Aug 06, 2013

Orbital Debris Assessment for PhoneSat v2.5 on the CRS SpX-3 / ELaNa-5 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. *P-POD Status SpX-3 Agreement History* (Orbital Information) , ISS_CM_019 Rev 01/2011
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. *UL Standard for Safety for Household and Commercial Batteries, UL 2054*. UL Standard. 2nd ed. Northbrook, IL, Underwriters Laboratories, 2005
I. Opiela, John. "RE: DAS 2.0 Orbital Lifetime Inquiry" April 5, 2013. E-mail.

The intent of this report is to satisfy the orbital debris requirements listed in ref. (a) for the PhoneSat v2.5 CubeSat on the ELaNa-5 auxiliary mission launching in conjunction with the SpX-3 primary payload. Sections 1 through 8 of ref. (b) are addressed in this document; sections 9 through 14 fall under the requirements levied on the launch vehicle compliance assessment and are not presented here.

The following table summarizes the compliance status of the PhoneSat v2.5 CubeSat as part of the ELaNa-5 auxiliary payload mission flown on SpX-3. This mission is fully compliant with all applicable requirements.

Table 1: Orbital Debris Requirement Compliance Matrix

Requirement	Compliance Assessment	Comments
4.3-1a	Compliant	Lifetime of debris is days
4.3-1b	Compliant	Lifetime of debris is days
4.3-2	Not applicable	No planned debris release
4.4-1	Compliant	On board energy source (batteries) incapable of debris-producing failure
4.4-2	Compliant	On board energy source (batteries) incapable of debris-producing failure
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 0.2yrs
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

Section 1: Program Management and Mission Overview

The ELaNa-5 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:

PhoneSat: Jasper Wolfe, Project Manager

Table 2: Program Milestone Schedule

Program Milestone Schedule	
Task	**Date**
CubeSat Selection	7/1/12
CubeSat Build, Test, and Integration	July 2012 to July 2013
MRR	7/23/13
CubeSat Delivery/integration at Cal Poly	9/16/12
P-POD Integration into LV	10/28/13
Launch	2/11/14

The ELaNa-5 mission will deploy 5 pico-satellites (or CubeSats) as a secondary payload on the mission. The ELaNa-5 mission will be launched as an auxiliary payload on the SpX-3 mission on a Falcon 9 launch vehicle from Cape Canaveral Air Force Station. The current launch date is in February 2014. The five CubeSats will be ejected from a P-POD carrier attached to the launch vehicle, placing the CubeSats in an orbit approximately 325 X 325 km at inclination of 51.6 deg (ref. (c)).

Section 2: Spacecraft Description

PhoneSat v2.5 aims to perform several experiments with the new sub-systems added to the first version PhoneSat 1.0. Each of the experiments will be performed in one different phase in order to prove the robustness of the different equipment on board. PhoneSat v2.5 will run 3 different threads at the same time.

After 30 minutes from P-POD deployment, the timer will initiate the deployment of the UHF antenna via Nichrome wire. After 45 the timer will power on the satellite. From this point the satellite computer (Nexus S) may take a few minutes to boot up before beginning Phase 1 which will last 1.5 days; performing Health checks of the satellite and beaconing down health data while charging the satellite. Phase 1 will continue as one of two threads in Phase 2. Phase 2 will last 2 days or less; the second thread will perform a de-tumble algorithm and de-spin the satellite to a pre-determined threshold. Phase 1 and 2 will continue as two of three threads in Phase 3. The focus of Phase 3 is to test the attitude control system in depth and to establish two-way communications.

The primary CubeSat structure is made of Aluminum 5052-H32. It contains all standard commercial off the shelf (COTS) materials, electrical components, PCBs and solar cells.

There are no pressure vessels, hazardous or exotic materials.

The electrical power storage system consists of common lithium-ion batteries with over-charge/current protection circuitry.

Table 3: PhoneSat v2.5

CubeSat Quantity	CubeSat size	CubeSat Names	CubeSat Masses (kg)
1	1U (10 cm X 10 cm X 10 cm)	PhoneSat v2.5	1.2

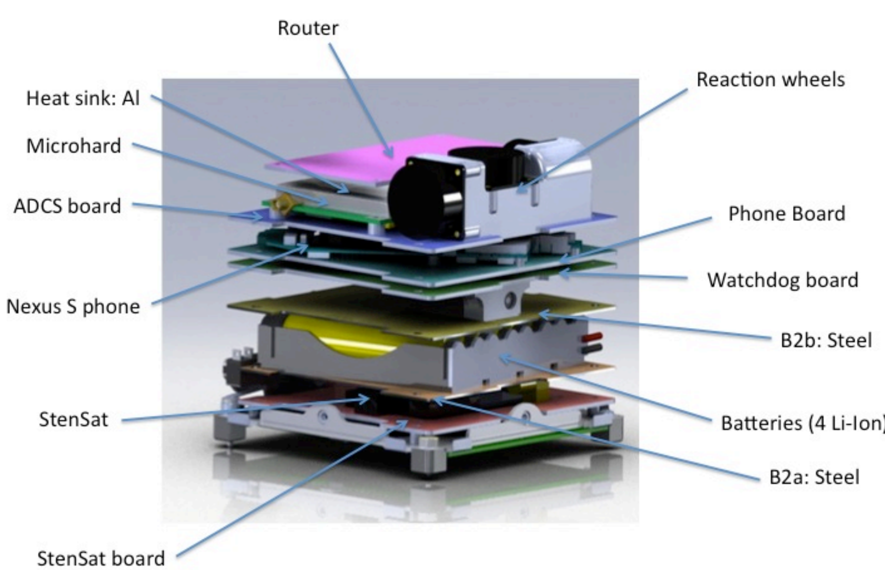

Figure 1: PhoneSat Expanded View

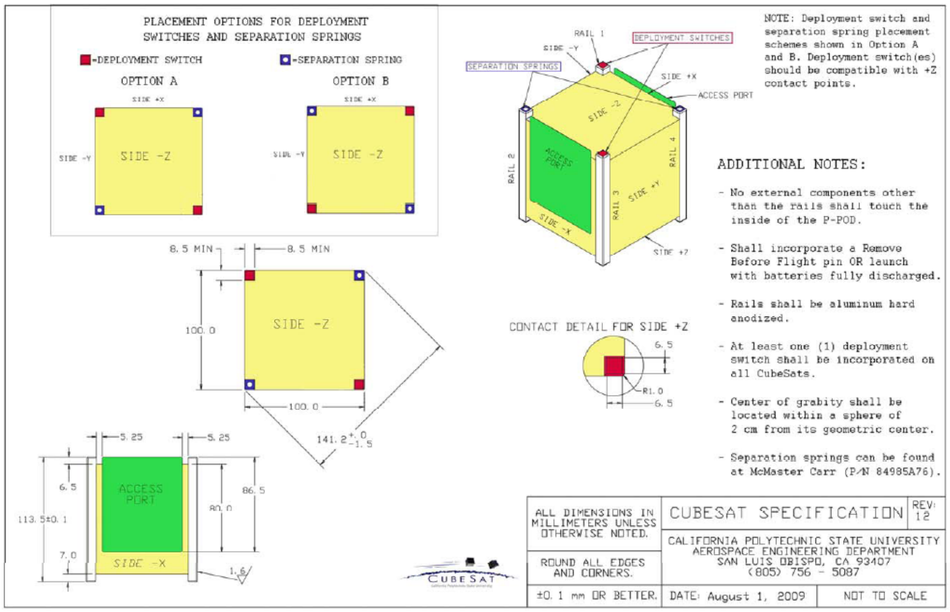

Figure 2: 1U CubeSat Specification

Total satellite mass (1 satellite) at launch, including all propellants and fluids: ~1.2kg

Dry mass of satellite at launch, excluding solid rocket motor propellants: ~1.2kg

Description of all propulsions systems (cold gas, mono-propellant, bi-propellant, electric, nuclear): None

Identification, including mass and pressure, of all fluids (liquids and gases) planned to be on board and a description of the fluid loading plan or strategies, excluding fluids in sealed heat pipes: None

Description of all fluid systems, including size, type, and qualifications of fluid containers such as propellant and pressurization tanks, including pressurized batteries: None. PhoneSat v2.5 use unpressurized standard COTS Lithium-Ion battery cells.

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: PhoneSat v2.5 has active three-axis attitude control by means of three orthogonal reaction wheels and three orthogonal sets of coupled magnetorquer coils. The PhoneSat v2.5 is cubical in shape – all of the sides have identical surface areas.

Description of any range safety or other pyrotechnic devices: No pyrotechnic devices are used.

Description of the electrical generation and storage system: Standard COTS Lithium-Ion battery cells are charged prior to payload integration and provide electric energy during the mission. The battery holder and protection circuit is a COTS item designed for the Lithium-Ion 18650 cell format batteries. Each face of the CubeSat has solar panels which charge the batteries via a recharge circuit. PhoneSat v2.5 carries four Lithium-Ion battery cells in the 18650 cell format.

Identification of any other sources of stored energy not noted above: None.

Identification of any radioactive materials on board: There are no radioactive materials on the PhoneSat v2.5.

Section 3: Assessment of Spacecraft Debris Released during Normal Operations

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 PhoneSat CubeSat mission therefore this section is not applicable.

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

Malfunction of lithium ion or lithium polymer batteries and/or associated control circuitry has been identified as a potential cause for spacecraft breakup during deployment and mission operations.

While no passivation of batteries will be attempted, natural degradation of the solar cell and battery properties will occur over the post mission period, which may be as long as 0.2 years. These conditions pose a possible 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 to the space environment 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 result in rapid energy release in the form of combustion.

There are NO plans for designed spacecraft breakups, explosions, or intentional collisions on the ELaNa-5 mission.

Section 4 asks for a list of components, which shall be passivated at End of Mission (EOM), as well as the method of passivation and description of the components, which cannot be passivated. No passivation of components is planned at the End of Mission for any of the ELaNa-5 CubeSats.

Since the batteries used do not present a debris generation hazard even in the event of rapid energy release (see assessment directly below), passivation of the batteries is not necessary in order to meet the requirement 4.4-2 (56450) for passivation of energy sources “to a level which cannot cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft.” Because passivation is not necessary, and in the interest of not increasing the complexity of the CubeSats, there was no need to add this capability to their electrical power generation and storage systems.
Assessment of spacecraft compliance with Requirements 4.4-1 through 4.4-2 shows that the ELaNa-5 CubeSats are compliant. Requirements 4.4-3 and 4.4-4, addressing intentional break-ups are not applicable.

The following addresses requirement 4.4-2. The CubeSats that have been selected to fly on the SpX-3 mission have not been designed to disconnect their onboard storage energy devices (lithium ion and lithium polymer batteries). However, the CubeSats batteries still meet Req. 56450 by virtue of the fact that they cannot “cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft”.

Table 4: PhoneSat v2.5 Cells

CubeSat	Technology	Manufactor	Model	UL Listing Number
PhoneSat v2.5	Lithium Ion	LG	LG ICR 18650C1	MH19896

The batteries are all consumer-oriented devices. All battery cells have been recognized as Underwriters Laboratories (UL) tested and approved. Furthermore, safety devices incorporated in these batteries include pressure release valves, over current charge protection and over current discharge protection.

The fact that these batteries are UL recognized indicates that they have passed the UL standard testing procedures that characterize their explosive potential. Of particular concern to NASA Req. 56450 is UL Standard 1642, which specifically deals with the testing of lithium batteries. Section 20 Projectile Test of UL 1642 (ref. (e)) 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).

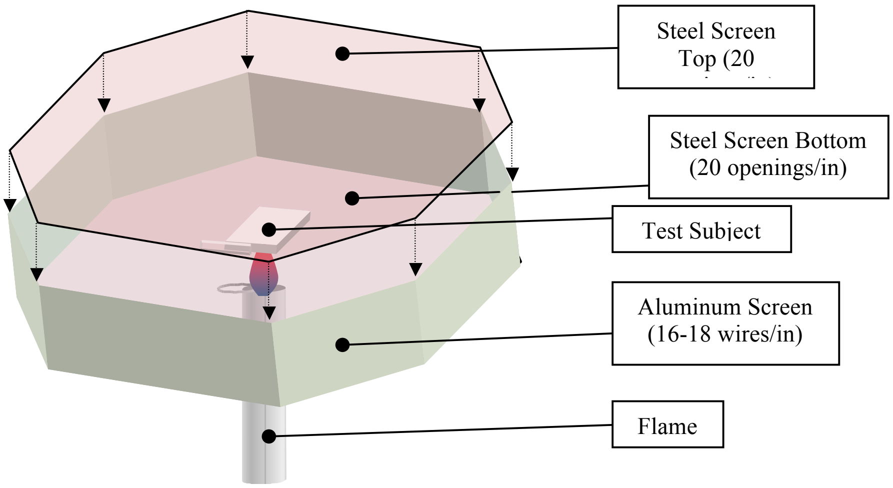

Figure 3: Underwriters Laboratory Explosion Test Apparatus

The batteries being launched via CubeSat will experience conditions on orbit that are generally much less severe that those seen during the UL test. While the source of failure would not be external heat on orbit, analysis of the expected mission thermal environment performed by NASA LSP Flight Analysis Division shows that given the very low (<=41.44 W-hr, maximum for PhoneSat) power dissipation for CubeSats, the batteries will be exposed to a maximum temperature that is well below their 212^{o}F safe operation limit (ref. (f)). It is unlikely but possible that the continual charging with 2 to 6 W of average power from the solar panels over an orbital life span greater than 2 years may expose the two to four batteries (per CubeSat) to overcharging which could cause similar heat to be generated internally. Through the UL testing, it has been shown that these batteries do not cause an explosion that would cause a fragmentation of the spacecraft.

A NASA Glenn Research Center guideline entitled Guidelines on Lithium-ion Battery Use in Space Applications (ref. (d)) explains that the hazards of Li-Ion cells in an overcharge situation result in the breakdown of the electrolyte found in Li-ion cells causing an increase in internal pressure, formation of flammable organic solvents, and the release of oxygen from the metal oxide structure. From a structural point of view a battery in an overcharge situation can expect breakage of cases, seals, mounting provisions, and internal components. The end result could be “unconstrained movement of the battery” (ref. (d), pg 13). This document clearly indicates that only battery deformation and the escape of combustible gasses will be seen in an overcharging situation, providing further support to the conclusion that CubeSat fragmentation due to explosion is not a credible scenario for this application. It is important to note that the NASA guide to Li-ion batteries makes no mention of these batteries causing explosions of any magnitude whatsoever.

Compliance Statement: Assessment of spacecraft compliance with Requirements 4.4-1 through 4.4-4 shows that the ELaNa-5 CubeSat is compliant. By inclusion, PhoneSat v2.5 is therefore compliant. Requirements 4.4-3 and 4.4-4 are not applicable.

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.

PhoneSat v2.5 was evaluated for this ODAR in a 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 all stowed CubeSats was calculated using Equation 1. This configuration renders the longest orbital life times for KickSat and the Sprites.

Once a CubeSat 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.

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

Equation 1: Mean Cross Sectional Area for Convex Objects

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

Equation 2: Mean Cross Sectional Area for Complex Objects

PhoneSat v2.5's orbit at deployment is 325 km apogee altitude by 325 km perigee altitude, with an inclination of 51.6 degrees. With an area to mass ratio of 0.0164 m^2/kg, DAS yields 0.2 years for orbit lifetime for its stowed state, which in turn is used to obtain the collision probability. PhoneSat in the deployed configuration has a probability of collision of $10^{-9.7}$, and a $10^{-9.7}$ probability of collision in the stowed configuration. Table 5 below provides complete results.

Table 5: CubeSat Orbital Lifetime & Collision Probability

	CubeSat	PhoneSat
	Mass (kg)	1.2
Stowed	Mean C/S Area (m^2)	0.0164
	Area-to Mass (m^2/kg)	0.0146
	Orbital Lifetime (yrs)	0.1
	Probability of collision (10^X)	-9.7
Deployed	Mean C/S Area (m^2)	0.0171
	Area-to Mass (m^2/kg)	0.0153
	Orbital Lifetime (yrs)	0.1
	Probability of collision (10^X)	-9.7

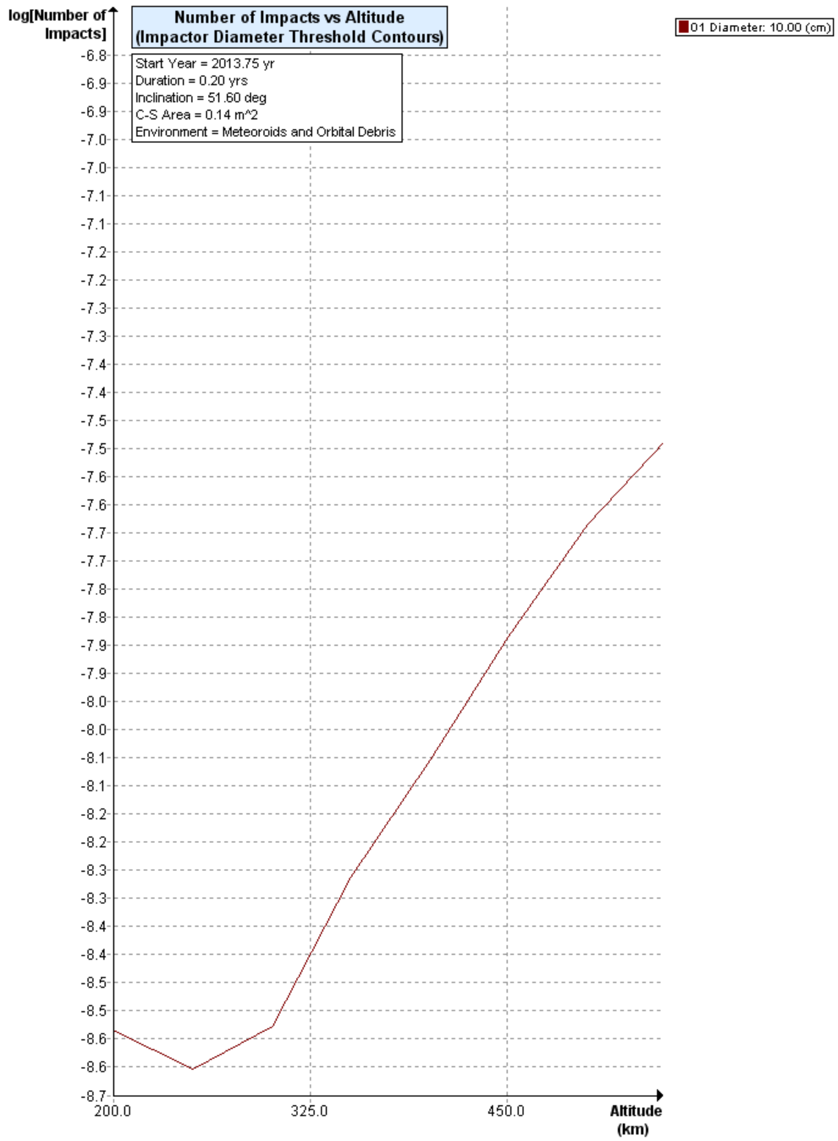

Figure 4: Highest Risk of Orbit Collision vs. Altitude

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 PhoneSat v2.5 spacecraft collision with debris and meteoroids greater than 10 cm in diameter and capable of preventing post-mission disposal is less than $10^{-9.7}$, for any configuration. This satisfies the 0.001 (10^{-6}) maximum probability requirement 4.5-1.

Since PhoneSat v2.5 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 the PhoneSat v2.5 mission to be compliant. Requirement 4.5-2 is not applicable to this mission.

Section 6: Assessment of Spacecraft Postmission Disposal Plans and Procedures

PhoneSat v2.5 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 is calculated for is as follows:

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

Equation 3: Area to Mass

$$\frac{0.0214 m^2}{2.8\ kg} = 0.0076 \frac{m^2}{kg}$$

<u>DAS 2.0.2 Orbital Lifetime Calculations:</u>

DAS inputs are: 325 km maximum perigee X 325 km maximum apogee altitudes with an inclination of 51.6 degrees at deployment in the year 2013. An area to mass ratio of 0.0076 m^2/kg.

Assessment results show compliance of PhoneSat v2.5. This meets requirement 4.6-1. For the PhoneSat v2.5 orbital lifetime, reference Table 5.

Section 7: Assessment of Spacecraft Reentry Hazards

A detailed assessment of the components to be flown on PhoneSat v2.5 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 15J 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 meet the human casualty requirement through a bounding DAS analysis of the highest temperature components, generally stainless steel (1500°C). A component of similar dimensions and possessing a melting temperature between 1000 °C and 1500°C, can be expected to posses as negligible risk similar to stainless steel components. Probability of human casualty was calculated if a component exceeded 15J of energy upon reentry. See Table 6.

The PhoneSat v2.5 mission complies with Requirement 4.7-1, to have less than 1:10,000 risk of human casualty.

PhoneSat has two large components that survive reentry but have less than 15J of energy, which satisfies the requirement.

The majority of high temperature components demise upon reentry. The components that DAS conservatively identifies as reaching the ground have less than 15 joules of kinetic energy. No high temperature component will pose a risk to human casualty as defined by the Range Commander's Council (ref. (g)).

As documented in, Table 6: PhoneSat v2.5 Survivability DAS Analysis, and Appendix A, the PhoneSat v2.5 mission is conservatively shown to be in compliance with Requirement 4.7-1 of NASA-STD-8719.14A.

See Appendix for a complete accounting of the survivability of all CubeSat components.

Table 6: PhoneSat v2.5 Survivability DAS Analysis

CubeSat	ELaNa-5 Stainless Steel Components	Mass (g)	Length / Diameter (cm)	Width (cm)	Height (cm)		Demise Alt (km)	KE (J)
PhoneSat	Reaction Control System	87.8	0.254	0.762	0.254		77.1	0
PhoneSat	B2a	55.0	9.1	9.5	0.1		0	8
PhoneSat	B2b	55.0	9.1	9.5	0.1		0	8

Note: Components are modeled as stainless steel unless otherwise noted in component name.

Compliance Statement: Through the method described above, Table 6: PhoneSat v2.5 Survivability DAS Analysis, and the full component lists in the Appendix all CubeSats launching under the ELaNa-5 mission are conservatively shown to be in compliance with Requirement 4.7-1 of NASA-STD-8719.14A. By inclusion, PhoneSat v2.5 is therefore compliant.

Section 8: Assessment for Tether Missions

ELaNa-5 CubeSats will not be deploying any tethers.

ELaNa-5 CubeSats satisfy requirement 4.8-1.

Compliance Statement: ELaNa-5 CubeSats satisfy Section 8's requirement 4.8-1. By inclusion, PhoneSat v2.5 is therefore compliant.

Section 9-14

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

Appendix Index:

Appendix A. ELaNa-5 Component List by CubeSat: PhoneSat v2.5

CubeSat	Row Number	Name	External/Internal (Major/Minor Components)	Qty	Material	Body Type	Mass (g)	Diameter/ Width (mm)	Length (mm)	Height (mm)	Low Melting	Melting Temp	Comment
PhoneSat	1	CubeSat Structure		1	Aluminum 6061	Box	381.3	10.0	10.0		Yes		Demises
PhoneSat	2	Antenna		1	ABSPlus and Aluminum 6061	Box	2.1	178.0	12.7	0.2	Yes		Demises
PhoneSat	3	Solar Cells		100	PCB	Box	0.2	15.5	31.8	0.1	Yes		Demises
PhoneSat	4	Magnetotorquer boards		6	Germanium, Gallium Arsenide, and Gallium Indium Diphosphorous	Box	33.9	104.8	82.6	2.5	Yes		Demises
PhoneSat	5	Reaction Control System		1	Mylar-coated Steel	Box	87.8	2.5	7.6	2.5	No	1500	Demises See **Error! Reference source not found.**
PhoneSat	6	Antenna Holders		1	---	Box	10.6	11.8	3.7	2.9	Yes		Demises
PhoneSat	7	PCB		6	ABSPlus	Box	N/A	8.0	0.2	8.0	Yes		Demises
PhoneSat	8	Nexus S		1	Conductive CV Silicone Elastomer Adhesive	Box	102.6	10.0	10.0	10.0	Yes		Demises
PhoneSat	9	Batteries		4	N/D	Cylinder	45.6	19.1		61.9	Yes		Demises
PhoneSat	10	Microhard MHX2420		1	N/D	Box	55.0	5.3	1.8	8.9	Yes		Demises
PhoneSat	11	StenSat		1	High Density Polyethylene and Nichrome wire	Box	59.3	9.1	1.0	9.6	Yes		Demises
PhoneSat	12	Battery Holder		1	PCB	Box	29.3	8.1	2.1	8.7	Yes		Demises
PhoneSat	13	Fasteners		4	Aluminum 6061	Other-Describe in Other Shape Section	N/A	N/A	N/A	N/A	Yes		Demises
PhoneSat	14	Cabling		Various	HAR-coated Silicon Window, Karonite/Epoxy-coated lens flange	Other-Describe in Other Shape Section	N/A	N/A	N/A	N/A	Yes		Demises
PhoneSat	15	Loctite 222 Threadlocker		1	N/D	Other-Describe in Other Shape Section	N/A	N/A	N/A	N/A	Yes		Demises
PhoneSat	16	B2a		1	Steel	Box	55.0	91.0	95.0	1.0	No	1500	Compliant (8J) See **Error! Reference source not found.**
PhoneSat	17	B2b		1	Steel	Box	55.0	91.0	95.0	1.0	No	1500	Compliant (8J) See **Error! Reference source not found.**
PhoneSat	18	Heat Sink		1	Aluminium	Box	13.0	93.0	80.0	1.0	Yes		Demises