Orbital Debris Assessment for The U2U Cubesat on the WorldView 4 Mission

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. 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
D. *UL Standard for Safety for Lithium Batteries, UL 1642*. UL Standard. 4th ed. Northbrook, IL, Underwriters Laboratories, 2007
E. Kwas, Robert. Thermal Analysis of ELaNa-4 CubeSat Batteries, ELVL-2012-0043254; Nov 2012
F. Range Safety User Requirements Manual Volume 3- Launch Vehicles, Payloads, and Ground Support Systems Requirements, AFSCM 91-710 V3.
G. *UL Standard for Safety for Household and Commercial Batteries, UL 2054*. UL Standard. 2nd ed. Northbrook, IL, Underwriters Laboratories, 2005
H. 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 U2U mission. 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 APIC ENTERPRISE U2U auxiliary payload mission flown on WorldView 4. The CubeSat manifested, comprising the U2U mission are 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 tether release

Section 1: Program Management and Mission Overview

The U2U mission is sponsored by the Air Force Research Labs at Kirtland Air Force Base. The sole communication radio is the Eyestar STX2 Simplex radio hosted payload built by NearSpace Launch. Program/project manager and senior scientific and management personnel are as follows:

Jeff Dailey: GlobalStar Radio Provider, Near Space Launch
Travis Willett Gies: Mission Manager, AFRL
Collin Enger: Mission Manager, AFRL

Program Milestone Schedule	
Task	**Date**
U2U kick off meeting	1/2016
CubeSat Build, Test, and Integration	1/2016 – 6/2016
Environmental Testing	6/1/2016
CubeSat Delivery/integration to CalPoly	7/11/2016
Launch	9/1/2016

Figure 1: Program Milestone Schedule

The U2U mission will deploy from Atlas 5.

U2U CubeSat size 10cm x 10cm x 20 cm, with mass of 3.4 kg total. U2U is designed and built by the Air Force Research Labs.

U2U will launch on the WorldView 4 Atlas 5 rocket. The current launch date is September 1st 2016 in an orbit approximately 550 X 580 km at inclination of 98.6 deg.

Section 2: Spacecraft Description

U2U is a CubeSat Mission.

	CubeSat Quantity	CubeSat size	CubeSat Names	CubeSat Masses (kg)
	1	2U (10 cm X 10 cm X 20 cm)	U2U	3.4

The following subsection contain descriptions of U2U CubeSat.

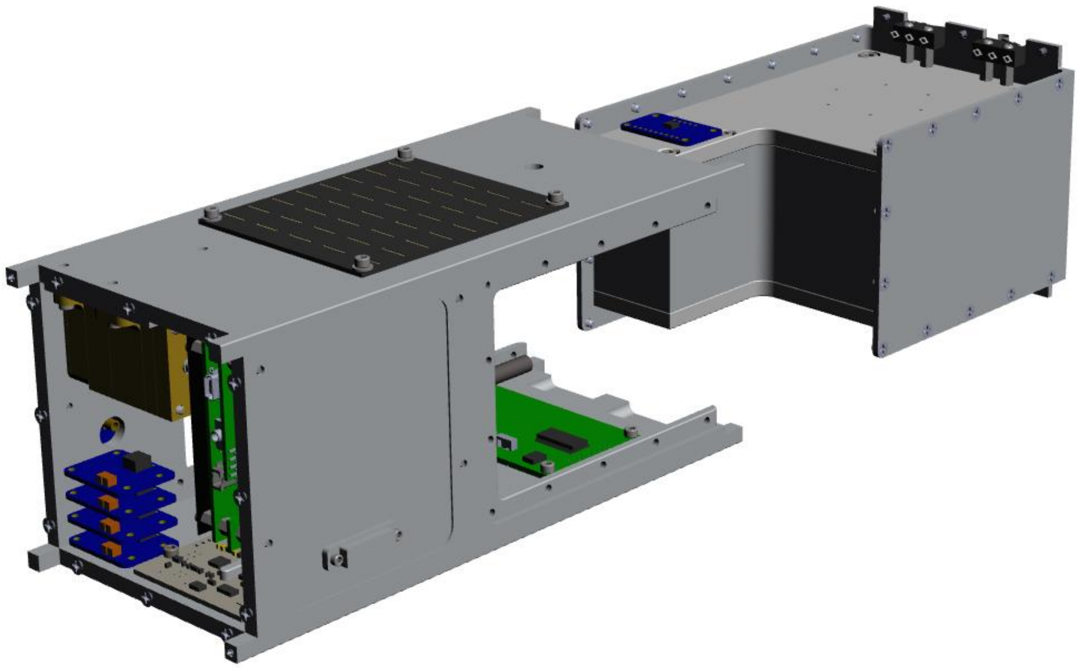

Figure 2:U2U CubeSat Description

The primary mission of U2U is to demonstrate a high latitude communications link to the GlobalStar network of satellites.

Once ejected from the Atlas 5, power management comes online after 45 minutes. 50 minutes after ejection the GlobalStar communications link is powered on and system status data is transmitted.

The U2U structure is made of 6061-T6 aluminum. Internal and external materials used are: standard electrical components, printed circuit boards, stainless steel hardware and solar cells. The GlobalStar radio uses a 25mm x 25mm ceramic patch antenna.

There are no hazardous materials used on U2U.

The power system consists of 9 Ultralife UHR-CR34610 U10016 $LiMnO_2$ batteries in parallel at 3.3V / 11000mAh with a total power of 36.3 Ah available to the system. The 9 cells are arranged in a 1s9p configuration. Each cell contains a PTC fuse to protect from short circuit. The Li-Poly batteries carry the UL-listing number BBCV2_MH14240.

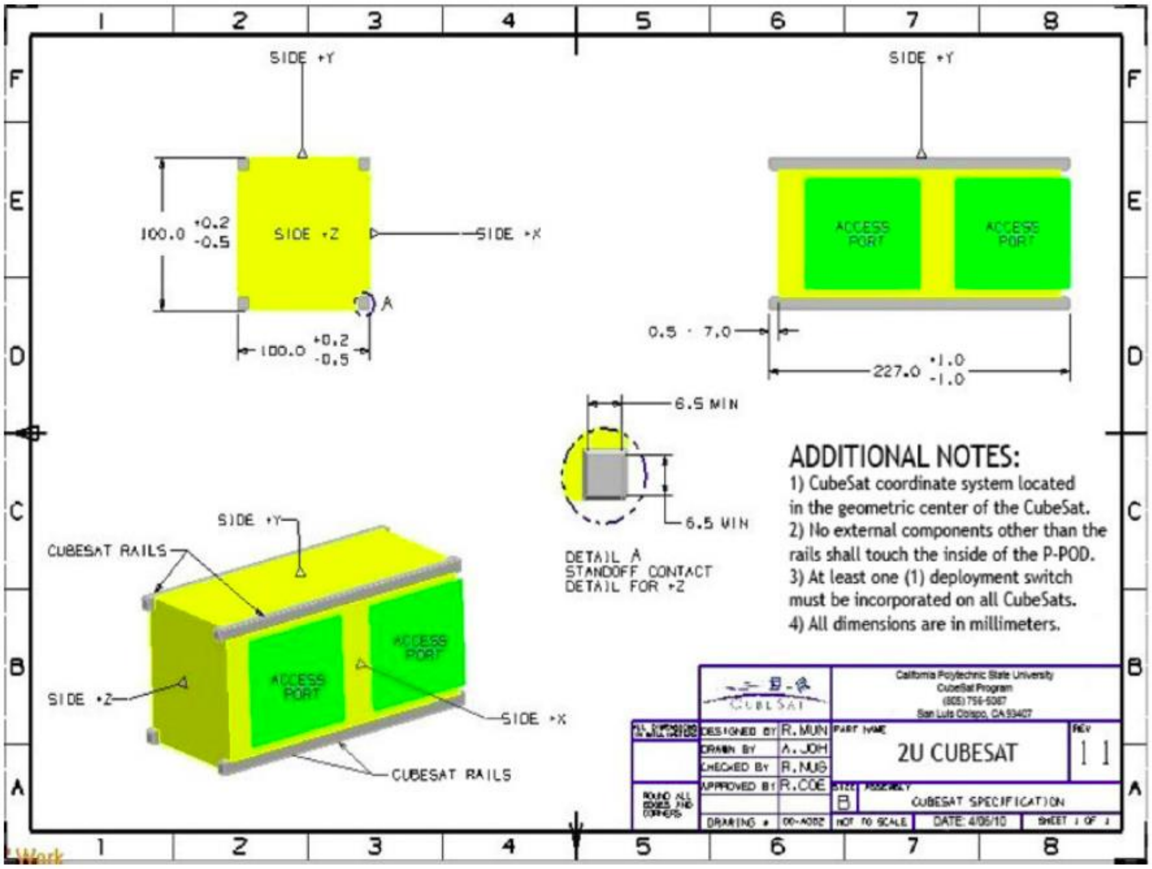

Figure 3: 2U CubeSat Specification

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.

No releases are planned on the U2U mission therefore this section is not applicable.

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

Note: This entire section applies to U2U mission.

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 battery properties will occur over the post mission period, which may be as long as 25 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 U2U 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.

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 U2U is compliant. Requirements 4.4-3 and 4.4-4, addressing intentional break-ups are not applicable.

The following addresses requirement 4.4-2. The CubeSat not been designed to disconnect their onboard storage energy devices (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”.

Table 2: U2U CubeSat Cells

CubeSat	Technology	Manufacturer	Model	UL Listing Number
U2U	Lithium Ion ($LiMnO_2$)	Ultralife	U10016	MH14240

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).

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.

$$MeanCSA = \frac{\sum SurfaceArea}{4} = \frac{[2*(w*l)+4*(w*h)]}{4}$$

Equation 1: Mean Cross Sectional Area for Convex 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. Refer to Appendix A for dimensions used in these calculations.

The U2U orbit at deployment is 580 km apogee altitude by 550 km perigee altitude, with an inclination of 98.6 degrees. With an area to mass (3.4 kg) ratio of 0.0081 m^2/kg, DAS yields 12.791 years for orbit lifetime, which in turn is used to obtain the collision probability. Orbital lifetime U2U will see an average of 10^{-5} probability of collision. Table 3 below provides complete results.

Table 3: CubeSat Orbital Lifetime & Collision Probability

CubeSat	U2U
Mass	3.4
Mean C/S Area (m^2)	0.0275
Area-to Mass (m^2/kg)	0.0081
Orbital Lifetime (yrs)	12.792
Probability of collision (10^X)	-9.7

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 U2U spacecraft collision with debris and meteoroids greater than 10 cm in diameter and capable of preventing post-mission disposal is less than $10^{-6.2}$. This satisfies the 0.001 (10^{-6}) 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 U2U to be compliant. Requirement 4.5-2 is not applicable to this mission.

Section 6: Assessment of Spacecraft Postmission Disposal Plans and Procedures

The U2U 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 for U2U in its configuration as the worst case. The area-to-mass is calculated for is as follows:

$$\frac{Mean\frac{C}{S}Area\left(m^2\right)}{Mass\left(kg\right)} = Area--Mass\left(\frac{m^2}{kg}\right)$$

Equation 2: Area to Mass

$$\frac{0.0275\,m^2}{3.4\,kg} = 0.0081\,\frac{m^2}{kg}$$

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

DAS inputs are: 580 km maximum perigee X 550 km maximum apogee altitudes with an inclination of 98.6 degrees at deployment in the year 2016.7. An area to mass ratio of 0.0081 m^2/kg for the U2U CubeSat was computed. DAS 2.0.2 yields a 12.792 year orbit lifetime for U2U.

This meets requirement 4.6-1. For the complete list of CubeSat orbital lifetimes.

Assessment results show compliance.

Section 7: Assessment of Spacecraft Reentry Hazards

A detailed assessment of the components to be flown on U2U 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 possess as negligible risk similar to stainless steel components. Probability of human casualty was calculated if a component exceeded 15J of energy upon reentry.

The U2U CubeSat complies with Requirement 4.7-1, to have less than 1:10,000 risk of human casualty.

CubeSat	Stainless Steel Components	Mass (g)	Length / Diameter (cm)	Width (cm)	Height (cm)	Demise Alt (km)	KE (J)
U2U	Sep Switches	8.0	0.45	2.0	0.00	76.4	0
U2U	Spring Plungers	2.0	0.35	1.50	0.00	76.5	0
U2U	Fasteners / Spacers	45.0	0.00	0.00	0.00	78	0
U2U	GlobalStar Patch Antenna	10.0	2.50	2.50	0.20	0	3

Table 4: U2U Survivability DAS AnalysisThe U2U 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.

CubeSat	Stainless Steel Components	Mass (g)	Length / Diameter (cm)	Width (cm)	Height (cm)	Demise Alt (km)	KE (J)
U2U	Sep Switches	8.0	0.45	2.0	0.00	76.4	0
U2U	Spring Plungers	2.0	0.35	1.50	0.00	76.5	0
U2U	Fasteners / Spacers	45.0	0.00	0.00	0.00	78	0
U2U	GlobalStar Patch Antenna	10.0	2.50	2.50	0.20	0	3

Table 4: U2U Survivability DAS Analysis

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

Section 8: Assessment for Tether Missions

U2U will not be deploying any tethers.

U2U satisfies 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. Component List for:U2U

CubeSat	Row Number	Name	External/Internal (Major/Minor Components)	Qty	Material	Body Type	Mass (g)	Width (mm)	Length (mm)	Height (mm)	Low Melting	Melting Temp (C)	Comment
U2U	1	U2U									Yes		Demises
U2U	2	External Structure	External - Major	1	Aluminum 6061	Box	830	100	100	227	Yes		Demises
U2U	3	Battery Box	External - Major	1	Aluminum 6061/PEEK	Box	650	100	100	170	Yes		Demises
U2U	4	GlobalStar Patch Antenna	External - Major	1	Ceramic	Square	10	25	25	2	No	1400	Compliant (3J)
U2U	5	Sep Switches	External - Minor	4	Steel / Plastic	Round	8	4.5	20		No	1500	Demises
U2U	6	Spring Plungers	External - Minor	2	Steel / Stainless Steel	Round	2	3.5	15		No	1500	Demises
U2U	8	Collimator	Internal-Major	1	Brass	Box	280	32	32	56	Yes		Demises
U2U	9	End Plate	External - Major	1	Aluminum 6061	Square	150	100	100	2	Yes		Demises
U2U	10	Batteries	Internal - Major	9	Aluminum Foil / Mylar / Lithium	Square	1026	50	100	13	Yes		Demises
U2U	11	GlobalStar Board	Internal - Minor	1	Fiberglass / Copper	Square	60	61	82	1.7	Yes		Demises
U2U	12	Power Management Boards	Internal - Minor	4	Fiberglass / Copper	Square	10	25	18	1.7	Yes		Demises
U2U	13	Atmega Microcontroller Board	Internal - Minor	1	Fiberglass / Copper	Square	45	61	82	1.7	Yes		Demises
U2U	14	Instrument Boards	Internal - Minor	3	Fiberglass / Copper	Square	50	61	82	1.7	Yes		Demises
U2U	16	Magnotometer	Internal - Minor	1	Fiberglass / Copper	Square	27	30	20	1.7	Yes		Demises
U2U	17	Fasteners / Spacers	Internal - Minor		Stainless Steel		45				No	1500	Demises
U2U	18	Cabling	Internal - Minor		Copper alloy		50				Yes		Demises
U2U	24	Damping	Internal - Minor		Grain-Oriented Steel	Square	40	50	75		Yes		Demises