April 8, 2014

Orbital Debris Assessment for ExoCube on the SMAP /ELaNa-10 Mission per NASA-STD 8719.14A

REFERENCES:

A. *NASA Procedural Requirements for Limiting Orbital Debris Generation*, NPR 8715.6A, 5 February 2008
B. *Process for Limiting Orbital Debris*, NASA-STD-8719.14A, 25 May 2012
C. SMAP / Delta II 7320-10 Interface Control Document, Orbital Document, ULA-Delta II-ICD-12-014, Baseline August 2013
D. McKissock, Barbara, Patricia Loyselle, and Elisa Vogel. *Guidelines on Lithium-ion Battery Use in Space Applications*. Tech. no. RP-08-75. NASA Glenn Research Center Cleveland, Ohio
E. *UL Standard for Safety for Lithium Batteries, UL 1642*. UL Standard. 4th ed. Northbrook, IL, Underwriters Laboratories, 2007
F. Kwas, Robert. Thermal Analysis of ELaNa-4 CubeSat Batteries, ELVL-2012-0043254; Nov 2012
G. Range Safety User Requirements Manual Volume 3- Launch Vehicles, Payloads, and Ground Support Systems Requirements, AFSCM 91-710 V3.
H. Preliminary Mission Analysis For the Delta II 7320-10 / SMAP Spacecraft Missio, CRDL C4-1, PGAA No.2, ULA-TP-13-245
I. *UL Standard for Safety for Household and Commercial Batteries, UL 2054*. UL Standard. 2nd ed. Northbrook, IL, Underwriters Laboratories, 2005
J. HQ OSMA Policy Memo/Email to 8719.14: CubeSat Battery Non-Passivation, Suzanne Aleman to Justin Treptow, 10, March 2014

The intent of this report is to satisfy the orbital debris requirements listed in ref. (a) for the ExoCube CubeSat on the ELaNa-10 auxiliary mission launching in conjunction with the SMAP primary payload. It serves as the final submittal in support of the spacecraft Safety and Mission Success Review (SMSR). Sections 1 through 8 of ref. (b) are addressed in this document; sections 9 through 14 fall under the requirements levied on the primary spacecraft and are not presented here.

The following table summarizes the compliance status of the ExoCube CubeSat as part of the ELaNa-10 auxiliary payload mission flown on SMAP. The four CubeSats, manifested and back-ups, comprising the ELaNa-10 mission are fully compliant with all applicable requirements.

Table 1: Orbital Debris Requirement Compliance Matrix

Requirement	Compliance Assessment	Comments
4.3-1a	Not applicable	No planned debris release
4.3-1b	Not applicable	No planned debris release
4.3-2	Not applicable	No planned debris release
4.4-1	Compliant	Minimal risk to orbital environment, mitigated by orbital lifetime
4.4-2	Compliant	Minimal risk to orbital environment, mitigated by orbital lifetime
4.4-3	Not applicable	No planned breakups
4.4-4	Not applicable	No planned breakups
4.5-1	Compliant	
4.5-2	Not applicable	
4.6-1(a)	Compliant	Worst case lifetime 8.0 yrs
4.6-1(b)	Not applicable	
4.6-1(c)	Not applicable	
4.6-2	Not applicable	
4.6-3	Not applicable	
4.6-4	Not applicable	Passive disposal
4.6-5	Compliant	
4.7-1	Compliant	Non-credible risk of human casualty
4.8-1	Compliant	No planned tether release under ELaNa-10 mission

Section 1: Program Management and Mission Overview

The ELaNa-10 mission is sponsored by the Space Operations Mission Directorate at NASA Headquarters. The Program Executive is Jason Crusan. Responsible program/project manager and senior scientific and management personnel are as follows:

ExoCube: Jordi Puig-Suari, Principle Investigator; Chad Taylor, Project Manager

Program Milestone Schedule	
Task	**Date**
CubeSat Selection	3/4/13
MRR	7/9/14
CubeSat Delivery to Cal Poly for Integration into P-PODs	8/11/14
Pre-Ship Review	10/1/14
CubeSat Delivery to VAFB/ Integration onto LV	10/25/14
Launch	11/5/2014

Figure 1: Program Milestone Schedule

The ELaNa-10 mission will be launched as an auxiliary payload on the SMAP mission on a Delta II 7320-10 launch vehicle from Vandenberg Air Force Base, California. The ELaNa-10, will deploy 4 pico-satellites (or CubeSats). The CubeSat slotted position is identified in Table 2: . The ELaNa-10 manifest includes: ExoCube, FireBird-2, and GRIFEX. The current launch date is in November 2014. The four CubeSats will be ejected from 3 PPOD carriers attached to the launch vehicle, placing the CubeSats in an orbit approximately 670 X 450 km at inclination of 98 deg (ref. (h)).

Section 2: Spacecraft Description

ExoCube will measure in-situ densities of various ions and neutrals in the upper ionosphere and lower exosphere. The densities are measured using a gated time-of-flight mass spectrometer designed and built by NASA Goddard. These measurements will be used to characterize the climatology of the upper ionospheric and lower exospheric composition. They will help validate current empirical and climatological atmospheric models. A satellite bus to house the mass spectrometer was designed and built by Cal Poly. The bus includes an environmental chamber to protect the instrument and a 3-axis attitude determination control system (ADCS) that will maintain stable Nadir and Ram pointing necessary for accurate data measurement. The ADCS uses gravity gradient stabilization with deployable booms and a Sinclair momentum wheel to stabilize the roll axis and Ram pointing. The mission life is expected to be 6 months to a year.

Table 2: ExoCube Properties

PPOD Slot	CubeSat Quantity	CubeSat size	CubeSat Names	CubeSat Masses (kg)
1	1	3U (10 cm X 10 cm X 30 cm)	Exocube	3.845

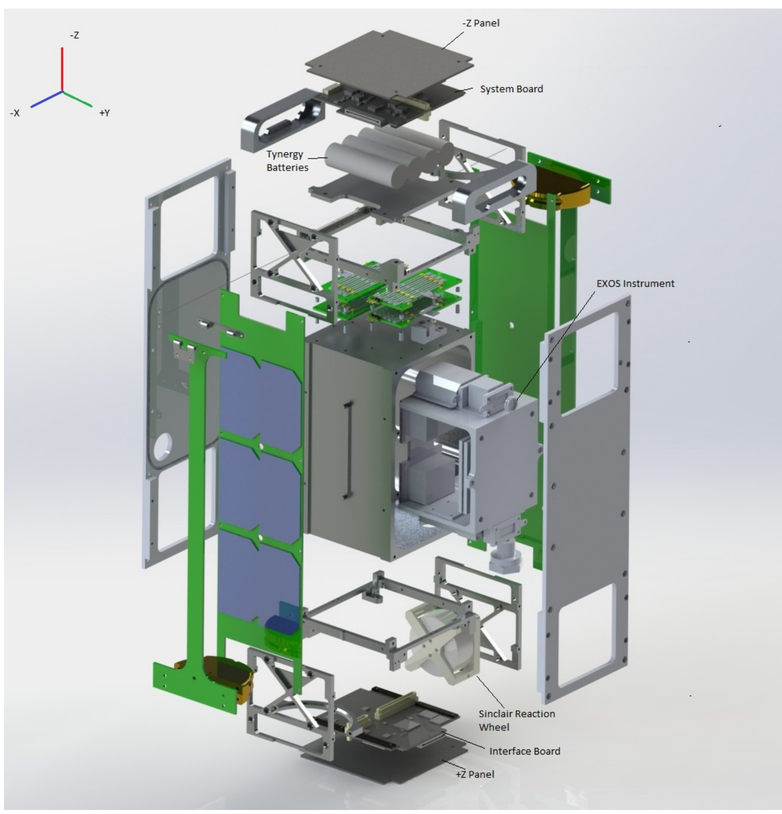

Figure 2: Exocube Expanded View

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After deployment from the P-POD, the satellite will power on. Approximately 40 minutes later, antenna deployment will occur. Upon verification of antenna deployment, the beacon will be activated and the satellite will acquire with the ground station. The ground station will uplink the current time and TLEs. The detumble process will then begin using magnetometers and magnetorquers. Once the rates have been reduced, the PD controller and Kalman Filter will be activated and the booms will be deployed. Once Nadir pointing is acquired, the momentum wheel will begin spinning up. Around 4 hours later, the wheel will be at full speed and then satellite will reacquire Nadir and Ram pointing. The camera on the –z panel will take pictures to verify the correct pointing. Once the correct orientation is verified, the instrument will be powered on. On every pass over a ground station (approx. every 12 hours), the satellite will downlink data from the instrument and uplink the current time for the clock and new TLEs to maintain accuracy of the orbital propagator.

The structure is made entirely of 6061-T6 Aluminum. The deployable booms are made of FR4 with the tip masses being brass. The Antenna is made of NiTi and Delrin. The satellite contains mostly standard commercial off the shelf materials, electrical components, PCBs, and solar cells. The cathode inside of the instrument is made of tungsten, but the tungsten is small enough that it does burn up during re-entry.

There are no pressure vessels, hazardous materials, or exotic materials.

There are four 1-cell batteries on the satellite. They are all Tenergy Li-Ion, 3.7 V 2600 mAh batteries (Item number 30011-02). The UL listing number is MH48285. There is battery protection circuitry and over-charge protection circuitry. All batteries are connected in parallel. These are the same batteries used on CP8.

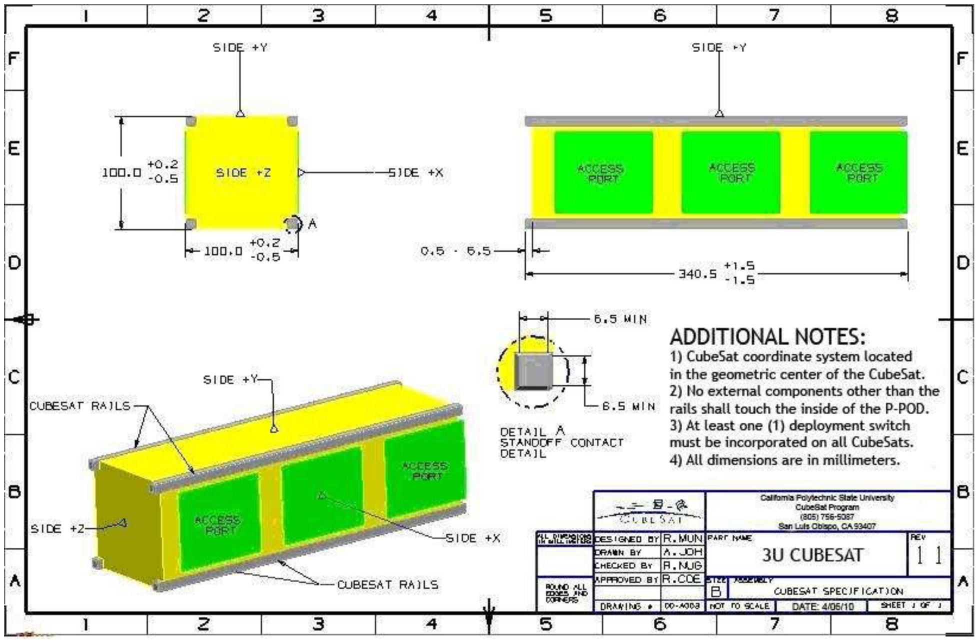

Figure 3: 3U CubeSat Specification

Section 3: Assessment of Spacecraft Debris Released during Normal Operations

The assessment of spacecraft debris requires the identification of any object (>1 mm) expected to be released from the spacecraft any time after launch, including object dimensions, mass, and material.

The section 3 requires rationale/necessity for release of each object, time of release of each object, relative to launch time, release velocity of each object with respect to spacecraft, expected orbital parameters (apogee, perigee, and inclination) of each object after release, calculated orbital lifetime of each object, including time spent in Low Earth Orbit (LEO), and an assessment of spacecraft compliance with Requirements 4.3-1 and 4.3-2.

No releases are planned on the ELaNa-10 CubeSat mission therefore this section is not applicable.

Section 4: Assessment of Spacecraft Intentional Breakups and Potential for Explosions.

There are NO plans for designed spacecraft breakups, explosions, or intentional collisions on the ELANA-10 mission. No passivation of components is planned at the End of Mission for the RACE CubeSat.

The probability of battery explosion is very low, and, due to the very small mass of the satellites and their short orbital lifetimes the effect of an explosion on the far-term LEO environment is negligible (ref (j)).

ExoCube's batteries still meet Req. 56450 (4.4-2) by virtue of the HQ OSMA policy statement regarding CubeSat battery disconnect, stating;

> "CubeSats as a satellite class need not disconnect their batteries if flown in LEO with orbital lifetimes less than 25 years." (ref. (j))

Assessment of spacecraft compliance with Requirements 4.4-1 through 4.4-4 shows that with a lifetime of 8.0 years maximum the ExoCube CubeSat is compliant.

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

Calculation of spacecraft probability of collision with space objects larger than 10 cm in diameter during the orbital lifetime of the spacecraft takes into account both the mean cross sectional area and orbital lifetime.

ExoCube was evaluated for this ODAR are stowed in a convex configuration, indicating there are no elements of the CubeSats obscuring another element of the same CubeSats from view. Thus, mean CSA for stowed ExoCube was calculated using Equation 1. This configuration renders the longest orbital lifetime.

Once ExoCube has been ejected from the P-POD and deployables have been extended Equation 2 is utilized to determine the mean CSA. A_{max} is identified as the view that yields the maximum cross-sectional area. A_1 and A_2 are the two cross-sectional areas orthogonal to A_{max}. Refer to Appendix A for dimensions used in these calculations.

$$\boldsymbol{Mean\ CSA} = \frac{\sum \boldsymbol{Surface\ Area}}{\mathbf{4}} = \frac{[\mathbf{2} * (\boldsymbol{w} * \boldsymbol{l}) + \mathbf{4} * (\boldsymbol{w} * \boldsymbol{h})]}{\mathbf{4}}$$

Equation 1: Mean Cross Sectional Area for Cubic Objects

$$\boldsymbol{Mean\ CSA} = \frac{(\boldsymbol{A_{max}} + \boldsymbol{A_1} + \boldsymbol{A_1})}{\mathbf{2}}$$

Equation 2: Mean Cross Sectional Area for Complex Objects

The ExoCube orbit at deployment is 670 km apogee altitude by 450 km perigee altitude, with an inclination of 98 degrees. With an area to mass (3.8 kg) ratio of 0.0104 m^2/kg, DAS yields 8.0 years for orbit lifetime for its stowed state, which in turn is used to obtain the collision probability. ExoCube's probability of collision is $10^{-5.8}$ in both the stowed and deployed configuration. **Table 3** below provides complete results.

Table 3: CubeSat Orbital Lifetime & Collision Probability

	CubeSat	ExoCube
	Mass (kg)	3.845
Stowed	Mean C/S Area (m^2)	0.0399
	Area-to Mass (m^2/kg)	0.0104
	Orbital Lifetime (yrs)	8.0
	Probability of collision (10^X)	-5.8
Deployed	Mean C/S Area (m^2)	0.0452
	Area-to Mass (m^2/kg)	0.0118
	Orbital Lifetime (yrs)	7.6
	Probability of collision (10^X)	-5.8

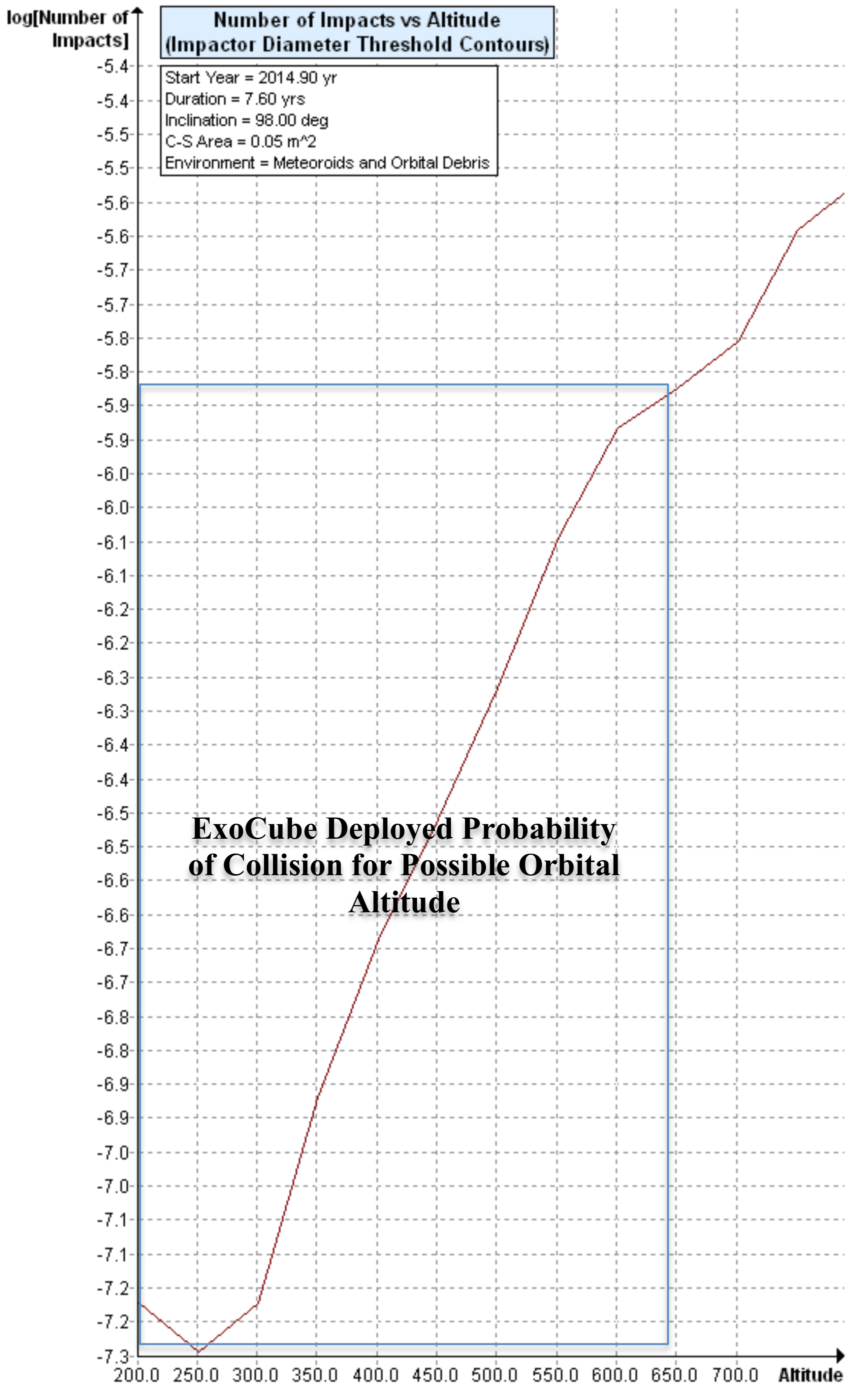

Figure 4: Highest Risk of Orbit Collision vs. Altitude (ExoCube Deployed)

There will be no post-mission disposal operation. As such the identification of all systems and components required to accomplish post-mission disposal operation, including passivation and maneuvering, is not applicable.

The probability of the ExoCube spacecraft collision with debris and meteoroids greater than 10 cm in diameter and capable of preventing post-mission disposal is less than $10^{-5.8}$, for any configuration. This satisfies the 0.001 maximum probability requirement 4.5-1.

Since ExoCube has no capability or plan for end-of-mission disposal, requirement 4.5-2 is not applicable.

Assessment of spacecraft compliance with Requirements 4.5-1 shows ExoCube to be compliant. Requirement 4.5-2 is not applicable to this mission.

Section 6: Assessment of Spacecraft Postmission Disposal Plans and Procedures

ExoCube will naturally decay from orbit within 25 years after end of the mission, satisfying requirement 4.6-1a detailing the spacecraft disposal option.

Planning for spacecraft maneuvers to accomplish postmission disposal is not applicable. Disposal is achieved via passive atmospheric reentry.

Calculating the area-to-mass ratio for the worst-case (smallest Area-to-Mass) post-mission disposal among the CubeSats finds ExoCube in its stowed configuration as the worst case. The area-to-mass is calculated for is as follows:

$$\frac{\boldsymbol{Mean}\ {}^{\boldsymbol{C}}\!/_{\boldsymbol{S}}\,\boldsymbol{Area}\ (\boldsymbol{m^2})}{\boldsymbol{Mass}\ (\boldsymbol{kg})} = \boldsymbol{Area - to - Mass}\ (\frac{\boldsymbol{m^2}}{\boldsymbol{kg}})$$

Equation 3: Area to Mass

$$\frac{0.0399\, m^2}{3.8\, kg} = 0.0104 \frac{m^2}{kg}$$

This assessment of the spacecraft illustrates they are compliant with Requirements 4.6-1 through 4.6-5.

DAS 2.0.2 Orbital Lifetime Calculations:

DAS inputs are: 450 km minimum perigee X 670 km apogee altitudes with an inclination of 98 degrees at deployment in November of 2014. An area to mass ratio of 0.0104 m^2/kg for the ExoCube CubeSat was inputed. DAS 2.0.2 yields a 8.0 years orbit lifetime for ExoCube in its stowed state.

This meets requirement 4.6-1. For the complete list of CubeSat orbital lifetimes reference Table 3: CubeSat Orbital Lifetime & Collision Probability

The DAS assessment shows compliance.

Section 7: Assessment of Spacecraft Reentry Hazards

A detailed assessment of the components to be flown on ExoCube was performed. The assessment used DAS 2.0, a conservative tool used by the NASA Orbital Debris Office to verify Requirement 4.7-1. The analysis is intended to provide a bounding analysis for characterizing the survivability of a CubeSat's component during re-entry. For example, when DAS shows a component surviving reentry it is not taking into account the material ablating away or charring due to oxidative heating. Both physical effects are experienced upon reentry and will decrease the mass and size of the real-life components as the reenter the atmosphere, reducing the risk they pose still further.

The following steps are used to identify and evaluate a components potential reentry risk relative to the 4.7-1 requirement of having less than 15 J of kinetic energy and a 1:10,000 probability of a human casualty in the event the survive reentry.

1. Low melting temperature (less than 1000 °C) components are identified as materials that would never survive reentry and pose no risk to human casualty. This is confirmed through DAS analysis that showed materials with melting temperatures equal to or below that of copper (1080 °C) will always demise upon reentry for any size component up to the dimensions of a 1U CubeSat.

2. The remaining high temperature materials are shown to pose negligible risk to human casualty through a bounding DAS analysis of the highest temperature components, stainless steel (1500°C). If a component is of similar dimensions and has a melting temperature between 1000 °C and 1500°C, it can be expected to posses the same negligible risk as stainless steel components. See Table 4.

Table 4: ExoCube Stainless Steel DAS Analysis

CubeSat	Stainless Steel Components	Mass (g)	Length / Diameter (cm)	Width (cm)	Height (cm)	Demise Alt (km)	KE (J)
ExoCube	Antennae	2.638	0.22	8	1.2	0	0
ExoCube	Hinge Pins	1.517	0.226	3.2		77.4	0
ExoCube	Tip Masses	226.729	6.38	1.68		70.3	0

The majority of stainless steel components demise upon reentry. The components that DAS conservatively identifies as reaching the ground have 1 or less joules of kinetic energy, far below the requirement of 15 joules. No stainless steel component will pose a risk to human casualty as defined by the Range Commander's Council. In fact, any injury incurred or inflicted by an object with such low energy would be negligible and wouldn't require the individual to seek medical attention.

Through the method described above, Table 4: ExoCube Stainless Steel DAS Analysis, and the full component lists in the Appendix ExoCube is conservatively shown to be in compliance with Requirement 4.7-1 of NASA-STD-8719.14A.

See the Appendix for a complete accounting of the survivability of ExoCube.

Section 8: Assessment for Tether Missions

ExoCube will not be deploying any tethers.

ExoCube satisfies Section 8’s requirement 4.8-1.

Section 9-14

ODAR sections 9 through 14 for the launch vehicle are addressed in ref. (g), and are not covered here.

Appendix A. ExoCube Component List

Name	External/Internal (Major/Minor Components)	Qty	Material	Body Type	Mass (g)	Diameter/ Width (mm)	Length (mm)	Height (mm)	Low Melting	Melting Temp (°C)	Comment
ExoCube		1	Various	Box		100	100	340.5	yes		Demise
CubeSat Structure	External - Major	1	Aluminum 6061	Box	1127.012	100	100	340.5	yes		Demise
Antennae	External - Major	1	NiTi and Delrin	Route	2.638	2.2	80	12	no	1981	Negligible Risk: KE ~ 0 J. See Table 4
Solar Panels	External - Major	28	Eglass	Flat Rectangular		0.5	68	40	yes		Demise
Side Panels	External - Major	4	FR4 Multilayer PCB	Rectangular	125	1.5	83	316.9	yes		Demise
Z-Panels	External - Major	2	FR4 Multilayer PCB	Square	50	1.5	100	100	yes		Demise
Deployable Booms	External - Major	2	FR4 Multilayer PCB	Rectangular	22.748	1.5	81.5	299.4	yes		Demise
Sep Switches	External - Minor	2	Plastic	Rectangular	2	6	8	7	yes		Demise
Hinge Pins	External - Minor	4	420 Stainless	Cylindrical	1.517	2.26	32	N/A	no	1455	Demise See Table 4
Torsion springs	External - Minor	6	302 Stainless	Cylindrical	n/a	n/a	n/a	n/a	no	1538	Demise
Tip Masses	Internal - Major	2	Brass 360	Half-Disk	226.729	63.8	16.8	N/A	yes		Demise See Table 4
Sinclair Reaction Wheel	Internal - Major	1	Aluminum 6061-T6, Stainless Steel 416	Wheel/Disk	122	50	29.5	N/A	yes		Demise
Tip Mass Brackets	Internal - Minor	2	Aluminum 7075	Half-Disk	6.936	67	5	N/A	yes		Demise
Batteries	Internal - Major	4	Lithium Ion	Cylindrical	45	18.6	65.2	N/A	yes		Demise
Payload Board	Internal - Major	2	FR4 Multilayer PCB	Board	36	1.5	83	83	yes		Demise
Comm Board	Internal - Major	1	FR4 Multilayer PCB	Board	13.6	1.5	83	36	yes		Demise
C&DH Board	Internal - Major	1	FR4 Multilayer PCB	Board	34.5	1.5	83	83	yes		Demise
Fasteners	Internal - Minor		18-8 Stainless	Screw	n/a	n/a	n/a	n/a	no	1450	Demise
Staking Compound	Internal/External - Minor	N/A	3M Scotch Weld 2216	n/a	25	n/a	n/a	n/a	yes		Demise