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Orbital Debris Assessment for the PAN CubeSat Mission per NASA-STD 8719.14A

Signature Page

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ELVL-0045486

Reply to Attn of: VA-H1

December 20, 2018

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

FROM: Yusef Johnson, a.i. solutions/KSC/AIS2

SUBJECT: Orbital Debris Assessment Report (ODAR) for the PAN CubeSat 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. International Space Station Reference Trajectory, delivered May 2017
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. HQ OSMA Policy Memo/Email to 8719.14: CubeSat Battery Non-Passivation, Suzanne Aleman to Justin Treptow, 10, March 2014
I. HQ OSMA Email:6U CubeSat Battery Non Passivation Suzanne Aleman to Justin Treptow, 8 August 2017

The intent of this report is to satisfy the orbital debris requirements listed in ref. (a) for the PAN CubeSat, which will be deployed from the Virgin Orbit LauncherOne vehicle. 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 mission and are not presented here.

RECORD OF REVISIONS		
REV	**DESCRIPTION**	**DATE**
0	Original submission	December 2018

The following table summarizes the compliance status of the PAN CubeSats to be deployed from Virgin Orbit's LauncherOne vehicle. PAN 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 14.6 years
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 for PAN

Section 1: Program Management and Mission Overview

PAN is sponsored by the Human Exploration and 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:

PAN: Dr. Mason Peck, Principal Investigator, Cornell University
Stewart Aslan, Technical Contact, Cornell University

Program Milestone Schedule	
Task	**Date**
CubeSat Selection	February 2018
Mission Readiness Review	NET 1 March 2019
Dispenser Integration	NET 1 April, 2019
Launch	NET 1 May, 2019

Figure 1: Program Milestone Schedule

The PAN CubeSats will be launched as a payload on the LauncherOne launch vehicle.

Section 2: Spacecraft Description

Table 2: PAN Attributes outlines the generic attributes of the spacecraft.

Table 2: PAN Attributes

CubeSat Names	CubeSat Quantity	CubeSat size (mm)	CubeSat Masses (kg)
PAN	2	376.5 x 100 x 100	4.6

The following pages describe the PAN CubeSats.

PAN – Cornell University – 3U

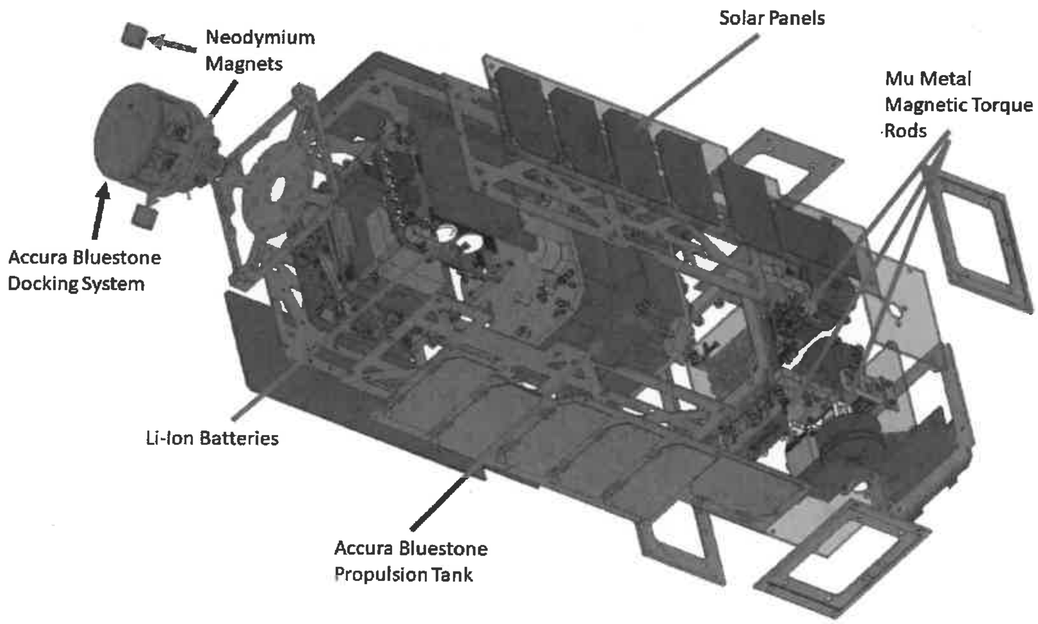

Figure 2: PAN exploded view

Overview

PAN aims to demonstrate autonomous rendezvous and docking technology. Two satellites will deploy simultaneously and navigate relative to one another before docking.

CONOPS

Upon deployment, each PAN satellite will wait for 30 minutes before turning on and 45 minutes before transmitting RF signals. Communication throughout the mission will be carried out through the Iridium satellite network, which will relay information to Cornell's ground station. The satellites also have GPS receivers and short range radios that they use to share GPS information, transmitting over a 1km range at 915MHz.

Materials

The CubeSat structure is made of Aluminum 6061-T6. It contains standard commercial off the shelf (COTS) materials, electrical components, PCBs and solar cells. The CubeSat has three ceramic patch antennae for the radios and GPS receiver as well as two neodymium magnets in the docking system. The three magnetic torque rods are made of Mu metal wrapped in copper magnet wire. The propulsion system and docking system are 3D-printed out of Accura Bluestone.

Hazards

The satellite contains a cold-gas propulsion system that uses R236FA, a commercially available refrigerant used in automotive applications, as its propellant. The refrigerant is not toxic but it is an asphyxiant because it displaces oxygen, so should only be handled in well-ventilated areas.

Batteries

Each PAN CubeSat contains a commercially available GOMSpace NanoPower battery board for CubeSats with two Li-Ion cells. The GOMSpace board has over-charge/current protection.

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 for PAN, 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 PAN 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 (h)).

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. (h))

Limitations in space and mass prevent the inclusion of the necessary resources to disconnect the battery or the solar arrays at EOM. However, the low charges and small battery cells on the CubeSat's power system prevents a catastrophic failure, so that passivation at EOM is not necessary to prevent an explosion or deflagration large enough to release orbital debris.

Assessment of spacecraft compliance with Requirements 4.4-1 through 4.4-4 shows that with a maximum CubeSat lifetime of 14.6 years, both PAN 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.

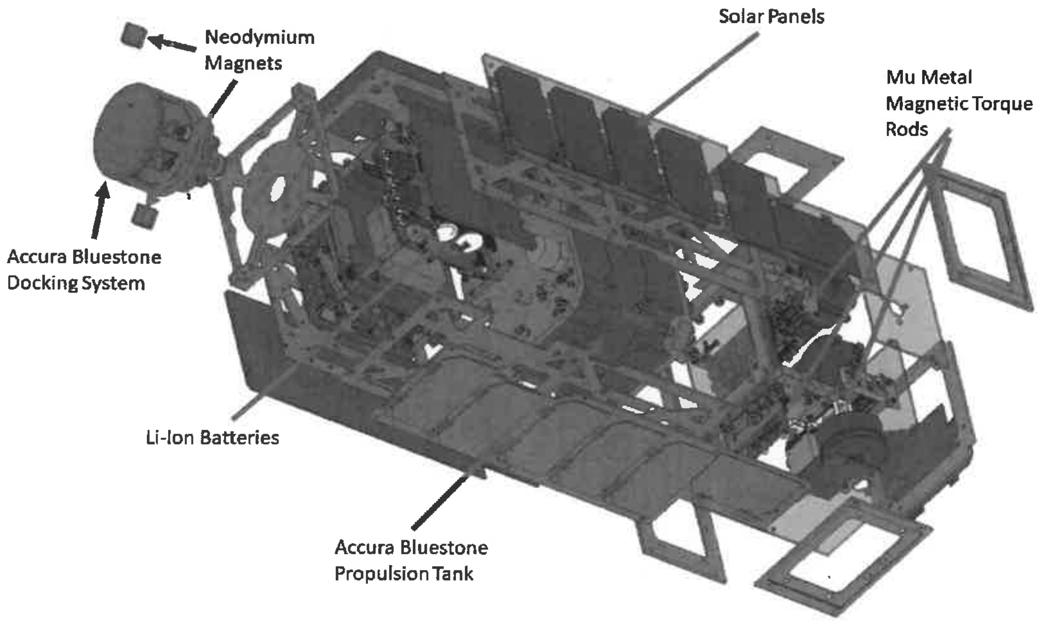

Figure 4: PAN Expanded View (with solar panels deployed)

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

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

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

Once a CubeSat has been ejected from the CubeSat dispenser 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 component dimensions used in these calculations

The PAN CubeSats (4.51 kg after propellant depletion) orbit at deployment will be 500 ± 10 km at a 45° ± 2° inclination. For this analysis, a 510 km circular orbit at a 47° inclination was used, as that is the worst case scenario. With an area to mass ratio of

0.0026 m^2/kg, DAS yields 14.6 years for orbit lifetime, which in turn is used to obtain the collision probability. PAN is calculated to have a probability of collision of 0.0. Table 3 below provides complete results.

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.

PAN	510 km	490 km
Mass (kg)	4.51*	4.51*
Mean C/S Area (m^2)	0.01188	0.01188
Area-to Mass (m^2/kg)	0.0026	0.0026
Orbital Lifetime (yrs)	**14.6**	**11.9**
Probability of collision (10^X)	**0.0000**	**0.0000**

*assumes propellant depleted

Solar Flux Table Dated
9/26/2018

Table 3: CubeSat Orbital Lifetime & Collision Probability

The probability of PAN colliding with debris and meteoroids greater than 10 cm in diameter and capable of preventing post-mission disposal is less than 0.00000, for any configuration. This satisfies the 0.001 maximum probability requirement 4.5-1.

The PAN CubeSats have no capability nor have plans for end-of-mission disposal, therefore requirement 4.5-2 is not applicable.

Assessment of spacecraft compliance with Requirements 4.5-1 shows PAN to be compliant. Requirement 4.5-2 is not applicable to this mission.

Section 6: Assessment of Spacecraft Postmission Disposal Plans and Procedures

Both PAN CubeSats 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 post-mission 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 the PAN CubeSats with their propellant depleted as the worst case. The area-to-mass is calculated for is as follows:

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

Equation 3: Area to Mass

$$\frac{0.0118\, m^2}{4.51\, kg} = 0.0026\frac{m^2}{kg}$$

The assessment of the spacecraft illustrates they are compliant with Requirements 4.6-1 through 4.6-5.

<u>DAS 2.1.1 Orbital Lifetime Calculations:</u>
DAS inputs are: 510 km maximum apogee 510 km maximum perigee altitudes with an inclination of 47° at deployment no earlier than May 2019. An area to mass ratio of ~0.0026 m^2/kg for the PAN CubeSats was used. DAS 2.1.1 yields 14.6 years of orbit lifetime for PAN with their propellant depleted.

This meets requirement 4.6-1. For the complete list of CubeSat orbital lifetimes reference **Table 3: CubeSat Orbital Lifetime & Collision Probability**.

Assessment results show compliance.

Section 7: Assessment of Spacecraft Reentry Hazards

A detailed assessment of the components of PAN was performed. The assessment used DAS 2.1.1, 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 possess the same negligible risk as stainless steel components.

Table 4: PAN High Melting Temperature Material Analysis

Part Name	Material	Total Mass (kg)	Demise Alt (km)	Kinetic Energy (J)
Magnets	Neodymium	.01	71.2	0
Motor	Stainless Steel 18-8	.016	0.0	4
Pressure/Temperature Sensors	Stainless Steel 316	.041	70.8	0
Solenoid valve	Stainless Steel 316	.005	75.9	0
Reaction wheel	Stainless Steel 316	.11	75.9	0
Magnetic Torque Rod	Mu Metal	.01	77.3	0

The majority of stainless steel components demise upon reentry and all CubeSats comply with the 1:10,000 probability of Human Casualty Requirement 4.7-1. A breakdown of the determined probabilities follows:

Table 5: Requirement 4.7-1 Compliance for PAN

Name	Status	Risk of Human Casualty
PAN	Compliant	1:0

*Requirement 4.7-1 Probability of Human Casualty > 1:10,000

If a component survives to the ground but has less than 15 Joules of kinetic energy, it is not included in the Debris Casualty Area that inputs into the Probability of Human Casualty calculation. This is why the PAN CubeSats have a 1:0 probability as none of their components have more than 15J of energy.

Both CubeSats launching under the PAN mission are shown to be in compliance with Requirement 4.7-1 of NASA-STD-8719.14A.

Section 8: Assessment for Tether Missions

Neither of the PAN CubeSats will not be deploying any tethers.

Both PAN CubeSats satisfy Section 8's requirement 4.8-1.

Section 9-14

ODAR sections 9 through 14 pertain to the launch vehicle, and are not covered here. Launch vehicle sections of the ODAR are the responsibility of the CRS provider.

If you have any questions, please contact the undersigned at 321-867-2098.

/original signed by/

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Flight Design Analyst
a.i. solutions/KSC/AIS2

cc: VA-H/Mr. Carney
VA-H1/Mr. Beaver
VA-H1/Mr. Haddox
VA-C/Mr. Higginbotham
VA-C/Mrs. Nufer
VA-G2/Mr. Treptow
SA-D2/Mr. Frattin
SA-D2/Mr. Hale
SA-D2/Mr. Henry
Analex-3/Mr. Davis
Analex-22/Ms. Ramos

Appendix Index:

Appendix A. PAN Component List

Item Number	Name	Qty	Material	Body Type	Mass (g) (total)	Diameter / Width (mm)	Length (mm)	Height (mm)	High Temp	Melting Temp (F°)	Survivability
1	PAN 3U+ CubeSat	1	N/A	Box	-	-	-	-	-	-	-
2	CubeSat Structure	1	Aluminum 6061	Box	255.62	100	260	100	No	-	Demise
3	Solar Panels	4	FR4	Flat Plate	358.5	82	323	2.6	No	-	Demise
4	Solar Panel (Single Cell)	1	FR4	Flat Plate	10.33	92	92	1.7	No	-	Demise
5	Docking Structure	1	Accura Bluestone	Cylinder	205.72	64	37	-	No	-	Demise
6	Magnets	2	Neodymium	Box	10	12.7	12.7	12.7	Yes	1860°	Demise
7	Motor	1	Stainless Steel 18-8	Cylinder	16.44	15	50	-	Yes	2500°	0
8	Umbilical Board	1	FR4	Flat Plate	70	92	92	1.7	No	-	Demise
9	Batteries	2	Steel shell, Li-ion components	Cylinder	50	18	64	-	No	-	Demise
10	Battery Board	1	FR4	Flat Plate	100	92	92	1.7	No	-	Demise
11	Iridium Radio	1	Steel	Box	30.3	47.4	47.4	15	No	-	Demise
12	Radio Board	1	FR4	Flat Plate	12.3	92	92	1.7	No	-	Demise
13	Voltage Converter Board	1	FR4	Box	50	92	92	10	No	-	Demise
14	Valve Switching Circuit Board	1	FR4	Flat Plate	15.5	92	92	1.7	No	-	Demise
15	GPS Receiver Board	1	FR4	Box	16.85	53	53	9.2	No	-	Demise
16	Intersatellite Radio Board	1	FR4	Flat Plate	1.42	30	20	3.2	No	-	Demise
17	Antennae	3	Rogers RO 3200	Box	3	25	25	3	No	-	Demise
18	Tank	1	Accura Bluestone	Cylinder	432	95	87	-	No	-	Demise
19	Propellant	1	R236FA	N/A	160	N/A	-	-	No	-	Demise
20	Tank Sealing Plate	2	Aluminum 6061	Box	120.5	95	95	5	No	-	Demise
21	Pressure/temperature sensors	3	Stainless Steel 316	Cylinder	41	19	20	-	Yes	2500°	Demise
22	Solenoid Valve	6	Stainless Steel 316	Cylinder	5.15	6.35	28	-	Yes	2500°	Demise

23	Nozzle Block	4	Accura Bluestone	Box	11.5	20	20	20	No	-	Demise
24	Structure	1	Aluminum 6061	Box	72	100	100	70	No	-	Demise
25	ADCS Electronics Board	6	FR4	Flat Plate	16	77	77	1.7	No	-	Demise
26	Reaction Wheel	3	Stainless Steel 316	Cylinder	110	42.4	21.3	-	Yes	2500°	Demise
27	Magnetic Torque Rod	3	Mu Metal	Cylinder	10	6.35	21.4	-	Yes	2650°	Demise
28	Sun Sensor	5	Accura Bluestone	Box	3	16	34	4.6	No	-	Demise
29	Sep Switches	2	Aluminum 6061	Cylinder	3	4.7	19	-	No	-	Demise
30	Fasteners/Bracketry	240	Aluminum 6061	Cylinder	1	3	10	-	No	-	Demise
31	Cabling	50	Copper, Teflon	Cylinder	10	2	30	-	No	-	Demise