March 20, 2013

Orbital Debris Assessment for IPEX on the NROL-39 / ELaNa-2 Mission per NASA-STD 8719.14A

Sensitive But Unclassified (SBU)

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. *GEMSat to ATLAS V / AFT BULKHEAD CARRIER INTERFACE CONTROL DOCUMENT*, Reference Orbit Requirements Baseline Draft, October 2012.
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. Myers, Gary. NROL-39_GEMSat_Gate#1_Mission_Design_final.ppt, 8.4 (U) Mission Design, Dec 13, 2012
I. *UL Standard for Safety for Household and Commercial Batteries, UL 2054*. UL Standard. 2nd ed. Northbrook, IL, Underwriters Laboratories, 2005

The intent of this report is to satisfy the orbital debris requirements listed in ref. (a) for the IPEX auxiliary mission launching in conjunction with the NROL-39 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 Department of Defense's Operationally Responsive Space Office and are not presented here.

The following table summarizes the compliance status of the IPEX auxiliary payload mission flown on NROL-39. IPEX as part of the ELaNa-2 mission is 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	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 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 IPEX mission

Section 1: Program Management and Mission Overview

The ELaNa-2 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:

IPEX: Dr. Steve Chien, Principle Investigator <steve.a.chien@jpl.nasa.gov>; Charles Norton, Project Manager <charles.norton@jpl.nasa.gov>

Program Milestone Schedule	
Task	**Date**
CubeSat Selection	5/16/12
CubeSat Build, Test, and Integration	1/1/12 through 3/31/13
MRR	4/27/13
CubeSat Delivery to Cal Poly	5/21/13
CubeSat Integration into P-PODs	5/21/13 through 5/31/13
Launch	12/1/13

Figure 1: Program Milestone Schedule

The ELaNa-2 mission will deploy 5 pico-satellites (or CubeSats) as a secondary payload on the NROL-39 mission. The CubeSat slotted position is identified in Table 2: ELaNa-2 CubeSats. The ELaNa-2 manifest includes: CUNYSAT-1, Firebird (2 cubes), IPEX, MCubed-2.

Each CubeSat ranges in sizes from a 10 cm cube to 10 cm x 10cm x 15 cm, with masses from about 1 kg to 4 kg total. The CubeSats have been designed and built by universities and government agencies and each have their own mission goals.

The ELaNa-2 mission will be launched as an auxiliary payload on the NROL-39 mission on an Atlas V 501 launch vehicle from Vandenberg Air Force Base. The current launch date is in 2013. The four CubeSats will be ejected from P-POD carriers attached to the launch vehicle, placing the CubeSats in an orbit approximately 464 X 898 km at inclination of 120 deg (ref. (h)).

Section 2: Spacecraft Description

There are four CubeSats flying on the ELaNa-2 Mission. They will be deployed out of two P-PODs, as shown in Table 2: ELaNa-2 CubeSats below.

Table 2: ELaNa-2 CubeSats

PPOD Slot	CubeSat Quantity	CubeSat size	CubeSat Names	CubeSat Masses (kg)
PPOD 1	3	1U (10 cm X 10 cm X 10 cm) 1U (10 cm X 10 cm X 10 cm) 1U (10 cm X 10 cm X 10 cm)	CUNYSAT-1 IPEX MCubed-2	1.21 1.28 1.1
PPOD 2	2	1.5U (10 cm X 10 cm X 15 cm) 1.5U (10 cm X 10 cm X 15 cm)	FIREBIRD-1 FIREBIRD-2	1.9 1.9

The following subsections contain description of IPEX.

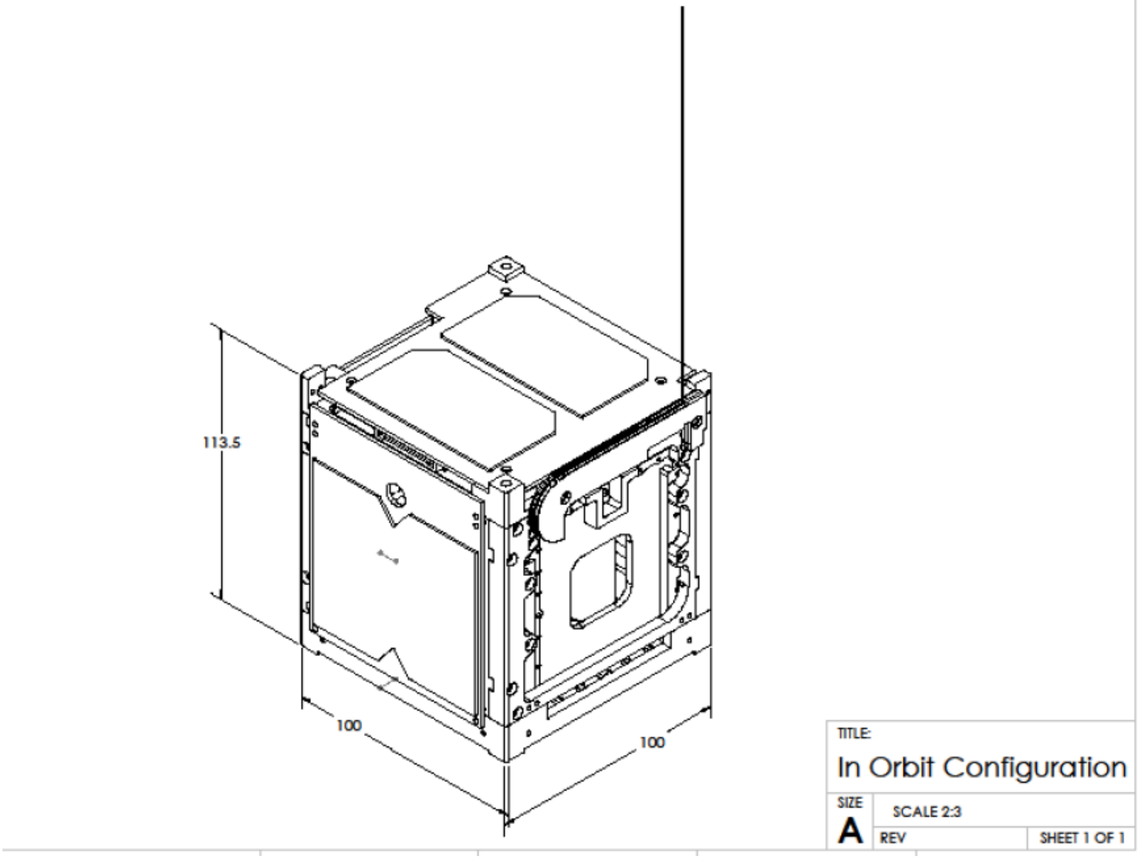

Figure 2: IPEX Dimensions

IPEX will validate direct broadcast, autonomous science, and product delivery technologies supporting TRL advancement of the Intelligent Payload Module (IPM) targeted for the proposed Hyperspectral Infrared Imager (HyspIRI) Earth science decadal survey mission. Specifically, IPEX will validate a method for 20x reduction in Gbps instrument raw data rate as well as validate Web-based autonomous payload operations with event/overflight-based product generation.

Following deployment from the PPOD, the IPEX CubeSat will release one the Ni-Ti antenna. The antenna will be released using nichrome burn wire that is wrapped around the fishing line.

The primary CubeSat structure is made of Aluminum 6061. It contains all standard commercial off the shelf (COTS) materials, electrical components, PCBs and solar cells.

The electrical power storage system consiste of 3 lithium ion Rose Electronics LI-1S1P-2200 Batteries. The battery board will keep track of the amount of current flowing into the batteries from the solar cells and the amount of current flowing out of the batteries into the satellites electronics. See Table 3 for UL Listing information.

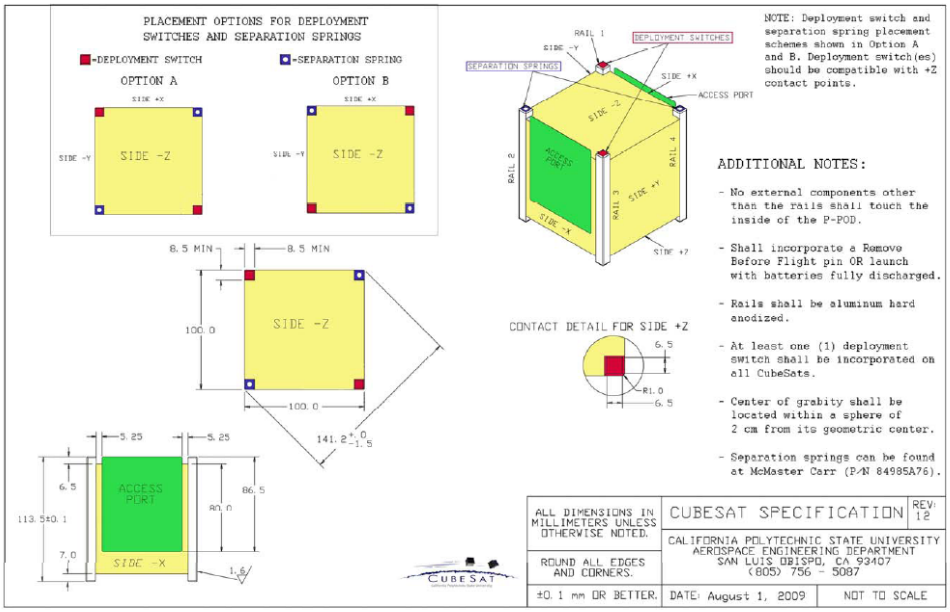

Figure 3: 1U CubeSat Specification

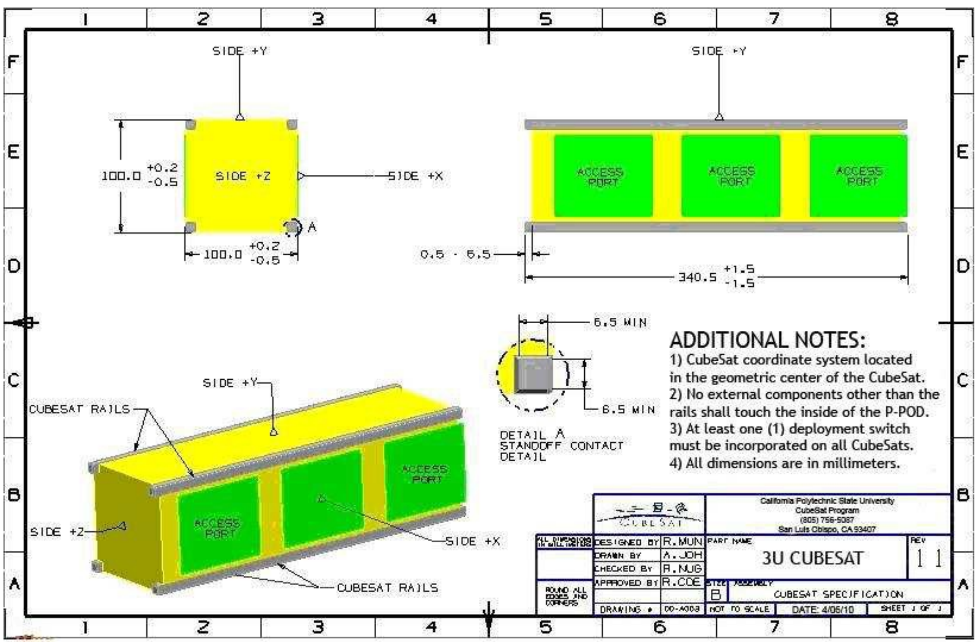

Figure 4: 3U CubeSat Specification

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 IPEX 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 13.2 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 IPEX 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 the IPEX CubeSat.

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 CubeSat, there was no need to add this capability to the electrical power generation and storage systems.

Assessment of spacecraft compliance with Requirements 4.4-1 through 4.4-4 shows that the IPEX CubeSat is compliant. Requirements 4.4-3 and 4.4-4 are not applicable.

The following addresses requirement 4.4-2. IPEX has not been designed to disconnect onboard storage energy devices (lithium ion and lithium polymer batteries). However, the CubeSat 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".

The cells utilize lithium ion technology and are compliant with Underwriters Laboratory (UL) Standard 1642.

Table 3: ELaNa-2 CubeSat Cells

CubeSat	Technology	Manufactor	Model	UL Listing Number
IPEX	Lithium Ion	Panasonic	CGR18650CG	MH12210

The batteries are 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).

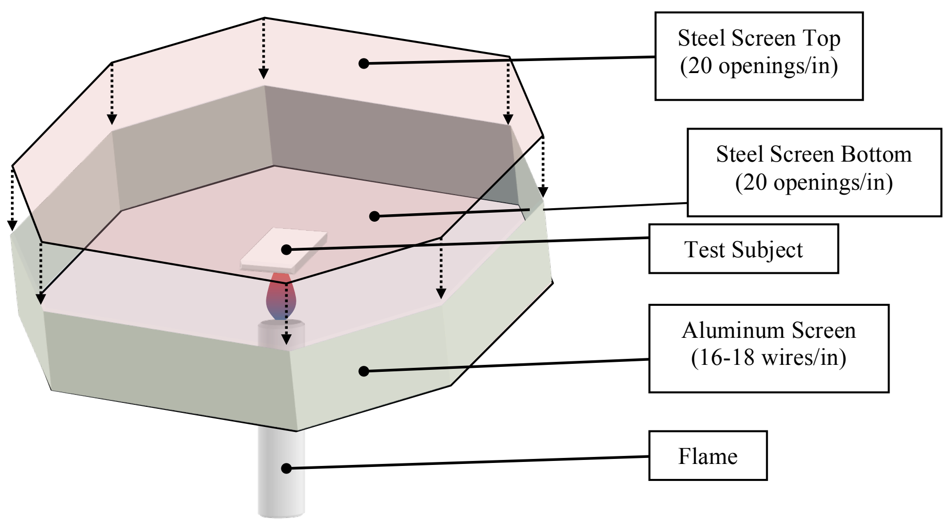

Figure 5: Underwriters Laboratory Explosion Test Apparatus

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 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 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.

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

Equation 1: Mean Cross Sectional Area for Convex Objects

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

Equation 2: Mean Cross Sectional Area for Complex Objects

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

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

The IPEX orbit at deployment is 898 km apogee altitude by 464 km perigee altitude, with an inclination of 120 degrees. With an area to mass ratio of 0.0121 m^2/kg, DAS yields 12.5 years for orbit lifetime for its stowed state, which in turn is used to obtain the collision probability. Table 4 below provides complete results.

Table 4: CubeSat Orbital Lifetime & Collision Probability

	CubeSat	IPEX
	Mass (kg)	1.28
Stowed	Mean C/S Area (m^2)	0.0155
	Area-to Mass (m^2/kg)	0.0121
	Orbital Lifetime (yrs)	12.5
	Probability of collision (10^X)	-6.7000
Deployed	Mean C/S Area (m^2)	0.0155
	Area-to Mass (m^2/kg)	0.0121
	Orbital Lifetime (yrs)	12.5
	Probability of collision (10^X)	-6.7

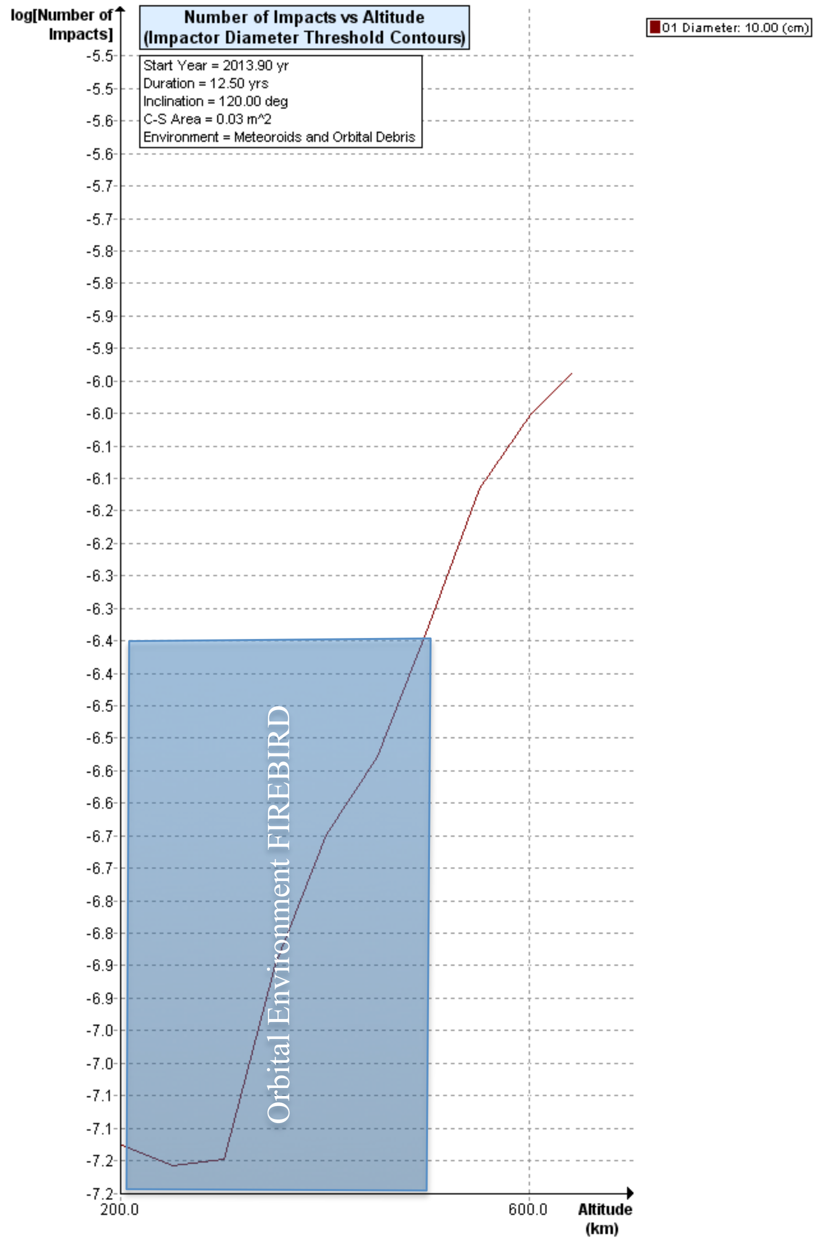

Figure 6: Highest Risk of Orbit Collision vs. Altitude (FIREBIRD Deployed)

The FIREBIRD deployed state is worst case and bounds the IPEX deployed state.

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 any ELaNa-2 spacecraft collision with debris and meteoroids greater than 10 cm in diameter and capable of preventing post-mission disposal is less than $10^{-6.4}$, for any configuration. This satisfies the 0.001 maximum probability requirement 4.5-1.

Since the CubeSats 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 IPEX to be compliant. Requirement 4.5-2 is not applicable to this mission.

Section 6: Assessment of Spacecraft Postmission Disposal Plans and Procedures

IPEX 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.

The worst case (smallest Area-to-Mass) post-mission disposal is IPEX in stowed configuration.The area-to-mass is calculated as follows:

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

Equation 3: Area to Mass

$$\frac{.0155\ m^2}{1.28\ kg} = 0.0121\frac{m^2}{kg}$$

The assessment of the spacecraft illustrates it is compliant with Requirements 4.6-1 through 4.6-5.

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

DAS inputs are: 464 km maximum perigee X 898 km maximum apogee altitudes with an inclination of 120 degrees at deployment in the year 2013. An area to mass ratio of 0.0121 m^2/kg for the IPEX CubeSat was input. DAS 2.0.2 yields a 12.5year orbit lifetime for IPEX in its stowed state.

This meets requirement 4.6-1.

Assessment results show compliance.

Section 7: Assessment of Spacecraft Reentry Hazards

A detailed assessment of the components to be flown on ELaNa-2 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 5.

CubeSat	ELaNa-4 Stainless Steel Components	Mass (g)	Length / Diameter (cm)	Width (cm)	Height (cm)		Demise Alt (km)	KE (J)
IPEX	Contains no high temperature materials. See Appendix A for full component list							

Table 5: ELaNa-2 Stainless Steel DAS Analysis

*HuMy80 is a magnet and not a steel alloy, however the melting temperature is 1450°C which is similar to that of stainless steel. Representing the component as steel provides a conservative analysis of the material's demise characteristics.

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 5, and the full component list in the Appendix, the IPEX CubeSat launching under the ELaNa-2 mission 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 all components.

Section 8: Assessment for Tether Missions

IPEX will not be deploying any tethers.

IPEX 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.

If you have any questions, please contact the undersigned at 321-867-2958.

/original signed by/

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cc: VA-H/Mr. Carney
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VA-G2/Mr. Atkinson
VA-G2/Mr. Fineberg
SA-D2/Mr. Frattin
SA-D2/Mr. Hale
SA-D2/Mr. Henry
Analex-3/Mr. Davis
Analex-22/Ms. Ramos

Appendix Index:

Appendix A. IPEX Component List

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
IPEX	1	IPEX 1U CubeSat	External - Major	1		Box	1280	100	100	113.5	Y		Demises
IPEX	2	CubeSat Structure	External - Major	1	Aluminum 6061	Box	172	100	100	113.5	Y		Demises
IPEX	3	Ballasts	Internal - Major	3	Aluminum 6061 / Delrin / Coated Brass Plates	Plates	282	83	83	63.5	Y		Demises
IPEX	4	Batteries	Internal - Major	2	Lithium Polymer	Box	42	35	52	10.5	Y		Demises
IPEX	5	Power Board	Internal - Major	1	Multilayer PCB	Board	48.5	1.5	83	83	Y		Demises
IPEX	6	Side Panels	External - Major	5	Multilayer PCB	Board	48	1.5	100	83	Y		Demises
IPEX	7	Gumstix	Internal-minor	1	Multilayer PCB	Board	4.5	1	58	17	Y		Demises
IPEX	8	CDH Board	Internal - Major	1	Multilayer PCB	Board	34.5	1.5	83	83	Y		Demises
IPEX	9	Payload Board	Internal - Major	1	Multilayer PCB	Board	33.5	1.5	100	83	Y		Demises
IPEX	10	Cameras	Internal - Minor	2	Multilayer PCB	Cylinderical	4.5	12	28	20	Y		Demises
IPEX	11	Antenna Route	External - Minor	1	Delrin	Box	10	82	110	6	Y		Demises
IPEX	12	Burnwire Board	Internal - Minor	1	Small PCB	Board	10	1.5	21	21	Y		Demises
IPEX	13	Antenna	External - Major	1	NiTi	Boom	0.67	0.3	160	4	N	1310	Negligible Risk, bounded by larger SS components. See Table 5.
IPEX	14	Fasteners	Internal - Minor	94	Steel	Cylinderical	54	Various	Various	Various	N	1500	Negligible Risk, bounded by larger SS components. See Table 5.
IPEX	15	Sep Switches	External - Minor	2	Plastic	Box	2	6	8	7	Y		Demises
IPEX	16	Cabling	Internal - Minor	Various	Coated Copper alloy	Cylinderical/Flat	20	1.3	Various	N/A	Y		Demises
IPEX	17	Staking Compound	Internal/External- Minor	N/A	3M Scotch Weld 2216	N/A	30	N/A	N/A	N/A	Y		Demises