October 24, 2014

Orbital Debris Assessment for ARC1 on the NRO L-55 / GRACE / ELaNa-12 Mission per NASA-STD 8719.14A

Signature Page

____
Justin Treptow, Analyst, NASA KSC VA-H1

____
Scott Higginbotham, Mission Manager, NASA KSC VA-C

____
Jason Crusan, Program Executive, NASA HQ SOMD

____
Suzanne Aleman, NASA HQ OSMA MMOD Program Executive

Signatures Required for Final Version of ODAR

____
Terrence W. Wilcutt, NASA Chief, Safety and Mission Assurance

____
William Gerstenmaier, NASA AA,
Human Exploration and Operations Mission Directorate.

National Aeronautics and
Space Administration

John F. Kennedy Space Center, Florida
Kennedy Space Center, FL 32899

ELVL-2014-0043865

Reply to Attn of: VA-H1 October 24, 2014

TO: Scott Higginbotham, LSP Mission Manager, NASA/KSC/VA-C

FROM: Justin Treptow, NASA/KSC/VA-H1

SUBJECT: Orbital Debris Assessment Report (ODAR) for the ELaNa-12 Mission (DRAFT)

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. Email, "FW: [GRACE-ULTRASat] Latest orbit parameter estimates" Scott Higginbotham to Justin Treptow, October 1, 2014
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. 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 ARC1 launching in conjunction with the NRO L-55 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 Department of Defense's National Reconnaissance Office and are not presented here.

The following table summarizes the compliance status of the ARC1 CubeSat flown on the GRACE mission. The CubeSat 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	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 20.6 yrs for the CubeSat LMRST-Sat
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-12 mission

Section 1: Program Management and Mission Overview

The ELaNa-12 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:

ARC1 : Dr. Denise Thorsen, Principle Investigator; Jesse Frey, Project Manager

Program Milestone Schedule	
Task	**Date**
CubeSat Selection	8/27/13
CubeSat Build, Test, and Integration	4/19/15
MRR	2/18/15
CubeSat Delivery to CalPoly	3/16/15
CubeSat Integration into P-PODs	3/16/15 - 3/25/15
Launch	8/27/15

Figure 1: Program Milestone Schedule

The ELaNa-12 mission will be launched as a component of the GRACE auxiliary payload on the NRO L-55 mission on an Atlas V launch vehicle from VAFS, Ca. The ELaNa-12, will deploy 4 pico-satellites (or CubeSats) with a fifth as a backup. The CubeSat slotted position is identified in **Error! Reference source not found.** and in the Appendix. The ELaNa-12 manifest includes:ARC1, BisonSat, Fox-1, LMRST-Sat, and the backup CADRE. The current launch date is in 8/27/2015. The 4 CubeSats will be ejected from a PPOD carrier attached to the launch vehicle, placing the CubeSats in an orbit approximately 509 X 796 km at inclination of 66 deg (ref. (c)).

Each CubeSat ranges in sizes from a 10 cm cube to 10 cm x 10cm x 30 cm, with masses from about ~1 kg to ~4 kg total. The CubeSats have been designed by universities and government agencies and each have their own mission goals.

Section 2: Spacecraft Description

ARC1 – University of Alaska Fairbanks – 1U

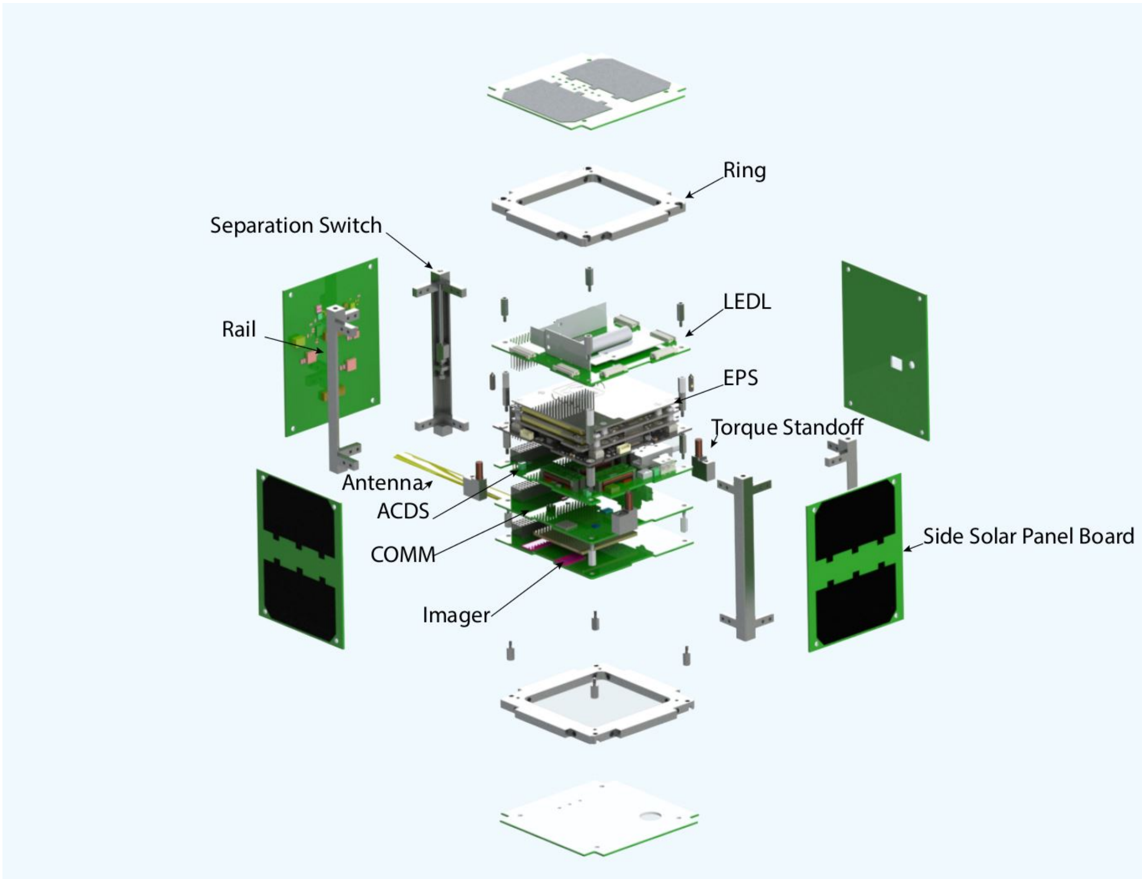

Figure 2: ARC1 Expanded View

The Alaska Research CubeSat 1 (ARC1) will be the first satellite designed, built, tested, and operated by students from the University of Alaska Fairbanks (UAF). This satellite is designed as both an educational tool and a platform to facilitate rapid development of scientific and technology demonstration missions at UAF. Successful implementation of this development platform will demonstrate the ability of UAF students to compete for future Low Earth Orbit (LEO) research opportunities. ARC1 will achieve one educational mission objective (EMO) and three science mission objectives (SMO) which serve to demonstrate what capabilities are available for future missions, and identify unforeseen system issues to be improved.

- EMO1: Provide an authentic, interdisciplinary, hands-on student experiences in science and engineering through the design, development, operation of a student small satellite mission.
- SMO1: Characterize thermal and vibration environment inside the launch vehicle from ignition to orbit insertion.
- SMO2: Validate a novel low power Attitude Control and Determination Systems (ACDS).
- SMO3: Validate a high bandwidth communication system by obtaining images of changing snow/ice coverage in arctic region.

Upon deployment from the P-POD, ARC1 will power up and start counting down timers. At 45 minutes, the antenna will be deployed and the beacon will start transmitting. Once contact has been established with ARC1 then the LEDL and ADCS data can be downloaded to complete the primary mission. Once the primary mission is complete the camera will be activated to take pictures of the arctic. This will continue until ARC1 is shut down after 1 year.

There are no pressure vessels, hazardous or exotic materials.

There are two power systems on ARC1, the Clyde EPS and the LEDL battery. The Clyde EPS uses standard Lithium Ion Polymer cells to store energy from the solar cells and power ARC1 after P-POD ejection. The Clyde EPS contains over-charge/current protection. The Clyde EPS cells carry the UL listing number MH13654. The LEDL battery uses Lithium Iorn Disulfide cells and powers the LEDL during launch so it can log launch data. The LEDL battery is not rechargeable and is not used after data logging is complete. The LEDL cells carry the UL listing number MH29980. Overcurrent protection is provided for the LEDL cells.

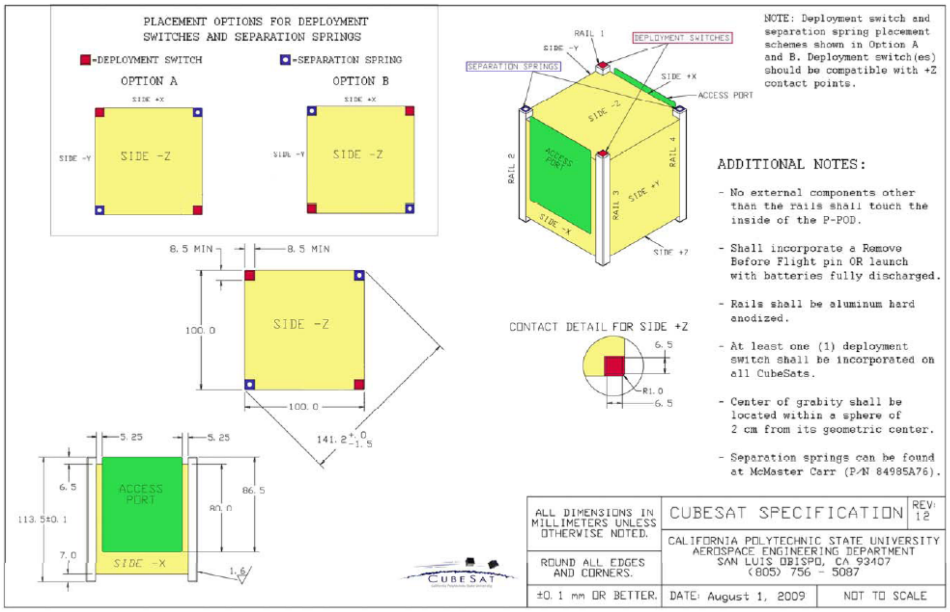

Figure 3: 1U CubeSat Specification

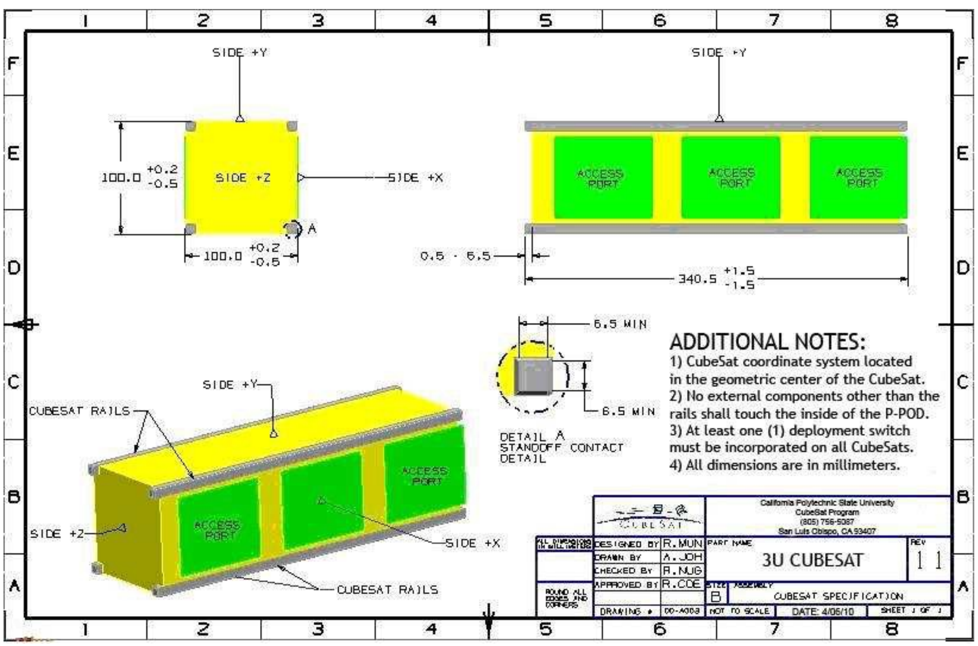

Figure 4: 3U CubeSat Specification

Section 3: Assessment of Spacecraft Debris Released during Normal Operations

No releases are planned on the ELaNa-12 CubeSat mission therefore this section is not applicable.

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.

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.

As no objects are being released rationale, timing, release velocity, orbit parameters, and orbital lifetime are unnecessary to report in this section.

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-12 mission. No passivation of components is planned at the End of Mission for the CubeSats on this mission.

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 (i)).

The CubeSats batteries still meet Req. 56450 (4.4-2) by virtue of the HQ OSMA policy 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. (i))

Assessment of spacecraft compliance with Requirements 4.4-1 through 4.4-4 shows that with a lifetime of 20.6 years maximum the ELANA-12 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 LMRST-Sat CubeSat with antennas deployed (10 X 10 X 30 cm with four deployable antennas 1.0 X 15.2 cm):

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

Equation 1: Mean Cross Sectional Area for Convex Objects

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

Equation 2: Mean Cross Sectional Area for Complex Objects

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 Fox-1 orbit at deployment is 509 km perigee altitude by 796 km apogee altitude, with an inclination of 66 degrees. With an area to mass (3.62 kg) ratio of 0.0097 m^2/kg, DAS yields 20.6 years for orbit lifetime for its stowed state, which in turn is used to obtain the collision probability. Regardless of variation in CubeSat design and orbital lifetime ELaNa-12 CubeSats see less than 0x10^-5 probability of collision. LMRST-Sat sees the similar probability of collision as the rest of the CubeSats on ELaNa-12. Table 4 below provides complete results. The backup, CADRE, has an orbit lifetime of 24.5 years in its stowed configuration. Because of its backup status it was not highlighted in this paragraph but is fully detailed in Appendix E.

Table 2: CubeSat Orbital Lifetime & Collision Probability

		ARC-1	BisonSat	Fox-1	LMRST-Sat
	Mass (kg)	**1.33**	1.09	1.33	3.62
Stowed	**Mean C/S Area (m^2)**	**0.0160**	0.0165	0.0150	0.035
	Area-to Mass (m^2/kg)	**0.0120**	0.0151	0.0113	0.0097
	Orbital Lifetime (yrs)	**18.4**	16.6	18.9	20.6
	Probability of collision	**0x10^-5**	0x10^-5	0x10^-5	0x10^-5
Deployed	**Mean C/S Area (m^2)**	**0.0170**	0.0192	0.0153	0.038
	Area-to Mass (m^2/kg)	**0.0128**	0.0176	0.0115	0.0105
	Orbital Lifetime (yrs)	**17.9**	12.5	18.9	1935
	Probability of collision	**0x10^-5**	0x10^-5	0x10^-5	0x10^-5

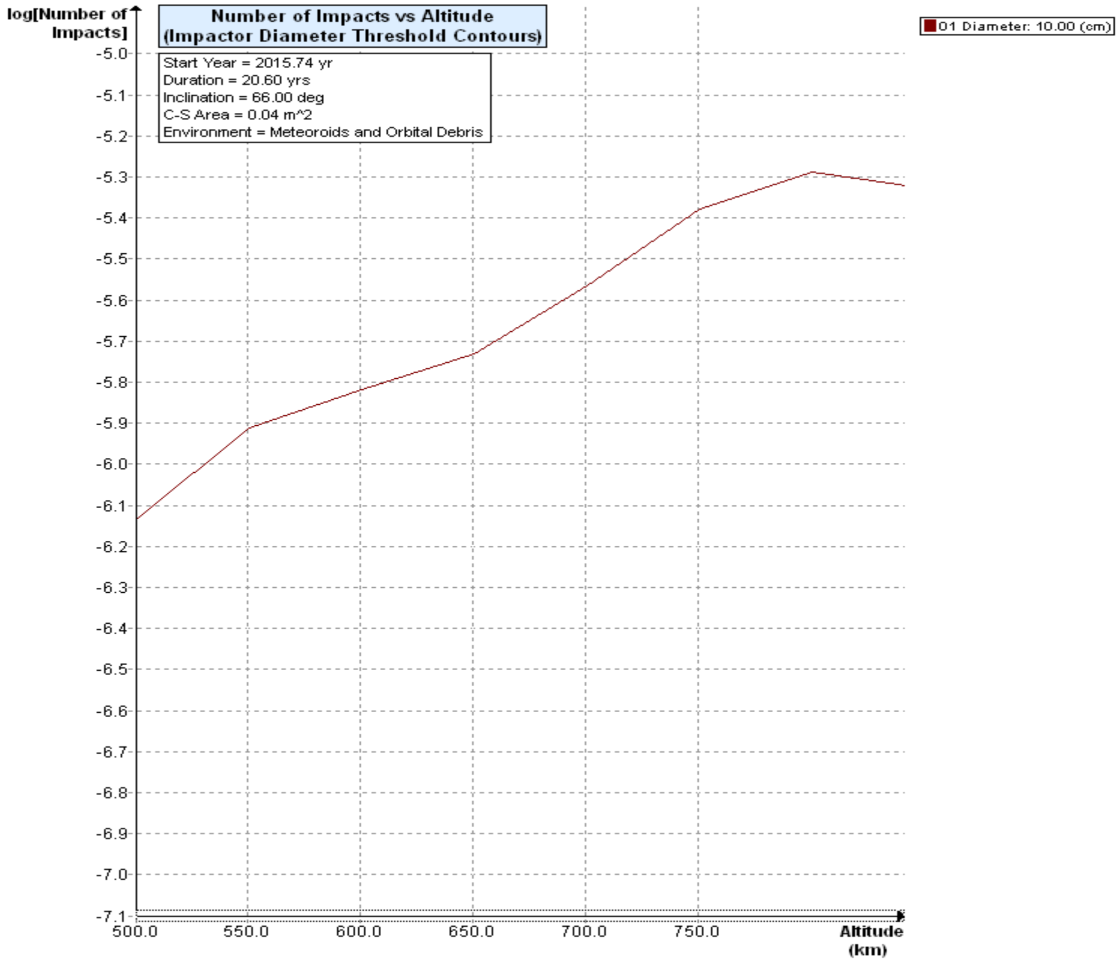

Figure 5: Highest Risk of Orbit Collision vs. Altitude (LMRST-Sat-Stowed)

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-12 spacecraft collision with debris and meteoroids greater than 10 cm in diameter and capable of preventing post-mission disposal has been calculated to be less than 0x10^-5 probability of collision, 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 ELaNa-12 to be compliant. Requirement 4.5-2 is not applicable to this mission.

Section 6: Assessment of Spacecraft Postmission Disposal Plans and Procedures

All ELaNa-12 spacecraft will naturally decay from orbit within 25 years after end of the mission, satisfying requirement 4.6-1a detailing the spacecraft disposal option.

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

Calculating the area-to-mass ratio for the worst-case (smallest Area-to-Mass) post-mission disposal among the CubeSats finds Fox-1 in its stowed configuration as the worst case. The area-to-mass is calculated for is as follows:

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

Equation 3: Area to Mass

$$\frac{0.015\ m^2}{1.33\ kg} = \ 0.0113\,\frac{m^2}{kg}$$

Fox-1 has the smallest Area-to-Mass ratio and as a result will have the longest orbital lifetime. The assessment of the spacecraft illustrates they are compliant with Requirements 4.6-1 through 4.6-5.

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

DAS inputs are: 509 km maximum perigee 796 km maximum apogee altitudes with an inclination of 66 degrees at deployment in the year 2015. The area to mass ratio of 0.00097 m^2/kg was imputed for the LMRST-Sat CubeSat. DAS 2.0.2 yields a 20.6 year orbit lifetime for LMRST-Sat in its stowed state. These same orbit parameters were used to determine the backup’s orbit lifetime, details can be found in the Appendix E.

This meets requirement 4.6-1. For the complete list of CubeSat orbital lifetimes reference Table 2: CubeSat Orbital Lifetime & Collision Probability.

Assessment results show compliance.

Section 7: Assessment of Spacecraft Reentry Hazards

A detailed assessment of the components to be flown on ELaNa-12 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, where the risk to human casualty shall not exceed 1:10,000. There is not enough energy to cause a human casualty if the surviving reentry component has less than 15J.

1. Low melting temperature (less than 1000 °C) components are identified as materials that would not 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 3.

Table 3: ELaNa-12 High Temperature DAS Analysis

CubeSat	ELaNa-12 Components	Mass (g)	Length / Diameter (mm)	Width (mm)	Height (mm)	Demise Alt (km)	KE (J)	Probability
ARC1	Camera Lens	4	14	14.3	-	75.5	0	0

The majority of high temperature components demise upon reentry. The majority of components that do not demise reentry have less than 15 J of energy. Of the components that DAS conservatively identifies as reaching the ground two of the five have more than 15J of kinetic energy. From the Debris Casualty Area and the orbit these components will be flying in the 1/74900 probability of human casualty satisfies the requirement (1/10,000).

Through the method described above, Table 3: ELaNa-12 High Temperature DAS Analysis, and the full component lists in the Appendix all CubeSats launching under the ELaNa-12 mission are 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 CubeSat components.

Section 8: Assessment for Tether Missions

ELaNa-12 CubeSats will not be deploying any tethers.

ELaNa-12 CubeSats satisfy 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/

Justin Treptow
Flight Design Analyst
NASA/KSC/VA-H1

cc: VA-H/Mr. Carney
VA-H1/Mr. Beaver
VA-H1/Mr. Haddox
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 A. ELaNa-12 Component List by CubeSat: ARC1

Name	External/Internal (Major/Minor Components)	Qty	Material	Body Type	Mass (g)	Diameter/ Width (mm)	Length (mm)	Height (mm)	Low Melting Temp	Melting Temp (°C)	Comment
ARC1	-	1	eg. Aluminum 6061	Box	-	-	-	-	-	-	-
CubeSat Structure	External - Major	1	Aluminum 6061	Box	144	100	100	110	Yes	-	Demise
UHF Antenna	External - Major	1	Steel	Measuring Tape	5	12.33	165	0.2	No	-	See Table 4
Solar Panel Boards	External - Major	6	Fiberglass	Box	28	82	103	1.7	Yes	-	Demise
S-Band Antenna	External - Minor	1	Rogers 5870	Box	10	53.5	53.5	1.64	Yes	-	Demise
Sep Switch Rod	External - Minor	1	Aluminum 6061	Cylinder	1	3.18	55	-	Yes	-	Demise
Camera Lens	External - Minor	1	Glass	Cylinder	4	14	14.3	-	No	1600	See Table 4
Clyde Cells	Internal - Major	4	Lithium Ion Polymer	Box	22.5	37	58.5	5	Yes	-	Demise
Magnetic torquers	Internal - Minor	12	Alnico1	Cylinder	0.4	1.6	25.4	-	Yes	-	Demise
LEDL board	Internal - Major	1	Fiberglass	Box	30	90	96	2.5	Yes	-	Demise
LEDL Cells	Internal - Minor	2	Lithium Iron disulfide	Cylinder	7.6	10.5	44.5	-	Yes	-	Demise
Clyde Board	Internal - Major	1	Fiberglass	Box	230	90	96	2.5	Yes	-	Demise
ACDS Board	Internal - Major	1	Fiberglass	Box	28	90	96	2.5	Yes	-	Demise
COMM Board	Internal - Major	1	Fiberglass	Box	30	90	96	2.5	Yes	-	Demise
IMG Board	Internal - Major	1	Fiberglass	Box	54.3	90	96	2.5	Yes	-	Demise
Fasteners	Internal - Minor		Black Oxide Steel	-	-	-	-	-	Yes	-	Demise
Cabling	Internal - Minor		Copper alloy	-	-	-	-	-	Yes	-	Demise