Slingshot-1

Orbital Debris Assessment Report (ODAR)

Report Version: 2, 20 July 2020

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

This document is suitable for public release.

Software used in this analysis: NASA DAS v3.1

Revision	Date	Pages	Description	Author
1.0	30 June, 2020	16	Initial Release	
2.0	20 July, 2020	16	Updated DAS results for v3.1.0	
3.0	27 Aug, 2020	16	Corrected area/mass numbers (p.11)	
4.0	3 Sept, 2020	16	Added solar array release device information to pg.6	

VERSION APPROVAL and FINAL APPROVAL*:

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* Approval signatures indicate responsibility that the information in the ODAR is correct.

** 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	SLINGSHOT1 will release no debris.
4.3-1b	The total object-time product shall be no larger than 100 object-years per mission.	Compliant	
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	SLINGSHOT1 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	SLINGSHOT1 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	
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	SLINGSHOT1 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	SLINGSHOT1 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	SLINGSHOT1 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	SLINGSHOT1 has no tether system.

NOTE: The Slingshot-1 spacecraft 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
Program Executive: Dr. Randy M Villahermosa, The Aerospace Corporation
Mission Director: Mr. Daniel Mabry, The Aerospace Corporation
Program Manager: Mr. David Wu, The Aerospace Corporation

Foreign government or space agency participation: none

Nominal Schedule of Mission Design and Development:

Event	Date
Project initiation	Jun 2019
System Requirements Review (SRR)	Oct 2019
Design Review (DR)	Oct 2020
System Test Readiness Review (TRR)	Mar 2021
Delivery	July 2021
Operations Readiness Review	Aug 2021
Target launch date	Oct 2021

Brief Description of the Mission: The Slingshot-1 program consists of a single 12U nanosatellite that will host many individual experiments including 1) one GPS 5 GHz transmitter; 2) one SDR S-band transceiver; 3) one satellite traffic management transceiver; 4) one hydrogen peroxide propulsion unit; 5) one Gbps laser transmitter; 6) two research star tracker cameras; 7) one cloud cover camera; and 8) two vehicle-focused cameras. The planned mission lifetime is 2 years.

Identification of the anticipated launch vehicle and launch site: The Slingshot-1 spacecraft is manifested as part of an upcoming STP S28-B launched on Virgin Orbit (VOX) Space LauncherOne rocket from an airborne platform.

Identification of the proposed launch date and mission duration: The Slingshot1 mission anticipates a launch in October 2021. The main mission phase is approximately 24 months.

Description of the launch and deployment profile: The Slingshot-1 spacecraft will be deployed from the launch vehicle from a single 12U dispenser. Typically, the launch vehicle will optimize separation timing to reduce the likelihood of collision between CubeSats.

Reason for selection of operational orbit: As a secondary payload, Slingshot-1 spacecraft have no control over the selection of their operational orbit. They can perform the 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 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 the Slingshot-1 spacecraft 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). There is no anticipated risk to any other operational spacecraft.

Section 2: Spacecraft Description

Physical Description: The Slingshot-1 spacecraft is a 12U CubeSat with stowed outer dimensions of 21.1 x 22.6 x 36.6 cm. Two deployable solar panels extend off the short axis of the spacecraft, one to each side. Each deployed panel has dimensions 60 cm x 22 cm. The exterior bus is made from 6061-T6 aluminum and houses all payload and electronics components. The deployed satellite dimensions are 21.1 x 140 x 36.6 cm. The solar arrays are restrained by a Blue Canyon Technologies designed and built device that uses a shape memory alloy to initiate the release of the solar arrays. This mechanism has previously flown on 3 missions (6 individual mechanisms) with 100% success.

Total spacecraft mass at launch: The Slingshot-1 spacecraft mass is 19.2 kg.

Dry mass of spacecraft at launch: The Slingshot-1 spacecraft dry mass is 19.18 kg.

Description of all propulsion systems: The Slingshot-1 spacecraft has a hydrogen peroxide (H_2O_2) propulsion system. The thruster is used only intermittently and is not required for any other purpose than to characterize its performance. The propulsion system contains 20 grams of H_2O_2 and can produce a theoretical maximum of 3 meter per second delta velocity on Slingshot-1. The pressure inside of the propulsion system will never exceed 75 psi. Any excess oxygen pressure due to any decomposition of H_2O_2 during storage and prior to operation is expelled through 2 parallel relief valves set to 75 psi. All valves, covers and sensor ports have double o-ring seals and are therefore single fault tolerant. All seals and relief valve function have been verified as part of an acceptance test program on the flight hardware. Prior to use in space, the propulsion system will activate a dedicated heater and heat the H_2O_2 propellant to a maximum of 80 deg Celsius before opening the valves to expel the H_2O_2 vapor through the single catalyst bed where the H_2O_2 will decompose into water vapor and oxygen and then proceed out a nozzle. The maximum pressure of H_2O_2 at 80 deg Celsius is less than 10 psi.

Identification of all fluids planned to be on board: The Slingshot-1 spacecraft carries 20 grams of hydrogen peroxide (H_2O_2 with maximum mass concentration 99%) propellant.

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: The Slingshot-1 spacecraft is 3-axis stabilized. Attitude is control via 3 torque rods for momentum management and 3 reaction wheels for precise attitude control. 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 approximately 0.6 A-m^2 when the spacecraft passes current through the wire. The rods generate negligible magnetic field when powered off. Attitude sensors include (4) sun sensors on various orthogonal spacecraft surfaces, (1) 3-axis magnetometer, and (2) star trackers. A high-accuracy 3-axis rate gyro will be used to provide an inertial attitude reference when pointing accuracy is required while the star trackers are not available.

Description of any range safety or other pyrotechnic devices: The Slingshot-1 spacecraft has no pyrotechnic devices.

Description of the electrical generation and storage system: Power for the Slingshot-1 spacecraft is generated by solar cells mounted onto panels that will be deployed from both sides of the bus. The total installed solar cells are capable of generating a maximum of 102W at their beginning of life. Power is stored on-board in 15 lithium-ion 18650 batteries, organized into 5 strings of 3 cells each. The batteries are mounted in 2 locations, 1 battery containing 3 strings is housed internal to the bus and 2 external batteries containing 2 strings are mounted in the payload cavity. All batteries are mounted in a way that they are shock and thermally isolated from the main satellite structure. The 15 18650 cells combined can store 17A-hr of energy per spacecraft. More battery details of the appear in Section 4.

The Blinker payload has a single 0.8A-hr lithium-ion 14500, 4.1V battery. It is attached to typical AeroCube power board with overcharge protection and undervoltage lockout. The same AeroCube power board is described and has flown on WH2XEY, WH2NXN, WI2XBG, WH2XLA and WI2XIA. The solar cells on the exterior of blinker charge the battery. Additionally, the battery can be charged by a 3.3V input from the Slingshot-1 spacecraft that enters the AeroCube power board as a solar input and thus does not directly charge the battery and does not bypass any of the aforementioned battery charge protection circuitry.

Identification of any other sources of stored energy: The only other source of stored energy is the Hyper thruster which uses hydrogen peroxide (H_2O_2) as a propellant. The H202 may decompose on its own and case a rise in pressure in the propellant tank. There are a redundant pair of 75 psi relief valves to keep the pressure in check. The propellant tank has a volume of 3.3 cubic inches, so the maximum stored energy is 28 J.

Identification of any radioactive materials on board: The Slingshot-1 spacecraft 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: None

Rationale/necessity for release of each object: Not applicable.

Time of release of each object, relative to launch time: Not applicable.

Release velocity of each object with respect to spacecraft: Not applicable.

Expected orbital parameters (apogee, perigee, inclination) of each object after release: Not applicable.

Calculated orbital lifetime of each object, including time spent in LEO: Not applicable.

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 because of exposure over extended 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 Slingshot-1 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." Underwriters Laboratories (UL) certifies the individual battery cells used on the Slingshot-1 spacecraft.

Table 1. Batteries present in Slingshot-1

Model Number (UL Listing)	Manufacturer	Number of Cells	Energy Stored
INR18650MJ1 UL # MH19896	LG Chem	15	<=12.5 W-hr per cell
UR14500P	Sanyo	1	<=3.2 W-hr

The batteries are consumer-oriented devices. The individual battery cells 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 are incorporated in these batteries including pressure release valves, over-current charge protection, and over-current discharge protection.

The fact that the Slingshot-1 spacecraft individual battery cells 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).

These batteries have also been certified against UN 38.3, which includes testing for altitude, thermal, vibration, shock, external short circuits, impacts, crushing, and forced discharge.

It is reasonable to expect the batteries on the Slingshot-1 spacecraft will 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 the batteries will be exposed to a maximum temperature well below their 212° F (100° C) safe operation limit.

In addition to the UL certification of the Slingshot-1 spacecraft batteries against explosion, ten potential failure modes for lithium batteries and their applicability or mitigation are addressed in the following table:

Table 2. Lithium battery failure modes and mitigations

	Failure Mode	Applicability or Mitigation
1	Internal short circuit	The Slingshot-1 spacecraft 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 charging circuitry limits both the charge rate and maximum/minimum voltages of the batteries.
4	Excessive discharge rate or short circuit due to external device failure	The battery circuitry limits the maximum discharge rate of the battery.
5	Inoperable vents	Vents have access through the structure that holds them and into the larger satellite volume. Cell venting is not inhibited.
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	A thermistor monitors the battery housing temperature and reports it as telemetry. 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 the Slingshot-1 spacecraft are UL-certified as non-explosive in over-heating scenarios.
9	Polarity reversal due to over-discharge	A 2.9 V discharge cutoff threshold circuit in SLINGSHOT1 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 4.2 V which has been verified in acceptance tests for the electric power system 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: The Slingshot-1 spacecraft have no plans for intentional breakups, explosions, or collisions.

List of components, which are passivated at EOM: No systems on The Slingshot-1 spacecraft require passivation at EOM. The Hyper propulsion system has a redundant pair of 75 psi pressure relief valves that will vent as pressure rises, for example during reentry heating.

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 Slingshot-1 spacecraft 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 3.1.0 for a 500 km x 500 km altitude orbit at 45° inclination. The spacecraft mass is 19.2 kg with a 0.0098 m^2/kg area-to-mass ratio in its nominal flight mode. Lifetime is calculated to be 2 years.

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 3.1.0.

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 Slingshot1 mission has selected atmospheric reentry for disposal. The Slingshot-1 spacecraft is 21.1 x 22.6 x 36.6 cm in dimension and 19.2 kg in mass with arrays undeployed. This is a fault configuration: the satelilte is tumbling with 0.0032 m^2/kg. DAS 3.1.0 predicts a 10 year orbit lifetime. In its nominal configuration (Figure 1) and pointing the arrays at the sun, Slingshot-1 spacecraft is 21.1 x 140 x 36.6 cm in dimension and 0.0098 m^2/kg and DAS 3.1.0 predicts a 2 year orbit lifetime.

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 the Slingshot-1 spacecraft. 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: 0.0079 m^2/kg when tumbling with solar arrays deployed.

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 Slingshot-1 spacecraft is primarily constructed of aluminum and PCB electronic board material. Components with a higher density or resistance to melting are specifically input as individual components to specifically assess their survivability. A table of the breakdown of components for both spacecraft is shown below.

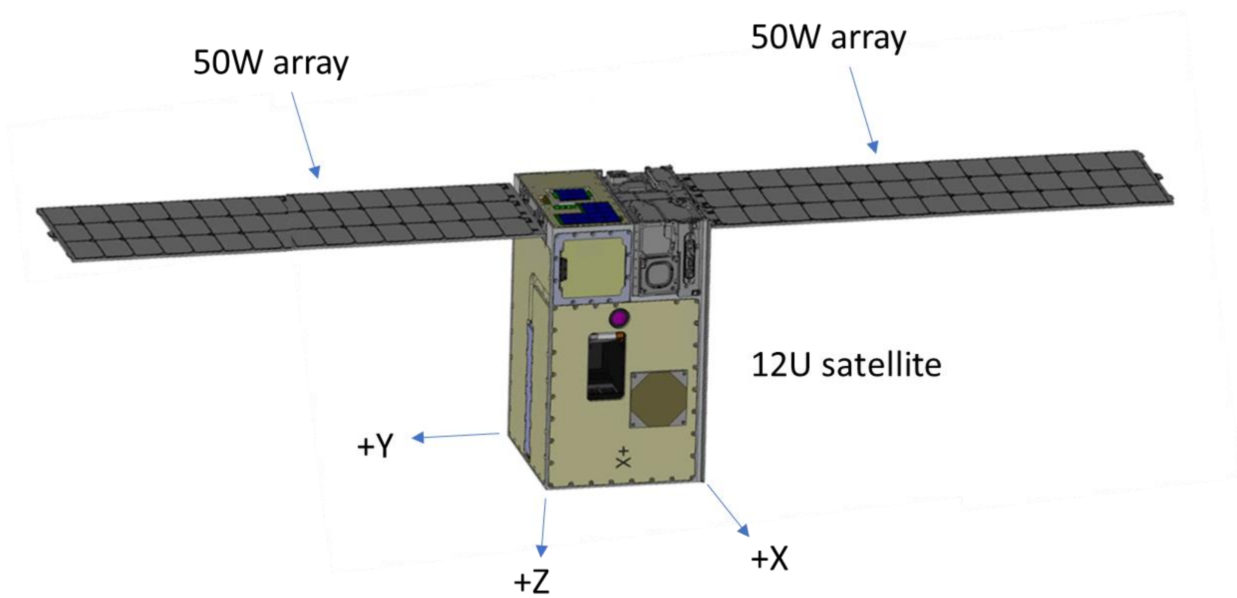

Figure 1: Slingshot-1 spacecraft shown with solar arrays deployed. CBE mass is 19.2 kg. Deployed outer dimensions are 21.1 x 140 x 36.6 cm

Table 3. The constituent elements of Slingshot-1 that were entered into DAS 3.1.0.

	Item	Parent	Qty	Shape	mass [kg]	extd mass	dia/width [m]	Length [m]	Height [m]	Material	Avg area	Area/mass
					kg	kg	m	m	m		m*m	m*m/kg
Slingshot-1 spacecraft	**1**	N/A	1	box	19.200	19.200	0.226	0.366	0.211	varies	0.069	0.0034
structure (frame only)	**2**	1	1	box	1.355	1.355	0.226	0.366	0.211	Aluminum 6061-T6	0.069	0.0481
electronics module (w/ RW and torque rods)	**3**	1	1	box	3.832	2.764	0.234	0.108	0.1	Aluminum 6061-T6	0.020	0.005
reaction wheel	**4**	3	3	box	0.229	0.687	0.023	0.055	0.055	316	0.002	0.008
torque rod	**5**	3	3	cylinder	0.127	0.381	0.018	0.062	N/A	Cu	0.001	0.009
Ext battery pack	**6**	1	2	box	0.305	0.610	0.078	0.079	0.033	Aluminum 6061-T6	0.004	0.012
solar array	**7**	1	2	plate	0.510	1.020	0.213	0.715	0.0025	Graphite epoxy 2	0.152	0.299
+X panel assembly 1	**8**	1	1									
+X panel 1	**9**	8	1	plate	0.601	0.601	0.199	0.254	0.005	Aluminum 6061-T6	0.051	0.084
Star tracker (includes structure)	**10**	8	1	cylinder	0.068	0.068	0.032	0.059	N/A	Aluminum 6061-T6	0.002	0.028
TT&C antenna	**11**	8	1	plate	0.085	0.085	0.076	0.076	0.005	ceramic	0.006	0.068
t.spoon	**12**	8	1									
structure	**13**	12	1	box	0.154	0.154	0.091	0.116	0.06	Aluminum 6061-T6	0.008	0.050
copper straps	**14**	12	3	plate	0.071	0.213	0.035	0.048	0.003	Copper	0.002	0.024
PCB	**15**	12	3	plate	0.100	0.300	0.090	0.090	0.005	fiberglass	0.008	0.081
SDR + ACETaTE	**16**	8	1									
structure (SDR)	**17**	16	1	box	0.143	0.143	0.0940	0.1080	0.0410	Aluminum 6061-T6	0.006	0.043
PCB	**18**	16	1	box	0.040	0.040	0.0400	0.0650	0.0100	fiberglass	0.001	0.030
NanoDock module	**19**	16	1	box	0.076	0.076	0.0900	0.0960	0.0140	Aluminum 6061-T6	0.004	0.049
NanoMind module	**20**	16	1	box	0.077	0.077	0.0400	0.0650	0.0149	Aluminum 6061-T6	0.001	0.018
TR-600 module	**21**	16	2	box	0.0653	0.131	0.0400	0.0650	0.0148	Aluminum 6061-T6	0.001	0.021
PCB (C-band)	**22**	16	1	box	0.160	0.160	0.0760	0.0890	0.0300	fiberglass	0.004	0.024
structure (C-band)	**23**	16	1	box	0.355	0.355	0.0840	0.0990	0.0390	Aluminum 6061-T6	0.005	0.015
+X panel assembly 2	**24**	1	1									
ExoRomper	**25**	24	1									
structure	**26**	25	1	box	0.545	0.545	0.091	0.086	0.058	Aluminum 6061-T6	0.036	0.066
visible camera & lens	**27**	25	1	box	0.046	0.046	0.046	0.044	0.04	Aluminum 6061-T6	0.011	0.243
Lepton 3.5 thermal camera & lens	**28**	25	1	box	0.008	0.008	0.022	0.030	0.01	Aluminum 6061-T6	0.002	0.291
0615 motor power train	**29**	25	2	cylinder	0.006	0.012	0.006	0.030	N/A	316	0.000	0.030
-X panel assembly	**30**	1	1									
-X panel 1	**31**	30	1	plate	0.636	0.636	0.199	0.254	0.005	Aluminum 6061-T6	0.051	0.079
star tracker (w/ structure)	**32**	30	1	cylinder	0.068	0.068	0.028	0.059	N/A	Aluminum 6061-T6	0.002	0.024
TT&C antenna	**33**	30	1	plate	0.085	0.085	0.076	0.076	0.005	ceramic	0.006	0.068
Hyper	**34**	30	1									
tank	**35**	34	1	box	0.363	0.363	0.081	0.050	0.0432	Aluminum 6061-T6	0.019	0.053
valve	**36**	34	2	cylinder	0.037	0.074	0.022	0.042	N/A	Aluminum 6061-T6	0.001	0.025
nozzle stand	**37**	34	1	cylinder	0.004	0.004	0.021	0.023	N/A	Ti	0.000	0.114
nozzle cap	**38**	34	1	cylinder	0.005	0.005	0.016	0.008	N/A	316	0.000	0.026
pressure sensor	**39**	34	2	cylinder	0.010	0.021	0.0158	0.0171	N/A	316	0.000	0.026
ceramic tube	**40**	34	1	Tube	0.000162	0.000	0.002286	0.0191	N/A	Al203	0.000	0.270
mounting bracket	**41**	34	1	box	0.03174	0.032	0.0563	0.0628	0.0381	Delrin	0.016	0.509
PCB	**42**	34	1	box	0.01706	0.017	0.0597	0.0429	0.002286	fiberglass	0.006	0.328
CoralReef	**43**	30	1									
structure	**44**	43	1	box	0.013	0.013	0.04	0.048	0.00511	Aluminum 6061-T6	0.005	0.365
PCB	**45**	43	1	plate	0.100	0.100	0.090	0.090	0.005	fiberglass	0.008	0.081
Laser comm transmitter	**46**	30	1									
structure	**47**	46	1	box	0.350	0.350	0.082	0.127	0.018	Aluminum 6061-T6	0.028	0.081
PCB	**48**	46	1	box	0.023	0.023	0.082	0.127	0.016	fiberglass	0.028	1.196
Spoon Handle	**49**	30	1		0.800							
structure	**50**	49	8	box	0.042	0.336	0.083	0.094	0.017	Aluminum 6061-T6	0.022	0.515
PCB	**51**	49	8	plate	0.059	0.472	0.080	0.080	0.005	fiberglass	0.006	0.108
-X panel assembly 2	**52**	1	1									
+X panel 2	**53**	52	1	box	0.103	0.103	0.101	0.105	0.015	Aluminum 6061-T6	0.005	0.044
diplexer	**54**	52	1	box	0.258	0.258	0.077	0.08	0.024	Aluminum 6061-T6	0.003	0.013
+Y panel assembly	**55**	1	1									
+Y panel	**56**	55	1	plate	1.290	1.290	0.21	0.329	0.008	Aluminum 6061-T6	0.069	0.054
Vertigo	**57**	55	1									
structure	**58**	57	1	box	0.202	0.202	0.094	0.083	0.073	Aluminum 6061-T6	0.041	0.205
Reaction Wheel	**59**	57	3	cylinder	0.071	0.213	0.025	0.016	N/A	316	0.000	0.006
Motor	**60**	57	3	cylinder	0.02	0.060	0.015	0.0523	N/A	316	0.001	0.039
EPSON IMU	**61**	57	2	box	0.010	0.020	0.024	0.024	0.01	316	0.002	0.211
PCB	**62**	57	3	box	0.050	0.150	0.079	0.079	0.013	fiberglass	0.017	0.333
Eclipse-RR	**63**	55	1									
structure	**64**	63	1	box	2.800	2.800	0.098	0.192	0.098	Aluminum 6061-T6	0.095	0.034
PCB	**65**	63	1	box	0.040	0.040	0.088	0.337	0.01	fiberglass	0.068	1.695
PCB 2	**66**	63	2	box	0.030	0.060	0.092	0.092	0.01	fiberglass	0.021	0.687
Mirror	**67**	63	1	box	0.091	0.091	0.092	0.041	0.008	Aluminum 6061-T6	0.010	0.106
-Y panel	**68**	1	1	plate	0.489	0.489	0.203	0.254	0.008	Aluminum 6061-T6	0.052	0.105
+Z panel assembly	**69**	1	1									
+Z panel	**70**	69	1	plate	0.373	0.174	0.193	0.21	0.014	Aluminum 6061-T6	0.041	0.109
ANT2000-S antenna	**71**	70	1	box	0.110	0.110	0.0826	0.1005	0.0201	fiberglass	0.024	0.218
NTE Payload	**72**	70	1	box	0.054	0.054	0.082	0.082	0.003	ceramic	0.014	0.267
C-Band patch antenna	**73**	70	1	box	0.005	0.005	0.0220	0.0230	0.0100	ceramic	0.002	0.382
Context Camera (includes structure)	**74**	70	1	cylinder	0.030	0.030	0.025	0.035	N/A	Varies	0.001	0.029

-Z panel assembly	**75**	1	1									
-Z panel	**76**	75	1	plate	0.256	0.256	0.105	0.22	0.005	Aluminum 6061-T6	0.023	0.090
Blinker	**77**	75	1			-0.326						
structure	**78**	77	1	box	0.066	0.066	0.092	0.099	0.028	Aluminum 6061-T6	0.029	0.438
avionics	**79**	77	1	box	0.190	0.190	0.100	0.092	0.028	fiberglass	0.029	0.153
antenna	**80**	77	1	box	0.030	0.030	0.041	0.041	0.005	ceramic	0.004	0.139
battery	**81**	77	1	cylinder	0.04	0.040	0.014	0.065	N/A	316	0.001	0.023
Harnesses	**82**	1	1	cylinder	0.365	0.365	0.005	0.03	N/A	Cu	0.000	0.000

Summary of objects expected to survive an uncontrolled reentry: The Slingshot1 vehicle is primarily constructed of aluminum and PCB electronic board material. The only components with a higher density or resistance to melting are the stainless steel reaction wheels and the carbon/epoxy solar panels. Requirement 4.7-1 states that all surviving debris from an uncontrolled spacecraft reentry must 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. DAS 3.1.0 analysis predicts that six objects from Slingshot-1 will reach the ground after reentry: 1) three 316-stainless steel reaction wheels, 2) one aluminum IMU housing , and 3) two graphite-epoxy solar panel substrates. Their impact kinetic energies are 214, 2 and 38 Joules, respectively. For the IMU housing, the kinetic impact energy is below 15 Joule threshold that NASA uses to define life-threatening debris. The DAS manual states that the DAS algorithm is conservative and if a part is predicted to survive reentry then a less conservative but still realistic program may be used to provide a more refined prediction. Therefore, we analyzed the reaction wheel and solar panel using the high fidelity “Atmospheric Heating and Breakup” (AHaB) analysis tool. The Aerospace Corporation uses this code to model and analyze breakup sequences and reentry survivability for National Security Space programs for the United States Air Force Space and Missile Systems Center (SMC). AHaB predicted that the stainless steel reaction wheel will not survive reentry - see the table below. However, AhaB predicts that while the epoxy component of the solar panel subtrate does not survive reentry, the graphite weaving component does - it calculates a casualty probability of 1: 16,667.

Part	DAS		AHaB	
	Impact Energy (J)	**Casualty Area (m^2)**	**Impact Energy (J)**	**Casualty Area (m^2)**
Reaction wheel	214	1.25	0	0
Solar panel	38	1.54	53	3.0

Calculation of probability of human casualty for the expected year of uncontrolled reentry and the spacecraft orbital inclination: 1: 10,000

Assessment of spacecraft compliance with Requirement 4.7-1:

Requirement 4.7-1: COMPLIANT .

Section 8: Assessment for Tether Missions

The Slingshot1 mission has no tether. All requirements are COMPLIANT.

Sections 9–14: Assessment of Launch Vehicle Debris

The Slingshot-1 spacecraft will fly as a secondary payload. Assessment of launch-vehicle debris is the responsibility of the primary payload. These sections are therefore N/A.

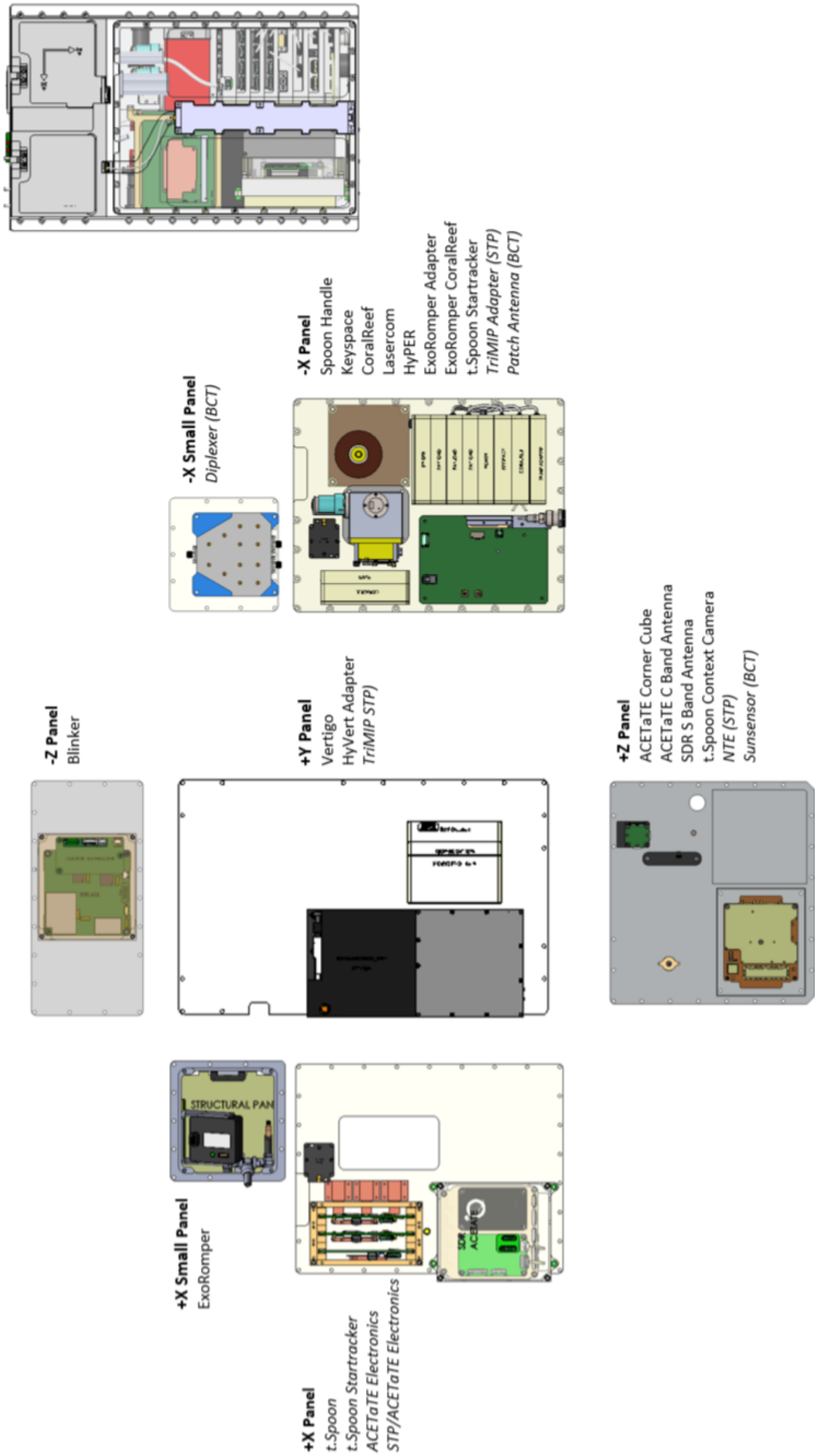

Figure 2. Subsystem distribution and construction of Slingshot-1.