June 4, 2013

Orbital Debris Assessment for KickSat 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 KickSat CubeSat on the ELaNa-5 auxiliary mission launching in conjunction with the SpX-3 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 launch vehicle compliance assessment and are not presented here.

The following table summarizes the compliance status of the KickSat 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:

KickSat: Mason Peck, Principle Investigator;
Zachary Manchester, 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

KickSat is a technology demonstration mission for the Sprite ChipSat developed at Cornell University. The Sprite is a tiny spacecraft with power, sensor, and communication subsystems integrated onto a single printed circuit board measuring 3.5 by 3.5 centimeters with a mass of 5 grams. KickSat is a 3U CubeSat with a 1U avionics bus (a derivative of the PhoneSat bus developed at NASA Ames) mated to a 2U Sprite deployer. The primary mission objective is to demonstrate the Sprite's CDMA communication architecture, which allows hundreds of Sprites to simultaneously communicate with a single ground station.

Table 3: KickSat Properties

CubeSat Quantity	CubeSat size	CubeSat Names	CubeSat Masses (kg)
1	3U (10 cm X 10 cm X 30 cm)	KickSat	2.6

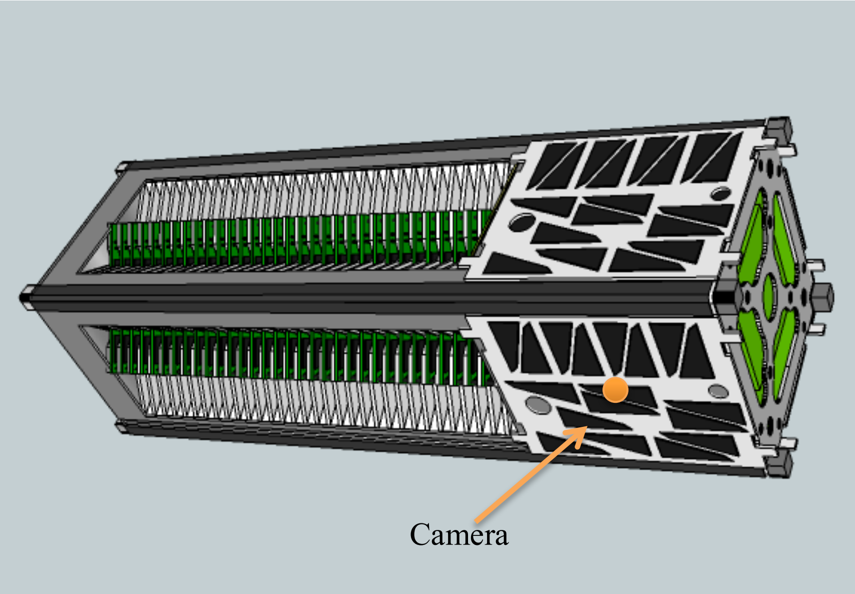


Figure 1: KickSat CAD Model

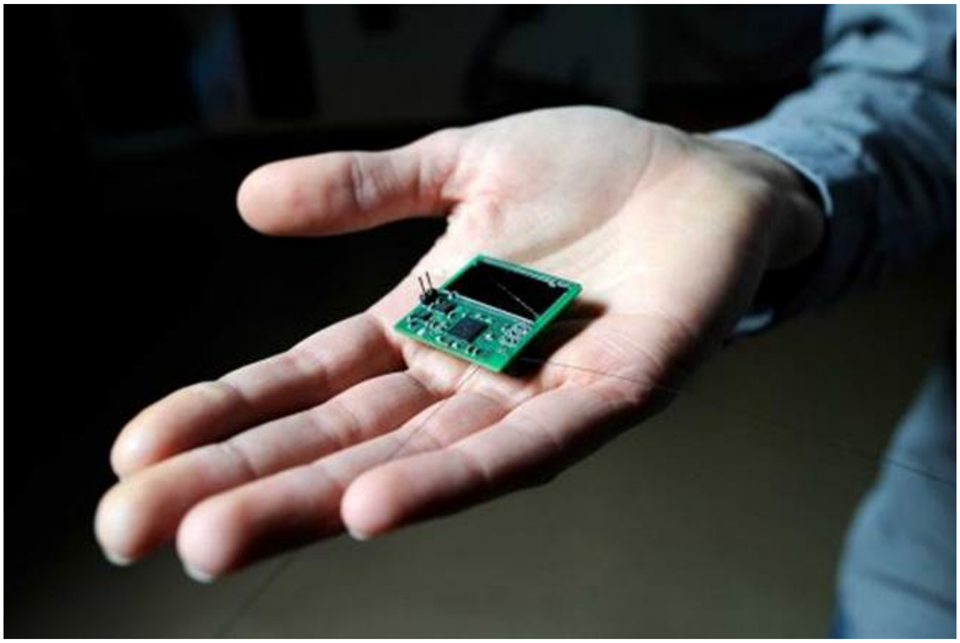


Figure 2: KickSat Individual Sprite

Upon deployment from the P-POD, KickSat will power up and start a countdown timer. At 30 minutes, the UHF beacon's antenna will be deployed, then at 45 minutes the beacon itself will be activated. During the first few passes, ground station operators will establish communication and perform checkouts of the spacecraft. Over the next three to four days, the attitude control system in the bus will be used to point KickSat's minor axis of inertia (long axis) at the sun, and then spin the spacecraft up to 10-15 RPM about this axis, thereby ensuring attitude stability during the deployment sequence.

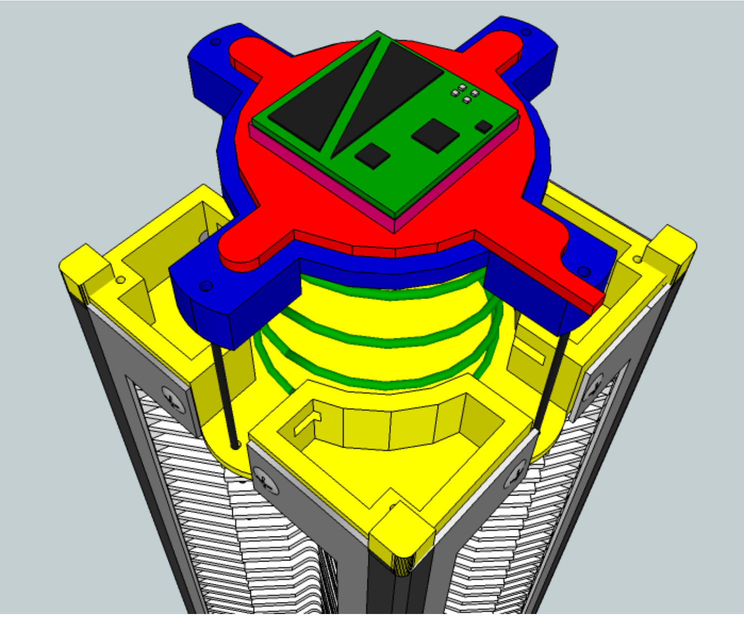
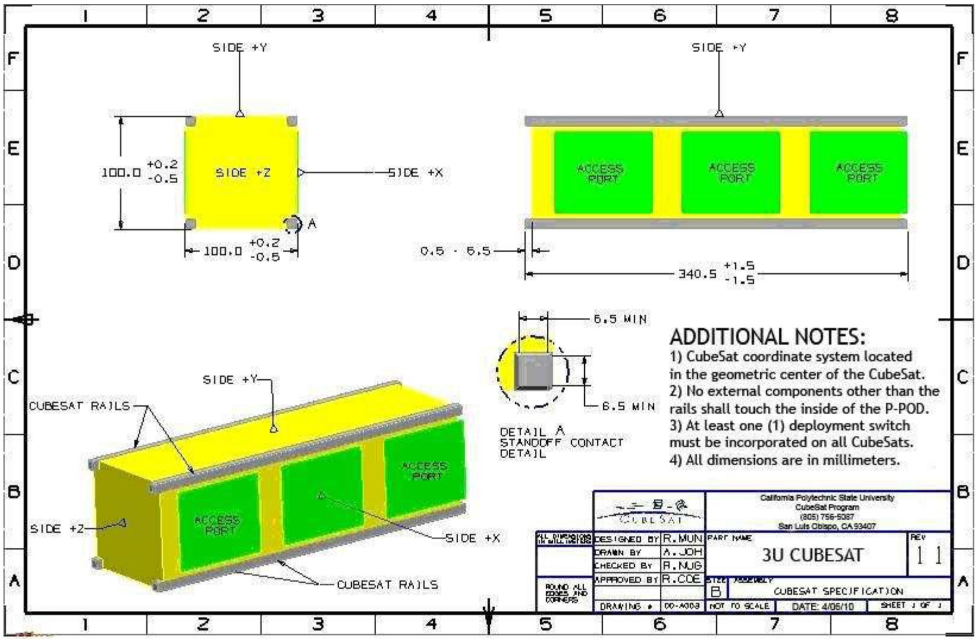


Figure 3: KickSat Deployment

Once the stable sun pointing attitude condition has been established, all systems have been checked out, and KickSat is in view of a ground station, a deployment signal from the ground will trigger a nichrome burn wire mechanism. A spring will then push the plunger, stacked with 128 Sprites in 4 stacks of 32, down the length of the deployer housing, releasing the Sprites as free-flying spacecraft. The delta-V imparted to the Sprites during deployment is expected to be 5-10 cm/sec. The on-board camera will attempt to image the deployment sequence.

KickSat uses a standard 3U Pumpkin structure made of 5052-H32 aluminum. The majority of its internal components are made of 6061 aluminum, ABS plastic, and FR4 printed circuit boards. There are few steel components (fasteners, deployment spring). 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. The lithium batteries, LG ICR18650 C1, carry the UL-listing number MH19896.



ADDITIONAL NOTES:
1) CubeSat coordinate system located in the geometric center of the CubeSat.
2) No external components other than the rails shall touch the inside of the P-POD.
3) At least one (1) deployment switch must be incorporated on all CubeSats.
4) All dimensions are in millimeters.

Figure 4: 3U CubeSat Specification

Section 3: Assessment of Spacecraft Debris Released during Normal Operations

Section 3 provides rationale/necessity for release of each object, time of release of each object relative to launch vehicle separation, release velocity of each object with respect to CubeSat, 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.

KickSat will be releasing a maximum of 128 Sprites as part of its primary mission to provide a technology demonstration for the use of CDMA communications across multiple vehicles to one ground station.

Upon deployment from the P-POD, KickSat will power up and start a countdown timer. At 30 minutes, the UHF beacon's antenna will be deployed, then at 45 minutes the beacon itself will be activated. During the first few passes, ground station operators will establish communication and perform checkouts of the spacecraft. Over the next three to four days, the attitude control system in the bus will be used to point KickSat's minor axis of inertia (long axis) at the sun, and then spin the spacecraft up to 10-15 RPM about this axis, thereby ensuring attitude stability during the deployment sequence.

The Sprite deployer contains 128 Sprites stacked 2-by-2 in four columns. Each Sprite is housed in an individual slot and constrained by a carbon fiber rod that runs the length of each column and passes through a hole in the corner of the Sprites (figure 2). The nitinol wire antennas on the Sprites are coiled in such a way that they act as springs, pushing the Sprites out of their slots. When the carbon fiber rod is removed, the Sprites' antennas will push them from the deployer housing with an estimated ΔV of 5-10 cm/sec.

In the event the Sprites are ejected along the deployer's velocity or anti-velocity vector, the orbital variation in the Sprites will be 325km +/- 0.35 km. This variation is based on their largest separation ΔV of 10 cm/sec.

The orbital lifetime was calculated to be 2-4 days depending on deployment date (ref. (i)). The large area to mass ratio, 20–100 times larger than most debris object, will render the Sprites highly susceptible to atmospheric drag and solar perturbations. The publically available version of DAS is not able to calculate orbital lifetimes this small. To satisfy the requirement 4.3-1 the NASA Orbital Debris Planning Office provided orbital lifetimes using the DAS Science and Engineering tool, a version of DAS that outputs the propagation steps into a text data table.

The short orbital lifetime of the Sprites satisfies the Requirements 4.3-1 and 4.3-2, whose purpose is to limit the debris in LEO.

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 KickSat 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: ELaNa-5 CubeSat Cells

CubeSat	Technology	Manufactor	Model	UL Listing Number
KickSat	Lithium Ion	LG	LG ICR18650 C1	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).

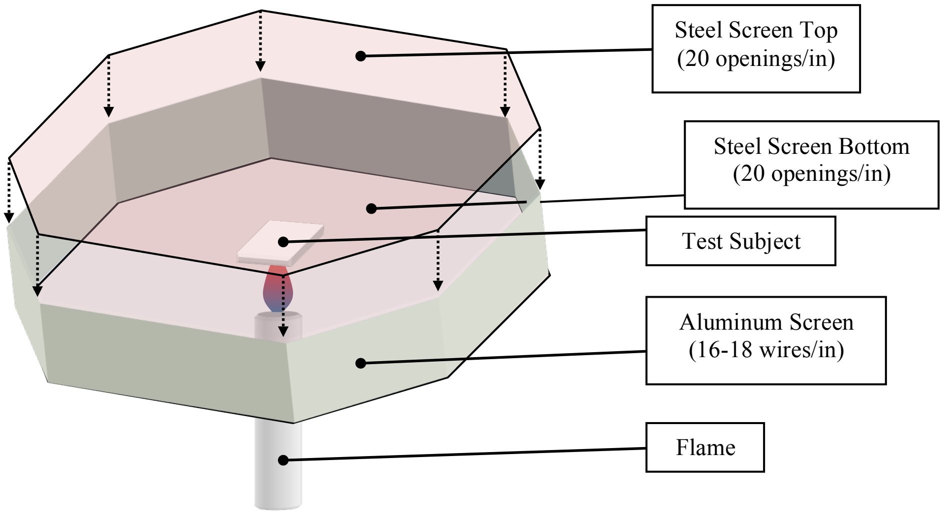


Figure 5: Underwriters Laboratory Explosion Test Apparatus

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.

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.

KickSat 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

The KickSat'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 0.027 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. KickSat in the deployed configuration has a probability of collision of $10^{-9.1}$, and a $10^{-9.1}$ probability of collision in the stowed configuration. Table 5 below provides complete results.

Table 5: CubeSat Orbital Lifetime & Collision Probability

CubeSat	KickSat
Mass (kg)	2.6

Stowed	Mean C/S Area (m^2)	0.0270
	Area-to Mass (m^2/kg)	0.0077
	Orbital Lifetime (yrs)	0.2
	Probability of collision (10^X)	-9.1

Deployed	Mean C/S Area (m^2)	0.0582
	Area-to Mass (m^2/kg)	0.0166
	Orbital Lifetime (yrs)	0.1
	Probability of collision (10^X)	-9.1

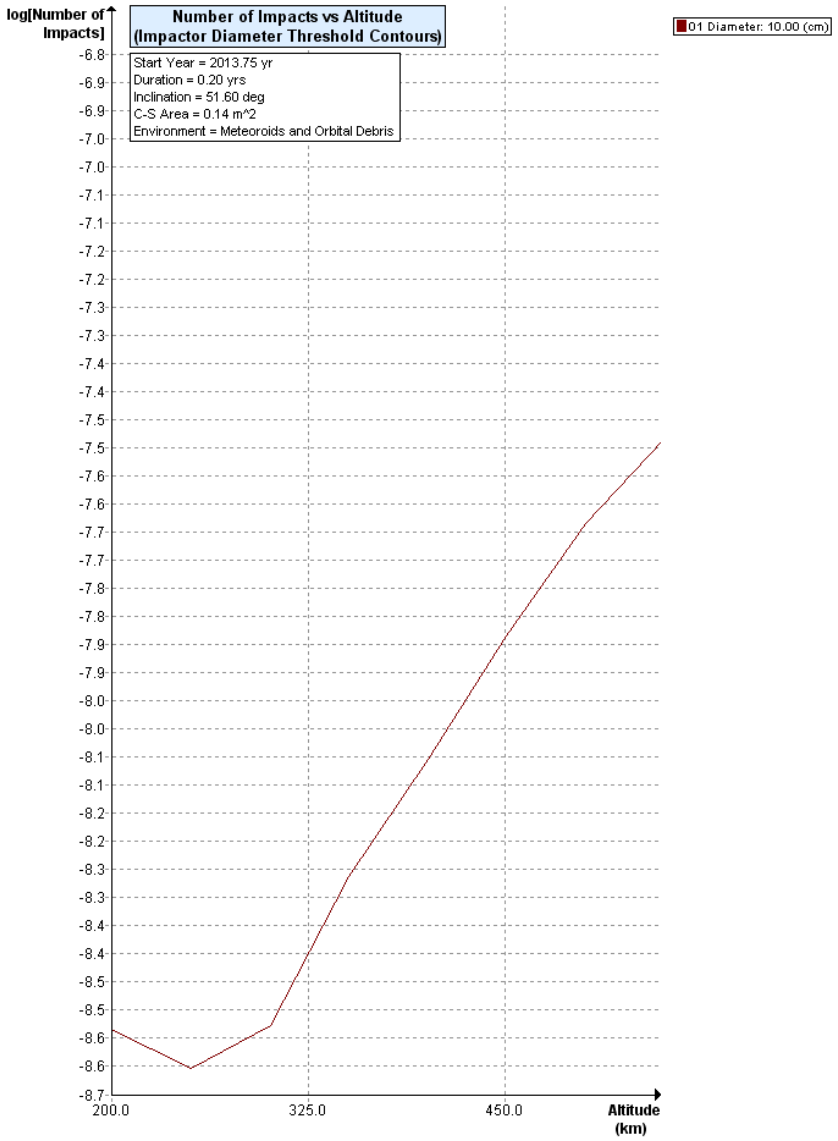


Figure 6: Highest Risk of Orbit Collision vs. Altitude

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 KickSat spacecraft collision with debris and meteoroids greater than 10 cm in diameter and capable of preventing post-mission disposal is less than $10^{-9.1}$, for any configuration. This satisfies the 0.001 (10^{-6}) maximum probability requirement 4.5-1.

Since KickSat and the Sprites have 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 KickSat mission to be compliant. Requirement 4.5-2 is not applicable to this mission.

Section 6: Assessment of Spacecraft Postmission Disposal Plans and Procedures

KickSat and the Sprites 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

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

<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 KickSat and the Sprites. This meets requirement 4.6-1. For the KickSat orbital lifetime, reference **Table 5**.

Section 7: Assessment of Spacecraft Reentry Hazards

A detailed assessment of the components to be flown on KickSat 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 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 KickSat mission complies with Requirement 4.7-1, to have less than 1:10,000 risk of human casualty.

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: KickSat Survivability DAS Analysis, and Appendix A, the KickSat 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: KickSat Survivability DAS Analysis

CubeSat	ELaNa-5 Stainless Steel Components	Mass (g)	Length / Diameter (cm)	Width (cm)	Height (cm)		Demise Alt (km)	KE (J)
KickSat	Sprite Deployer Spring	22.9	6.30	6.30	19.90		0	0
KickSat	Reaction Control System	87.8	2.54	2.54	7.62		70.6	0
KickSat	Fasteners	3.0	0.00	0.00	0.00		77.9	0

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

Section 8: Assessment for Tether Missions

ELaNa-5 CubeSats will not be deploying any tethers.

ELaNa-5 CubeSats satisfy 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 Index:

Appendix A. ELaNa-5 Component List by CubeSat: KickSat

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
KickSat	1	CubeSat Name	KickSat								Yes		Demises
KickSat	2	CubeSat Structure	External - Major	1	Aluminum 5052-H32	Box	366	100	100	340.5	Yes		Demises
KickSat	3	Sprite Deployer Housing	Internal - Major	1	ABS Plastic	Box	206.5	96	96	201	Yes		Demises
KickSat	4	Sprite Deployer Pusher	Internal - Major	1	ABS Plastic	Box	107.6	81	81	175	Yes		Demises
KickSat	5	Sprite Deployer Spring	Internal - Major	1	Steel	Cylinder	22.9	63	63	199		1500	Negligible Risk (<1J) See Table 6
KickSat	6	Sprite ChipSat	Internal - Major	128	FR4 PCB	Flat Plate	5.1	35	35	1.75	Yes		Demises
KickSat	7	Antenna	External - Major	1	ABS Plastic and Aluminum 6061	Flat Plate	2.1	178	12.7	0.15	Yes		Demises
KickSat	8	Solar Cells	External - Major	100	Gallium Arsenide	Flat Plate	0.234	0.155	0.318	-	Yes		Demises
KickSat	9	Magnetorquer / Solar Panel Boards	External - Major	6	FR4 PCB	Flat Plate	33.9	104.8	82.6	2.5	Yes		Demises
KickSat	10	Reaction Control System	Internal - Major	1	ABS Plastic and Mylar Coated Steel	Box	87.8	25.4	25.4	76.2		1500	Demises See Table 6
KickSat	11	Antenna Mount	External - Minor	1	Aluminum 6061	Box	10.6	28.6	117.5	36.5	Yes		Demises
KickSat	12	Batteries	Internal - Major	4	Lithium Ion	Cylinder	45.6	19.1	19.1	61.9	Yes		Demises
KickSat	13	Microhard MHJX2420 Radio	Internal - Major	1	FR4 PCB	Flat Plate	55	89	53.4	17.8	Yes		Demises
KickSat	14	Battery Mount	Internal - Major	1	ABS Plastic	Box	29.3	86.8	80.5	21.2	Yes		Demises
KickSat	15	Nexus S (C&DH) Board with Camera	Internal - Minor	1	FR4 PCB	Flat Plate	22	80	80	2.5	Yes		Demises
KickSat	16	Fasteners	Internal - Minor	14	Stainless Steel	Cylinder	3					1500	Demises See Table 6
KickSat	17	Cabling	Internal - Minor		Copper Alloy						Yes		Demises
KickSat	18	Loctite 222	Internal - Minor	1	Acrylic						Yes		Demises