April 11, 2014

Orbital Debris Assessment for FIREBIRD-2 a/b on the SMAP /ELaNa-10 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. 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 FIREBIRD-2 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 GRIFEX 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:

FireBird-2: Dave Klumpar, Principle Investigator; Keith Mashburn, 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

There are four CubeSats flying on the ELaNa-10 Mission. They will be deployed out of three PPODs, as shown in Table 2: ELaNa-10 CubeSats below.

Table 2: ELaNa-10 CubeSats

PPOD Slot	CubeSat Quantity	CubeSat size	CubeSat Names	CubeSat Masses (kg)
2.1	2	1.5U (10 cm X 10 cm X 15 cm)	FireBird-2a	1.7
2.2		1.5U (10 cm X 10 cm X 15 cm)	FireBird-2b	1.7

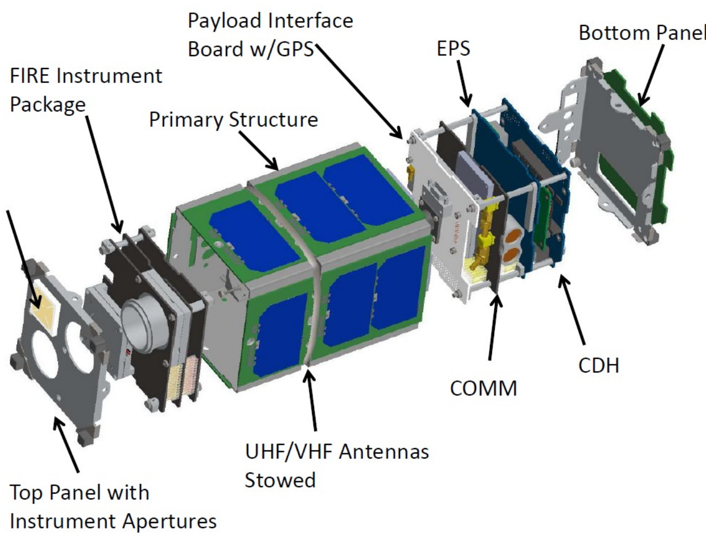

Figure 2: Exploded view of the FireBird-2 CubeSats

FireBird-2, which stands for **F**ocused **I**nvestigations of **R**elativistic **E**lectron **B**urst, **I**ntensity, **R**ange, and **D**ynamics, is funded by the National Science Foundation.

The mission is a targeted, goal-directed, space weather CubeSat mission to resolve the spatial scale size and energy dependence of electron microbursts in the Van Allen radiation belts. Relativistic electron microbursts appear as short durations of intense electron precipitation measured by particle detectors on low altitude spacecraft, seen when their orbits cross magnetic field lines which thread the outer radiation belt. Previous spacecraft missions (e.g., SAMPEX) have quantified important aspects of microburst properties (e.g., occurrence probabilities), however, some crucial properties (i.e., spatial scale) remain

elusive owing to the space-time ambiguity inherent to single spacecraft missions. While microbursts are thought to be a significant loss mechanism for relativistic electrons, they remain poorly understood, thus rendering space weather models of Earth's radiation belts incomplete. FireBird-2's unique two-point, focused observations at low altitudes, that fully exploit the capabilities of the CubeSat platform, will answer three fundamental scientific questions with space weather implications:

The CubeSats will deploy out of the P-POD and when the system turns on thereafter a 45 minute timer begins to tick. After 45 minutes, the flight computer will engage the antenna deployment sequence and the system will begin UHF beacon transmissions at a 15 second cadence. The payloads, which are solid state particle detectors, are powered on following the automated antenna deployment sequence and the mission will begin gathering science data. Periodic downlink of science telemetry will take place only when initiated by the ground station at MSU. After the initial contact is established with the CubeSats, the beacon cadence is increased to a 30 second cadence. This mission is set to last 3 months nominally with an extended period of 6 months pending vehicle performance and operations funding.

The CubeSat structural components are made of the following aluminum alloys: 5052-H32, 7075-T6, and 6061-T6. It contains all standard commercial off the shelf (COTS) materials, electrical components, PCBs and solar cells. The GPS patch antenna radio uses a ceramic patch antenna and the UHF/VHF antennas are made of spring steel.

There are no pressure vessels, hazardous or exotic materials.

FIREBIRD-2 (a/b) uses 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.

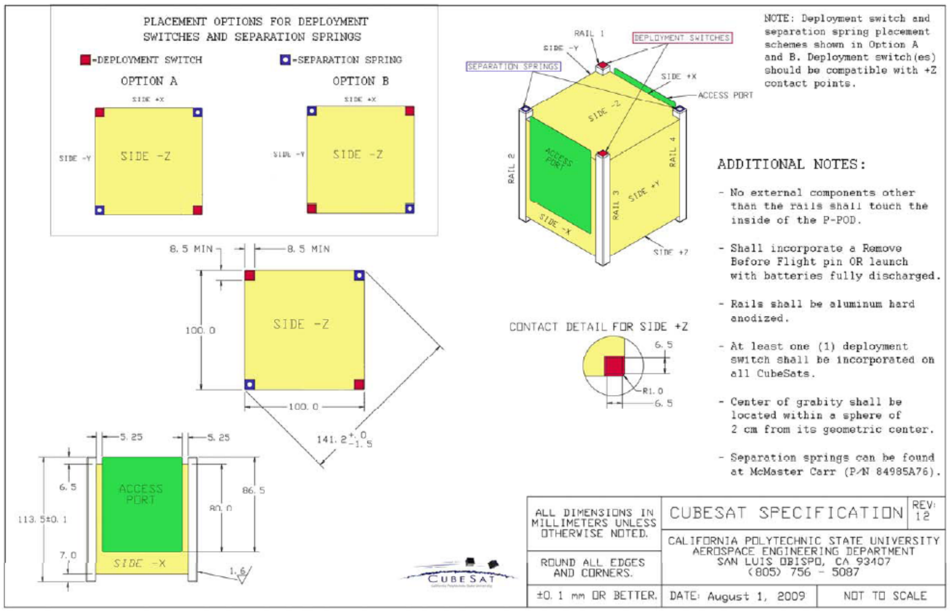

Figure 3: 1U CubeSat Specification

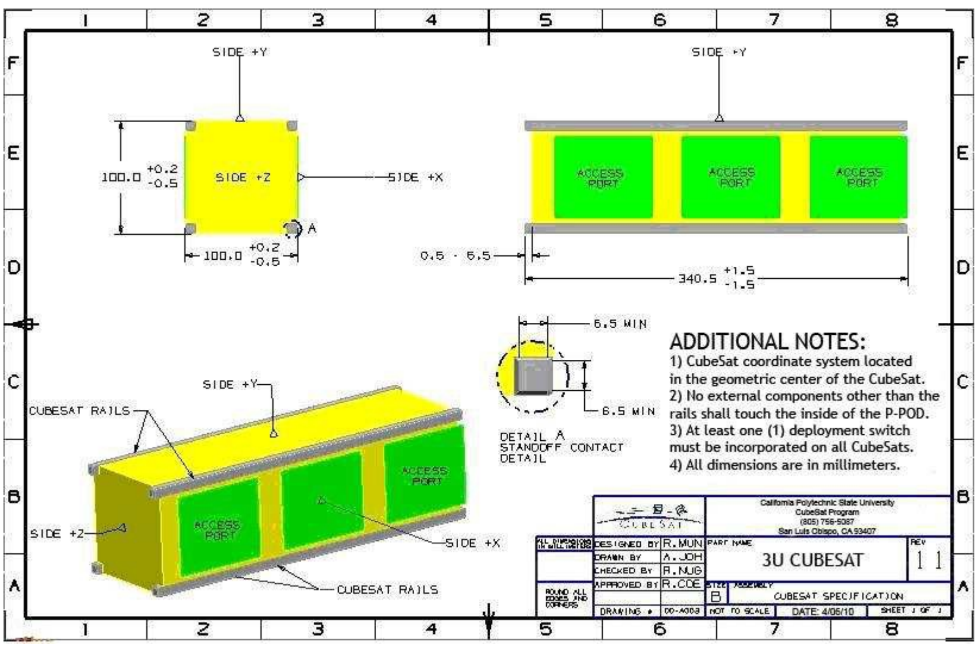

Figure 4: 3U CubeSat Specification

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 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)).

FIREBIRD-2'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 ELANA-10 CubeSats are 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.

The largest mean cross sectional area (CSA) among the four CubeSats is that of the ExoCube CubeSat with booms deployed (10 X 10 X 30 cm with two deployable, "T" shaped booms 1.5 X 30 cm):

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

Equation 1: Mean Cross Sectional Area for Cubic Objects

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

Equation 2: Mean Cross Sectional Area for Complex Objects

All CubeSats 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 all stowed CubeSats was calculated using Equation 1. This configuration renders the longest orbital life times for all CubeSats.

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 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. Even with the variation in CubeSat design and orbital lifetime ELaNa-10 CubeSats see an average of $10^{-6.0}$ probability of collision. ExoCube sees the highest probability of collision of $10^{-5.8}$. Table 4 below provides complete results.

Table 3: CubeSat Orbital Lifetime & Collision Probability

	CubeSat	FireBird-2 a/b
	Mass (kg)	1.7
Stowed	**Mean C/S Area (m^2)**	0.0185
Stowed	**Area-to Mass (m^2/kg)**	0.0109
Stowed	**Orbital Lifetime (yrs)**	7.8
Stowed	**Probability of collision (10^X)**	-6.2
Deployed	**Mean C/S Area (m^2)**	0.0255
Deployed	**Area-to Mass (m^2/kg)**	0.0150
Deployed	**Orbital Lifetime (yrs)**	7.1
Deployed	**Probability of collision (10^X)**	-6.1

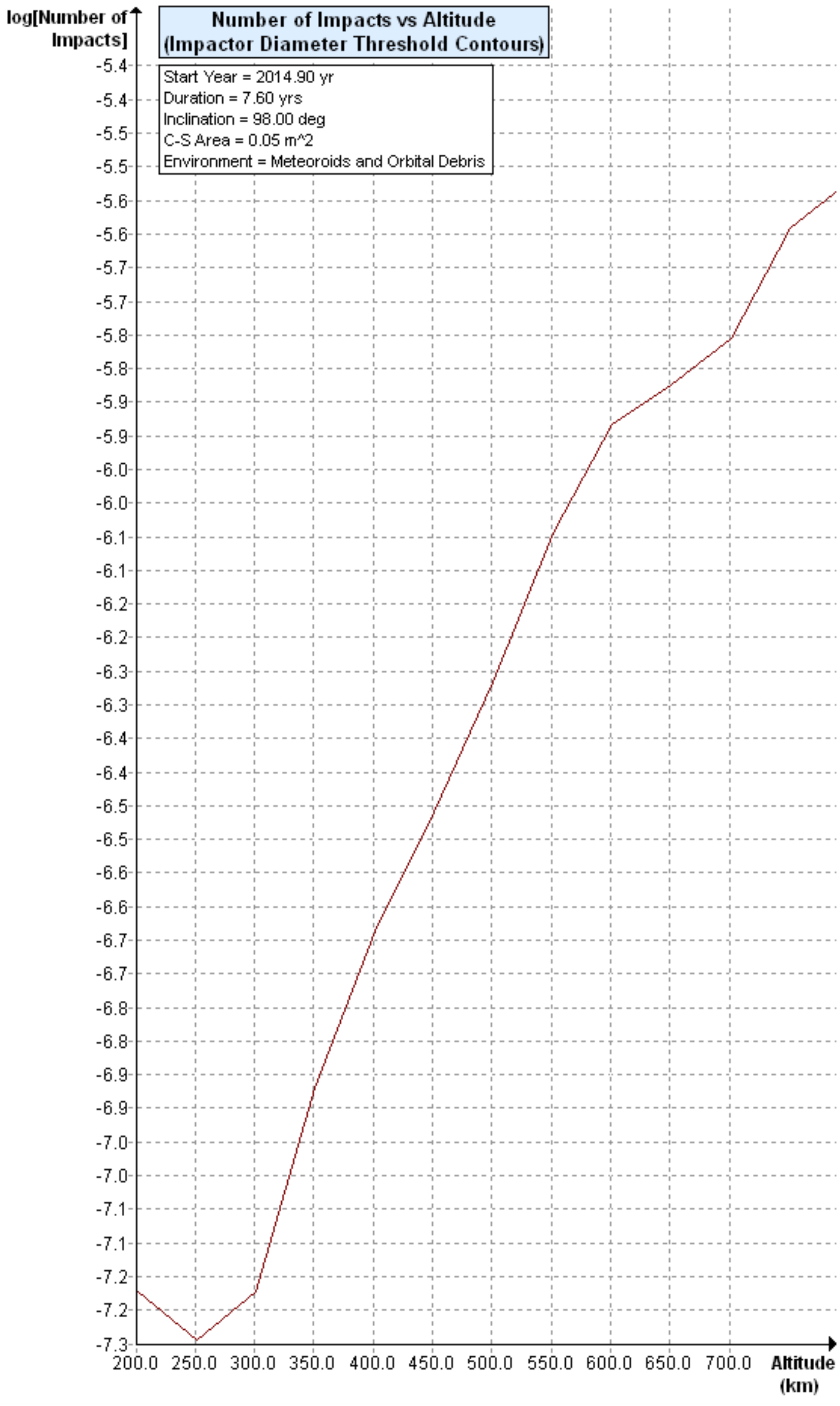

Figure 5: Highest Risk of Orbit Collision vs. Altitude

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 a FIREBIRD-2 collision with debris and meteoroids greater than 10 cm in diameter and capable of preventing post-mission disposal is less than $10^{-6.2}$, for any configuration. This satisfies the 0.001 maximum probability requirement 4.5-1.

Since FIREBIRD-2 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 FIREBIRD-2 to be compliant. Requirement 4.5-2 is not applicable to this mission.

Section 6: Assessment of Spacecraft Postmission Disposal Plans and Procedures

FIREBIRD-2 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 finds FIREBIRD-2 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

$$\frac{0.0185\ m^2}{1.7\ kg} = 0.0109\frac{m^2}{kg}$$

The assessment of FIREBIRD-2 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 0.0109 m^2/kg for the FIREBIRD-2 CubeSat was inputted. DAS 2.0.2 yields a 7.8 years orbit lifetime for FIREBIRD-2 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 FIREBIRD-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 4.

Table 4: FIREBIRD-2 Stainless Steel DAS Analysis

CubeSat	Stainless Steel Components	Mass (g)	Length / Diameter (cm)	Width (cm)	Height (cm)	Demise Alt (km)	KE (J)
FireBird-2	VHF Antenna	15	1	50	<0.1	0	1
FireBird-2	UHF Antenna	8	1	10	<0.1	0	0
FireBird-2	Sep Switches	1	0.2	0.5		77.9	0
FireBird-2	ADCS Magnets	5.09	0.952		0.952	74	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: FIREBIRD-2 Stainless Steel DAS Analysis, and the full component lists in the Appendix FIREBIRD-2 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 FIREBIRD-2 components.

Section 8: Assessment for Tether Missions

FIREBIRD-2 will not be deploying any tethers.

FIREBIRD-2 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. FIREBIRD-2 a/b 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
FireBird-2		2	CubeSat	Box	2000	100	100	150	yes		Demise
CubeSat Structure	External - Major	1	5052H32 aluminum	Box	308				yes		Demise
VHF Antenna	External - Major	1	Spring Steel 410	Rectangle	15	10	500	<1	no	1532	Negligible Risk: KE ~ 1 J See Table 4
UHF Antenna	External - Major	1	Spring Steel 410	Rectangle	8	10	100	<1	no	1532	Negligible Risk: KE ~ 0 J See Table 4
Solar Panels	External - Major	4	FR4 PCB Fiberglass	Rectangle	52.5	85	130	n/a	yes		Demise
Sep Switches	External - Minor	1	Steel and Delrin	Rectangle	1	2	5	n/a	no	1500	Demise See Table 4
GPS Antenna	External - Minor	1	FR4 PCB Fiberglass and Copper	Square	30	20	20	n/a	yes		Demise
Batteries	Internal - Major	2	Lithium Ion	Cylinder	48	18.29	N/A	65.05	yes		Demise
ADCS Magnets	Internal - Major	1	Nickel-plated Neodymium Grade N52	Cylinder	5.09	9.52	N/A	9.52	no	1300	Demise See Table 4
Payload Board	Internal - Major	3	FR4 PCB Fiberglass	Square	120	95	95	n/a	yes		Demise
Comm Board	Internal - Major	1	FR4 PCB Fiberglass	Square	78	95	95	n/a	yes		Demise
Battery Board	Internal - Major	1	FR4 PCB Fiberglass	Square	158	95	95	n/a	yes		Demise
C&DH Board	Internal - Major	1	FR4 PCB Fiberglass	Square	92	95	95	n/a	yes		Demise
Fasteners	Internal - Minor	57	Stainless Steel	Rectangle	1	n/a	n/a	n/a	no	1500	Demise
Cabling - Board Traces	Internal - Minor	1	Copper Alloy	N/A	n/a	n/a	n/a	n/a	yes		Demise
Cabling - Solar Array Harness	Internal - Minor	4	Teflon	Wire	5	3	40	n/a	yes		Demise