AeroCube 11 (AC11)/Testbed for Optical Missions Satellite (TOMSat)

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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Revision	Date	Pages	Description	Author
1.0	16 Aug 2016	12	First version	J. Wilson, Astrodynamics Dept.
2.0	7 Nov 2017	12	Updated dates	D. Hinkley SSAL

VERSION APPROVAL and FINAL APPROVAL*:

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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	AC11/TOMSat will release no debris.
4.3-1b	The total object-time product shall be no larger than 100 object-years per mission.	Compliant	AC11/TOMSat 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	AC11/TOMSat 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	AC11/TOMSat 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	AC11/TOMSat 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	AC11/TOMSat 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	AC11/TOMSat 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	AC11/TOMSat 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	AC11/TOMSat has no tether system.

NOTE: The AC11/TOMSat satellites are 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 Sciences Application Laboratory

Program Executive: Dr. James Clemmons, The Aerospace Corporation

Program Manager: Bonnie Hattersley, The Aerospace Corporation

Foreign government or space agency participation: none

Nominal Schedule of Mission Design and Development:

Event	Date
Project initiation	26 Dec 2014
System Requirements Review (SRR)	26 Jan 2015
Preliminary Design Review (PDR)	17 Jun 2015
Final Design Review (FDR)	17 Oct 2016
Mission Readiness Review (MRR)	6 Dec 2017
Delivery	15 Jan 2018
Target launch date	1 Mar 2018

Brief Description of the Mission: The AeroCube 11 (AC11)/Testbed for Optical Missions Satellite (TOMSat) program consists of two nearly-identical spacecraft that will demonstrate the technological capability of two imaging sensors. One satellite will host focal plane array #1 that is configured as a pushbroom time delay integration (TDI) sensor to provide normalized difference vegetation index (NVDI) data for comparison to NVDI provided by Landsat's Operational Land Imager (OLI). The second satellite will host focal plane array #2 that will image terrestrial, lunar, and stellar targets. Both satellites will have a laser communication downlink. The goal of each AC11/TOMSat is to show that these sensors can perform comparably to flagship missions, such as Landsat and to characterize their performance in a space environment.

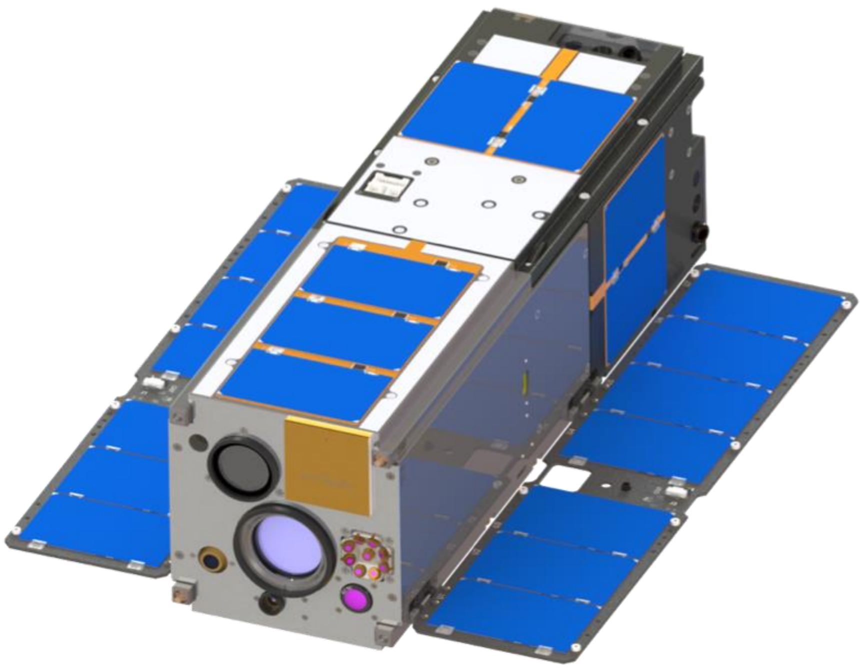

Figure 1: AC11/TOMSat spacecraft with solar panels deployed.

Identification of the anticipated launch vehicle and launch site: AC11/TOMSat 3U pair are manifested as part of NASA's Educational Launch of Nanosatellites (ELaNa) XIX program. The ELaNa XIX satellites will launch on a Rocket Lab Electron rocket from its launch site on the Mahia Peninsula in New Zealand. Each of the two AC11/TOMSats will be deployed from a LV provided spacecraft dispenser integrated with the Electron rocket. The Electron rocket will deploy the satellites into a 500 km altitude circular orbit with an inclination of 85°.

Identification of the proposed launch date and mission duration: The AC11/TOMSat mission anticipates a launch in March 2018. The main mission phase is approximately 12 months.

Description of the launch and deployment profile: The AC11/TOMSat 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. Each AC11/TOMSat will fill a 3U slot in a flight qualified spacecraft dispenser.

Reason for selection of operational orbit: As a secondary payload, AC11/TOMSat spacecraft have no control over the selection of operational orbit. The spacecraft have been designed to perform 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 our satellites) satisfies that requirement.

Identification of any interaction or potential physical interference with other operational spacecraft: As one of about 14 CubeSats deployed on the mission, there is a small risk of contact between AC11/TOMSat 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 AC11/TOMSat spacecraft are 3U CubeSats with outer dimensions of 34 cm x 11 cm x 11 cm. Deployable solar panels extend off the long axis of the spacecraft with dimensions 34 cm x 10 cm. The exterior bus is made from 6061-T6 aluminum and houses all payload and electronics components. The nadir face contains an earth sensor and a sun sensor for attitude determination, a fish-eye camera, laser collimator and uplink receiver, and a radio patch antenna. The zenith face also contains a radio patch antenna as well as two star trackers. The payload for each spacecraft is a custom-made telescope made from aluminum, glass lenses, and titanium spacers and uses about 1.5U of space. A radiator is built into the bus to help the payload maintain proper temperatures. All parts remain attached to the spacecraft. The satellite with the wings open is shown in Figure 1.

Total spacecraft mass at launch: The AC11/TOMSat spacecraft testing focal plane array #1 will weigh about 4.5 kg at launch and the AC11/TOMSat spacecraft testing focal plane array #2 will weigh about 5 kg at launch.

Dry mass of spacecraft at launch: Same as total spacecraft mass noted above.

Description of all propulsion systems: The AC11/TOMSat satellite has no propulsion system.

Identification of all fluids planned to be on board: The AC11/TOMSat satellite 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: Both AC11/TOMSat spacecraft have identical 3-axis attitude control systems. 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 pico reaction wheels are a mutually orthogonal triad consisting of stainless steel rims mounted on brushless DC motors. 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 are flying 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.

The satellites will either have no attitude control (tumble) or constantly point the solar arrays at the sun (solar inertial). When they have to point for taking images, they will initialize their attitude control system and then execute the desired pointing trajectory. These image collection experiments and their associated pointing trajectories are very infrequent (1-2 hours per day) relative to the tumbling or sun pointing attitudes (22-23 hours per day).

Description of any range safety or other pyrotechnic devices: The AC11/TOMSat spacecraft have no pyrotechnic devices.

Description of the electrical generation and storage system: Power for the AC11/TOMSat spacecraft are 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 19 W of peak solar power. Solar energy is stored on-board in lithium-ion batteries. The satellite has 4 batteries that are shock and thermally isolated by a Delrin frame. Two of the 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 the AC11/TOMSat spacecraft.

Identification of any radioactive materials on board: The AC11/TOMSat spacecraft carry 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: AC11/TOMSat 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, the AC11/TOMSat spacecraft still meet 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.”

Model (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 (see model numbers in table above). 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. Of particular concern to NASA is UL Standard 1642, which specifically deals with the testing of lithium batteries. Section 20 <u>Projectile Test</u> 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 satellite batteries 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 these satellites, the batteries will be exposed to a maximum temperature well below their 212° F (100° C) safe operation limit. Continual charging with 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. But as mentioned, 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 AC11/TOMSat satellite batteries against explosion, ten potential failure modes for lithium ion batteries in general and their applicability or mitigation to the AC11/TOMSat satellite design are addressed in the following table:

	Failure Mode	**Applicability or Mitigation**
1	Internal short circuit	The AC11/TOMSat 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 AC11/TOMSat 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 AC11/TOMSat 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 AC11/TOMSat 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.

In summary, 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: The AC11/TOMSat spacecraft have no plans for intentional breakups, explosions, or collisions.

List of components, which are passivated at EOM: No systems on the AC11/TOMSat 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. Therefore, 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: 500 km x 500 km altitude orbit, 85° inclination, 5 kg mass (initial and final), and 0.054262 m^2/kg area-to-mass ratio (the likely area-to-mass configuration of the spacecraft post-mission).

In addition to the DAS analysis, The Aerospace Corporation has performed additional analysis looking at the collision probability of AC11/TOMSat 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 AC11/TOMSat mission has selected atmospheric reentry for disposal. The vehicle is a 34 x 11 x 11 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 100 cm^2. However, since the AC11/TOMSat satellites will spend most of its time in a tumble state, the actual cross-sectional area will be about 540 cm^2, which is the area assumed for the analysis in DAS. DAS evaluates a lifetime of 6 years, using the orbit assumptions listed at the beginning of Section 5. This lifetime is compliant with ODAR requirements.

In addition to the DAS analysis, The Aerospace Corporation has performed additional analysis looking at the orbital lifetime of the AC11/TOMSat satellites assuming several different attitude profiles within the nominal mission orbit. In almost all cases studied, the lifetime is below the 25-year requirement. The outlier cases that do not reenter within 25 years occur only with a combination of low solar activity over several solar cycles and the spacecraft constantly maintaining a minimum drag profile. Each event by itself is unlikely, and the probability of both events occurring simultaneously is considered negligible.

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. 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 AC11/TOMSat spacecraft are primarily constructed of aluminum and PCB electronic board material. The only components with a higher density or resistance to melting are seven titanium spacer plates within the payloads, ceramic path antennas, nine nickel-iron alloy torque rods, and three small stainless steel reaction wheels.

Summary of objects expected to survive an uncontrolled reentry: The seven titanium spacers within the AC11/TOMSat payloads are expected to survive reentry. These disks are small and are expected to impact the ground with an energy of about 4 J, per the DAS analysis. This is equivalent to the energy imparted by a medium tomato dropping from a height of about 4 m. Should these objects survive reentry, it is not expected that these spacers will pose a threat to human lives or property.

Calculation of probability of human casualty for the expected year of uncontrolled reentry and the spacecraft orbital inclination: Zero. The DAS analysis shows these materials pose no risk per the ODAR requirement.

Assessment of spacecraft compliance with Requirement 4.7-1:

Requirement 4.7-1: COMPLIANT

Section 8: Assessment for Tether Missions

The AC11/TOMSat mission uses no tethers. All requirements are COMPLIANT.

Sections 9–14: Assessment of Launch Vehicle Debris

The AC11/TOMSat satellites are a secondary payload. Assessment of launch-vehicle debris is the responsibility of the primary payload. These sections are therefore N/A.