifetime analysis assumes that the solar panels properly deploy. In the event of a deployment failure, the worst-case cross-sectional area becomes 100 cm^2. This again requires active attitude control, which will not be the case. The orbital lifetime calculated by DAS is 28.912 years, which exceeds the 25-year lifetime requirement. Even though ISARA will have no attitude control at the end of its mission and will tumble (which would reduce its orbital lifetime to 16.515 years, per DAS), The Aerospace Corporation has taken steps to ensure that solar panel deployment reliability is greater than 0.9, as required by NASA-STD 8719.14 Section 4.6.4.3, which states that a valid debris assessment "includes two areas: (1) design or component failure which leads to loss of control during the mission and (2) failure of the postmission disposal system. Total reliability for postmission disposal operations not involving directed reentry is 0.90."

Area (2) of Section 4.6.4.3 is satisfied by the insertion of ISARA into an orbit with perigee lower than 700 km, as recommended by NASA-STD 8719.14 Section 4.6.5. Area (1) is satisfied by demonstrating that solar panel deployment, which increases the post-mission cross-sectional area to 770 cm^2, has a reliability greater than 0.9. Solar panel deployment involves two systems, communications and the solar panel deployment mechanism. The communications system, which is necessary for solar panel deployment, has flown on previous CubeSat missions, including The Aerospace Corporation's AeroCube-4 and AeroCube-5 missions, with a reliability greater than 0.99. The solar panel deployment mechanism itself is heritage hardware from The Aerospace Corporation's AeroCube-7 mission, which begins operations in May 2015. Flight experience with the deployment mechanism will allow the team to assess its reliability. Furthermore, the deployment mechanism is resettable, which allows for additional attempts at deployment in the event of deployment failure. Compliance of Requirement 4.6-4 is in progress, but should be favorably resolved by the Flight Readiness Review.

In addition to the DAS analysis, The Aerospace Corporation has performed additional analysis looking at the orbital lifetime of ISARA assuming several different perigee and apogee altitudes in the event the main payload or SHERPA deployment vehicle deliver ISARA into an off-nominal orbit. In all cases studied, with the exception of SHERPA deploying ISARA into a circular sun-synchronous orbit above 620 km, the lifetime is below the 25-year requirement. The risk of deploying ISARA and the other secondary payloads into this kind of orbit is assumed to be negligible. A summary of the Aerospace analysis is appended to this ODAR in Appendix A.

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 ISARA. Natural orbit decay is sufficient to terminate the mission.

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 ISARA vehicles are primarily constructed of aluminum and PCB electronic board material. The only components with a higher density or resistance to melting are ceramic path antennas, nine nickel-iron alloy torque rods, and three small stainless steel reaction wheels. The DAS analysis, which is in Appendix B, shows these materials pose no risk per the ODAR requirement.

Summary of objects expected to survive an uncontrolled reentry: No objects are expected to survive uncontrolled reentry.

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

Assessment of spacecraft compliance with Requirement 4.7-1:

Requirement 4.7-1: COMPLIANT

Section 8: Assessment for Tether Missions

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

Sections 9–14: Assessment of Launch Vehicle Debris

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