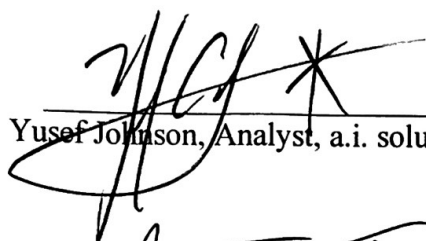


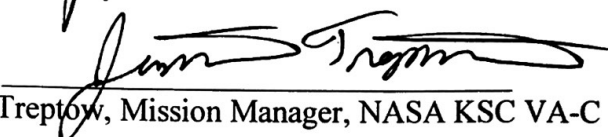
ELVL-2017-0044744
June 22, 2018 (FCC Rev3)

**Orbital Debris Assessment for
The CubeSats on the
Virgin Orbit LauncherOne /ELaNa-20 Mission
per NASA-STD 8719.14A**

Signature Page



Yusef Johnson, Analyst, a.i. solutions, AIS2



Justin Treptow, Mission Manager, NASA KSC VA-C

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



ELVL-2017-0044744

June 22, 2018

Reply to Attn of: VA-H1

TO: Justin Treptow LSP Mission Manager, NASA/KSC/VA-C

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

SUBJECT: Orbital Debris Assessment Report (ODAR) for the ELaNa-20 Mission
(FCC Rev 3)

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. VCLS Spacecraft to LauncherOne Interface Control Document (ICD), MA-0002 Rev 4. Virgin Galactic
- 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

The intent of this report is to satisfy the orbital debris requirements listed in ref. (a) for the ELaNa-20 auxiliary mission launching on 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.

The following table summarizes the compliance status of the ELaNa-20 payload mission to be flown using Virgin Galactic's LauncherOne. The 12 CubeSats comprising the ELaNa-20 mission are fully compliant with all applicable requirements.

RECORD OF REVISIONS		
REV	DESCRIPTION	DATE
0	Initial Release	7-Apr-17
1	Rev 1 removes references to CNGB, AeroCube 12A/B, and SurfSat as they have been demanifested from the ELaNa-20 mission	20-Apr-17
2	Rev 2 updates syntax and table errors.	20-Apr-17
3	Rev 3 updates manifest to remove Albus and SHFT-2, adds TechEdSat-7 and Prometheus. Updates mission milestones, and analysis to reflect current launch date NET Oct 15, 2018.	22-Jun-18

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 7.2 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-20 mission

Section 1: Program Management and Mission Overview

The ELaNa-20 mission 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:

CACTUS-1: Sandy Antunes, Technical Point-of Contact

CAPE 3: Jacob Desotels, Project Manager

ExoCube: Alex Saunders, Technical Point of Contact

INCA: Steven Stochaj, Principal Investigator

MicroMAS2b: William Blackwell, Principal Investigator

MiTEE: Brian Gilchrist, Principal Investigator

PICS: David Long, Principal Investigator

PolarCube: Albin Gasiewski, Principal Investigator

Q-PACE: Joshua Colwell, Principal Investigator

RadFXSat-2: Robert Reed, Project Manager

TechEdSat-7: Marcus S. Murbach , Project Manager

Prometheus: Los Alamos National Labs

Program Milestone Schedule	
Task	Date
CubeSat Selection	6/10/2016
Mission Readiness Review	7/10/2018
CubeSat Delivery to TriSept	9/30/2018
Launch	NET 10/15/2018

Figure 1: Program Milestone Schedule

The ELaNa-20 mission will be launched as payloads on the Virgin Galactic LauncherOne launch vehicle from Mojave, CA. The ELaNa-20 mission will deploy 12 pico-satellites (or CubeSats). Each CubeSat slotted position is identified in Table 2: ELaNa-20 CubeSats. The ELaNa-20 manifest includes: Cactus-1, CAPE 3, ExoCube, INCA, MicroMAS2b, MiTEE, PICS, PolarCube, Q-PACE, RadFXSat-2, TechEdSat-7 and Prometheus. The current launch date is in October 15, 2018. The 12 CubeSats will be ejected from the FANTM-INVERSE carrier which is the vehicle's main payload, placing the CubeSats in an orbit approximately 500 X 500 km at inclination of 90 deg.

The CubeSats on this mission range in size from a 10 cm x 10 cm x 11 cm to 11.5 cm x 11.5 cm x 37.5 cm, with masses from about 1.3 kg to 4.5 kg, with a total mass of 42.3 kg being manifested on this mission. The CubeSats have been designed and universities and government agencies and each have their own mission goals.

Section 2: Spacecraft Description

There are 12 CubeSats flying on the ELaNa-20 Mission. Table 2: ELaNa-20 CubeSats outlines their generic attributes.

Table 2: ELaNa-20 CubeSats

CubeSat Names	CubeSat Quantity	CubeSat size	CubeSat Masses (kg)
CACTUS-1	1	3U (36.6 x 10.3 x 11 cm ³)	2.8
Cape-3	1	1U (11.35 x 10 x 10 cm ³)	1.3
Q-PACE	1	3U (30 x 10 x 10 cm ³)	4.2
MiTEE	1	3U (34 x 10 x 10 cm ³)	4.0
RadFXSat-2	1	1U (11.35 x 11.1 x 11.1 cm ³)	1.3
PICS	2	1U (11.2 x 11.2 x 11.2 cm ³)	2.7
INCA	1	3U (37.5 x 11.5 x 11.5 cm ³)	3.83
MicroMas-2b	1	3U (34.05 x 10 x 10 cm ³)	4.5
EXOCUBE	1	3U (35.05 x 10 x 10 cm ³)	3.2
PolarCube	1	3U (34 x 10.1 x 10.5 cm ³)	3.9
TechEdSat-7	1	2U (21.75 x 10.6 x 10.6 cm ³)	2.49
Prometheus (-04/-05)	2	1.5U (17.05x 10 x 10.5 cm ³)	2.68 / 2.69

The following subsections contain descriptions of these 12 CubeSats.

CACTUS-1 – Capital Tech University – 3U

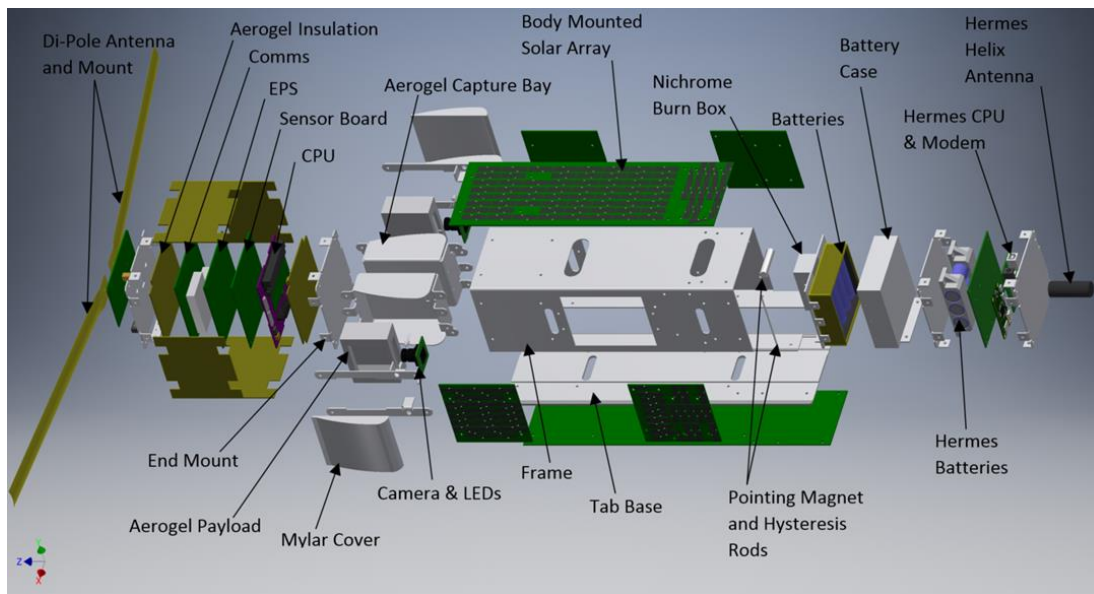


Figure 2: CACTUS-1 Expanded View

Overview

The overall goal of the CACTUS-1 mission is to profile and capture micrometeorites and micro-debris using aerogel in an effort to initiate the cleanup of LEO as well as provide a platform for a technology demonstration for an experimental communication and command subsystem.

The CACTUS-1 flight system is a 3U CubeSat (roughly $10 \times 11 \times 36 \text{ cm}^3$, 2.8 kg) that will operate in low Earth orbit. The payload consists of the main payload, a debris capture mechanism, the HERMES CPU and data modem, and imaging camera.

CONOPS

Upon deployment from the FANTM-Rail dispenser, CACTUS-1 will conduct one or more charge-up orbits. Once sufficient power is available, the CPU will power up, verify system status, and automatically activate the nichrome burn wires to release the dipole (tape measure) antenna. Within the first available contact passes with our primary ground station, we will request health-and-safety telemetry. The TRAPSat subsystem passively collects orbital debris; image data of the captured particles will be periodically requested via ground commands after initial health and safety telemetry is validated. The secondary Hermes payload will power up after at least 3 days of charging orbits to receive commands and send health and safety data via the Iridium network.

Materials

The primary CubeSat structure is made of Aluminum 7075. It contains all standard commercial off the shelf (COTS) materials, electrical components, PCBs and solar cells

Hazards

CACTUS-1 contains no pressure vessels. The aerogel being used as a debris capture mechanism, could be considered an exotic material. This material is contained as two 51 x 51 x 13 mm³ volumes. There is also a small amount of aerogel being using as thermal blanketing.

Power System/Batteries

The electrical power storage system consists of common *Lithium Ion (Li-ion)* batteries with over-charge/current protection circuitry. The primary EPS is a direct energy transfer system using the solar array to produce 3.08W average. This is composed of (6) 1U and (2) 0.5U solar panels using Trisol 28% efficient GaAs triple junction solar cells, it utilizes (4) COTS 18650 3.7V 28090 mAhr Lithium Ion battery cells. The EPS drives the primary PiSat board, which acts as the distribution hub for the sensors and payloads. Nominal power usage is 1.77W with an additional +1.1W when transmitting. The Hermes experiment EPS consists of (4) 0.5U solar panels using Trisol GaAs 28% efficiency solar cells, and (3) COTS 18650 battery cells. To turn on the entire CubeSat, there are two power inhibit switches and 1 SW timer to ensure that the spacecraft is triggered on when launched from the dispenser.

CAPE3 –University of Louisiana – 1U

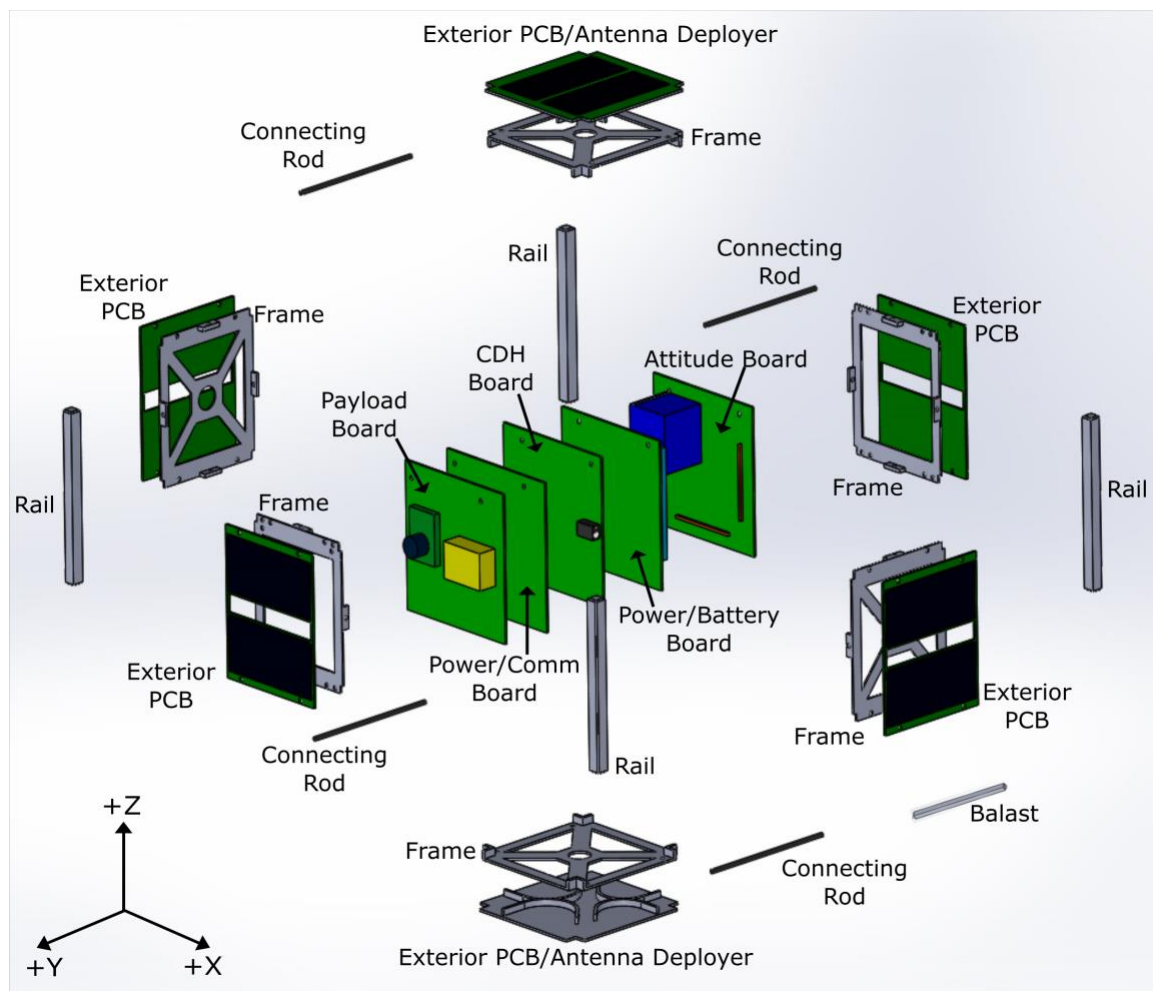


Figure 3: CAPE3 Expanded View

Overview

CAPE 3's primary mission is to create a CubeSat, improving upon the CAPE program's previous satellites, with the intent of generating grade school interest and involvement in aerospace. This includes the use of portable smartphone-controlled ground stations as an educational outreach. The secondary mission includes experimental radiation detection through triboluminescent crystals, as well as taking pictures of the earth utilizing active attitude control.

CONOPS

CAPE-3 will begin in BLUE mode upon deployment from the PPOD, and for 30 minutes after deployment will remain on, but inactive. Following the 30 minutes, the satellite will begin attempts to deploy antennas. Upon successful deployment of antennas, the satellite will enter PINK mode. The satellite will then send telemetry beacons until a ground station receives a successful transmission, and is able to activate the satellite into normal operations. From this point, the satellite will enter one of three modes (GREEN, ORANGE, or RED) autonomously based on several factors from the satellite, such as temperature, power levels, and others.

Material

The primary CubeSat structure will be composed of Aluminum 6061 and stainless steel. The antenna deployment mechanism will be made of Delrin material. The scientific payload will consist of triboluminescent crystals. The rest of the satellite will contain COTS materials, electrical components, PCBs, and solar cells.

There are no pressure vessels or hazardous materials on the satellite. The solar panel cover glass will be coated with ITO. A boom constructed from LoadPath P/N 1106-03TS-0050-180-041-005 polymer will be used. The communications and science antennas will be constructed from steel measuring tape.

Hazards

There are no pressure vessels, hazardous, or exotic materials.

Power Systems/Hazards

The electrical power storage system consists of the Clyde Space Third Generation 10Whr Lithium Polymer battery. The battery has over-charge, over-current, over-voltage, and under-voltage protection circuitry. The battery is qualified to NASA standards EP-Wi-032.

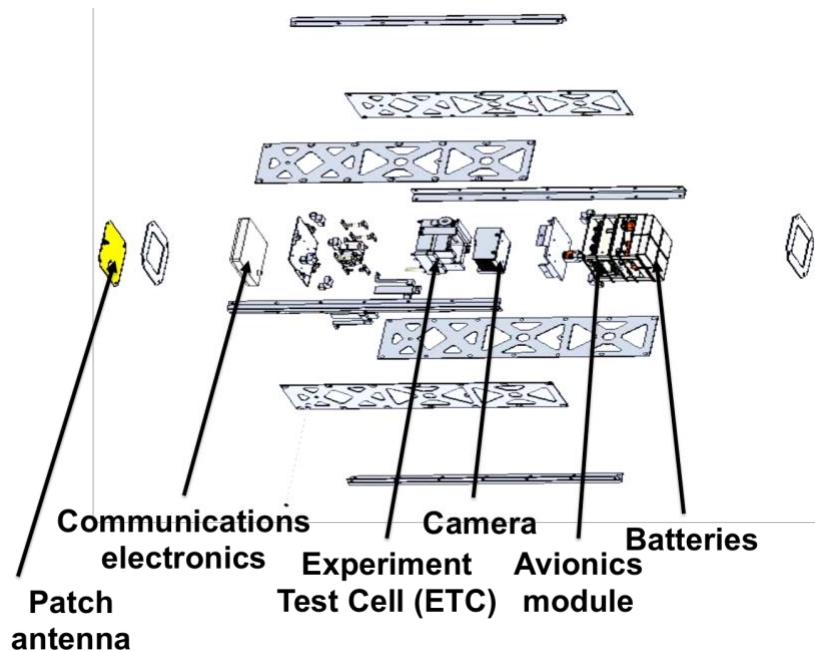


Figure 4: Q-PACE Expanded View

Overview

Q-PACE is a planetary mission to the orbital free-fall environment necessary for long duration microgravity experiments to study collisions in the early protoplanetary disk. The CubeSat will observe low-velocity collisions between cm-scale and smaller particles and the formation of clusters of particles. The experiments run during the 3 years mission time will make it possible to determine whether collisional growth can proceed into this size range, confronting the decades-old question of how bodies grow past the meter-size barrier into planetesimals that can go on to become planets through gravitational accretion.

CONOPS

After deployment, Q-PACE will start its on-orbit experiment plan consisting of 5-minute experiment runs. During each experiment run, the experiment test cell (ETC) containing the dust particles will be agitated in a sequence of high and low frequencies, while video of the colliding particles will be recorded by the on-board camera. After each experiment run, the video data will be processed on board and downlinked for analysis. During the 3-year mission time, four different particle combinations will be studied amongst cm-, mm- and 100 μm -sized particles

Materials

The primary CubeSat structure is made of Aluminum 6061-T6. The experiment cell is made of Aluminum 6061 and includes two transparent fused quartz plates to allow for the particle observation. The particles contained in the experiment cell will be composed of SiO_2 either in the form of glass beads or as dust particles, brass and meteoritic material. The Q-PACE camera is a GoPro Hero3+ black edition. Standard PCB material and electronics components were used.

Hazards

There are no pressure vessels, hazardous or exotic materials.

Batteries

The solar cells are 23% Spectrolab CICs. The electrical power storage system consists of common LFP (Lithium Iron Phosphate) batteries with over-charge/current protection circuitry (UN38.3 passed).

MiTEE– University of Michigan – 3U

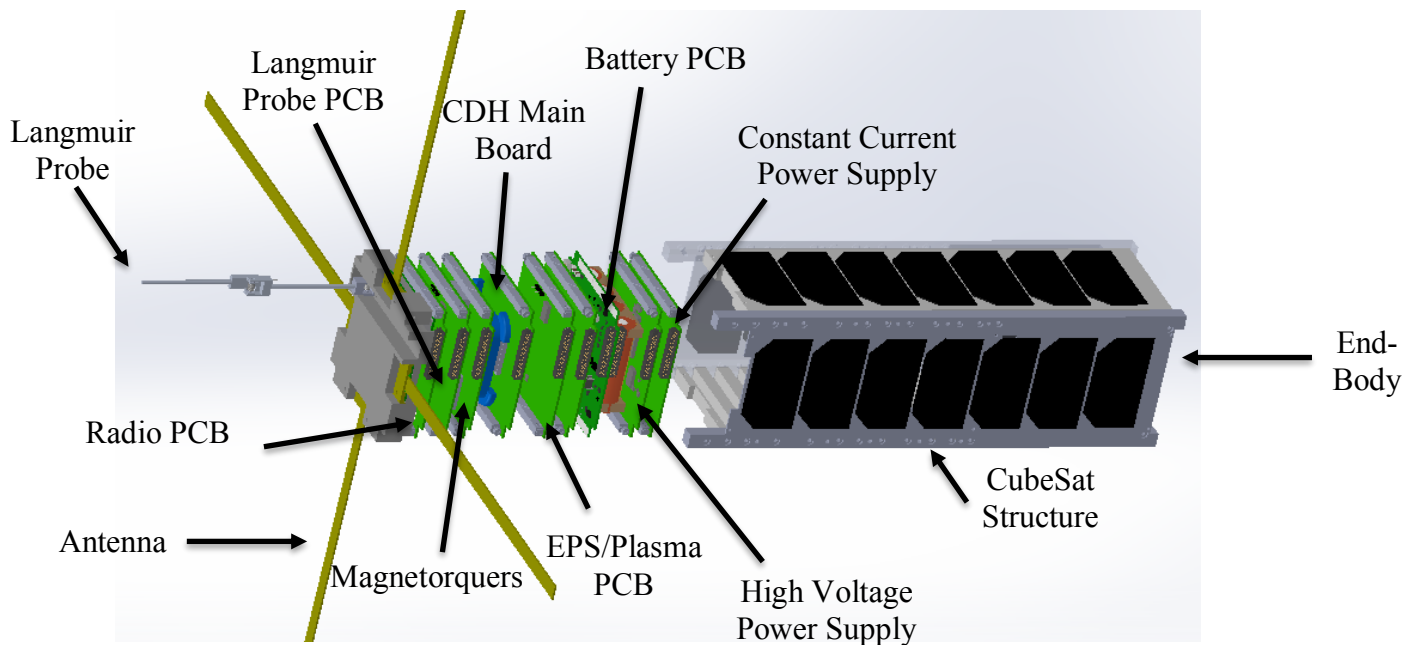


Figure 5: MiTEE Expanded View

Overview

MiTEE will demonstrate the use of CubeSat capabilities to deploy a Pico/Femto Satellite-tether system (satellite mass up to 200 g). The mission will allow students to work on a real-world, research driven, mission to assess the key dynamics and electrodynamic fundamentals of a very short tether system for pico/femto satellites. The central technical questions motivating the student mission include: (I) (Primary) Can the miniature tether provide stable, practical thrust for drag make-up and basic propulsion for “smart phone” sized pico/femtosatellites? (II) (Secondary) Can the miniature tether and pico/femtosatellite system serve in other roles. This could include, among others, that the miniature tether can be the basis for a useful, enhanced antenna for communication with the ground.

CONOPS

Upon deployment from the PPOD, MiTEE will wait around 15 minutes before powering up and beginning a subsystem and instrument performance assessment. After this check out is complete, MiTEE will initiate the antenna deployment, Langmuir probe deployment, and de-tumble procedure. We will then perform a check the performance of the Langmuir probe and antenna array, and begin transmission and plasma measurement as soon as possible. It is anticipated that after 2 days, MiTEE will be rotating less than 0.5 degrees per second. At this time, MiTEE can initiate the boom deployment procedure. A ~120 g end-body will deploy 100 cm by means of a semi-rigid boom. After a payload instrument checkout, MiTEE will proceed to begin the primary science mission by biasing the end-body, activating the thermionic cathode, and measuring the current flow through controlled voltage sweeps.

Materials

The primary material of the structure is 6061 Aluminum. It contains commercial off the shelf components, electrical components, science instruments, PCBs, and solar cells

Hazards

There are no pressure vessels, hazardous or exotic materials.

Batteries

The electrical power storage system consists of common lithium-ion batteries with over-charge/current protection circuitry.

RadFXSat 2– Vanderbilt University – 1U

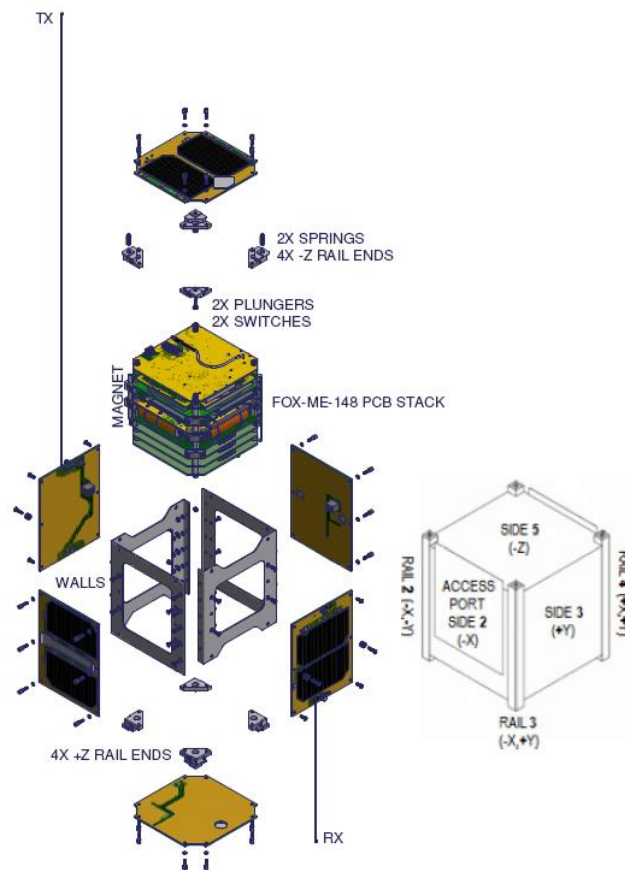


Figure 6:RadFXSat-2 Expanded/Deployed View

Overview

RadFxSat-2 is a 1U CubeSat designed by Vanderbilt University and AMSAT. It is controlled by AMSAT. Its mission has two objectives: collect data on the effects of space radiation on SRAMs designed using FinFETs for the purpose of validating single-event error rate predictions, and two-way linear transponder communications in the amateur radio band. The experiment consists of four boards: VUC, LEP, LEPF, and REM. The linear transponder (radio) consists of two boards: RX/TX and ICR.

CONOPS

P-POD Ejection + 00:00 mm:ss - CubeSat deployed from the P-POD and CubeSat switches indicate successful deployment. IHU starts. Solar Panels may charge battery.

P-POD Ejection + 50:05 mm:ss - transmit antenna deployed (fishing line melt anticipated)

P-POD Ejection + 50:15 mm:ss - receive antenna deployed (fishing line melt anticipated)

P-POD Ejection + 50:21 mm:ss - transmission may begin

Design life is 5-15 years. Typical operations include V/u amateur radio communications and low duty-cycle telemetry. Operations are planned until re-entry.

Materials

The primary CubeSat structure is made of Aluminum 5052-H32. Small machined parts are Aluminum 6061-T6, Copper 110, black Delrin, or G10 Fiberglass. The four long #4 threaded rods, and all #2 screws and jackposts are stainless steel. The PCB Stack includes experiments and avionics. Select ICs have small pieces of Tantalum as radiation shielding. The RF board(s) will have copper RF Shield(s). A large sheet of Lead is used as ballast on the bottomside of MPPT.

There is a Neodymium magnet approximately centered in Rail 2, and two Permalloy hysteresis rods bottomside of Battery.

Hazards

RadFX-2 contains no pressure vessels, hazardous or exotic materials.

Batteries

The electrical power storage system consists of six commercial off the shelf (COTS) NiCad “A” size batteries (Sanyo KR1400AE; UL listing N/A; total capacity 11.5 Watt hours).

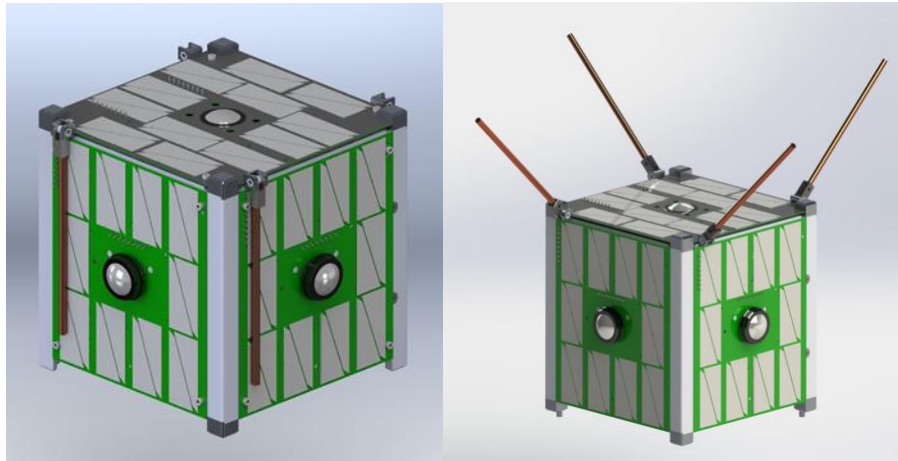


Figure 7: ALBus Stowed/Deployed View

Overview

The primary objective of PICS is to demonstrate inspection of the parent vehicle by a passive, fly-away probe. PICS will evaluate structural condition, validate state vector models, identify potential separation debris, and confirm separation.

CONOPS

After deployment, they rapidly bootup and image the launch vehicle. Out of view of the upper stage, each will characterize the other's tumble using the cameras. At 30 mins, the cameras will be used to observe each PIC's own antenna deployment. At 45 mins, the system will downlink primary mission data, including telemetry used for evaluating system performance.

Materials

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

Hazards

There are no pressure vessels, hazardous or exotic materials.

Batteries

The electrical power storage system consists of common LiPo batteries with over-charge/current protection circuitry. They are not UL listed.

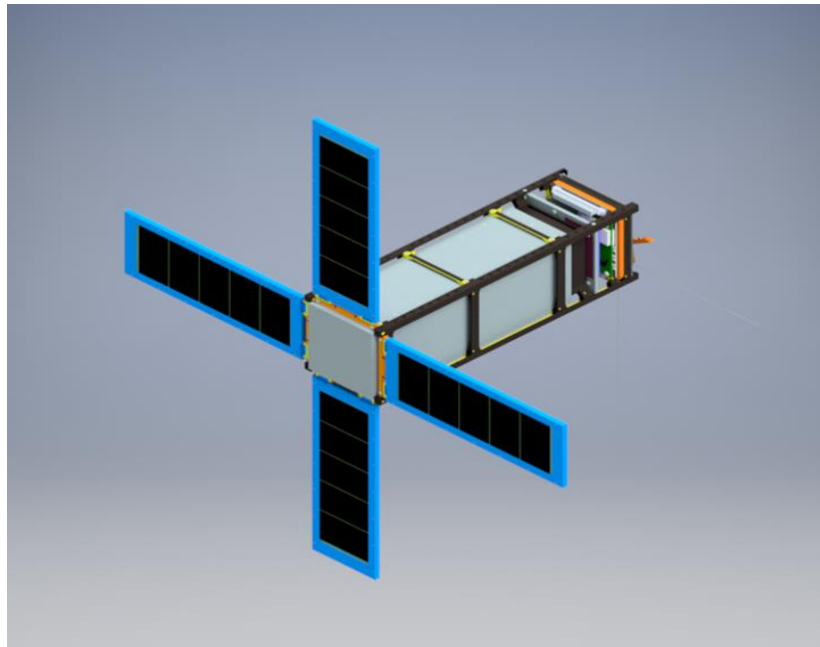


Figure 8: ALBus Expanded/Deployed View

Overview

The Ionospheric Neutron Content Analyzer (INCA) is a 3U CubeSat being built by New Mexico State University carrying a scintillator (silicon photomultiplier-based neutron detector) being built by NASA's Goddard Space Flight Center. The INCA mission will, for the first time, study the latitude and time dependencies of the neutron spectrum in low Earth orbit (LEO). INCA will focus on albedo neutrons; however, the instrumentation will also be sensitive to solar neutrons.

CONOPS

Upon deployment from the launch vehicle, INCA will enter a 45 min sleep period. Once the sleep period is complete, it will deploy its antenna and solar panels. After deployment, the vehicle will begin science operations, and begin the de-tumbling sequence. Once the vehicle is detumbled, it will be spin stabilized about the Z-axis, with the +Z axis pointed towards the sun.

Materials

The primary material of the structure is Aluminum 7075. It contains standard commercial off the shelf components, electrical components, science instruments, PCBs, and solar cells.

Hazards

There are no pressure vessels, hazardous or exotic materials.

Batteries

The electrical power storage system consists of common lithium-ion batteries with over-charge/current protection circuitry.

MicroMAS-2b – Massachusetts Institute of Technology – 3U

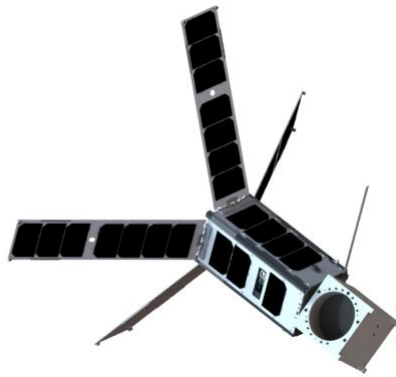


Figure 9: MicroMAS-2b Deployed View

Overview

The Micro-sized Microwave Atmospheric Satellite (MicroMAS-2b) will validate new ultra-compact and low-power technology for CubeSat-sized scanning microwave radiometer including 1) multiband (W/F band 89 GHz – 120 GHz and G band 175 GHz – 207 GHz) total power radiometer payload with 2) cross track scanner assembly in a dual-spinning local vertical local horizontal (LVLH) stabilized 2U CubeSat spacecraft. These core technology elements will directly improve atmospheric science measurements by demonstrating high-fidelity, well-calibrated radiometric sensing from very small satellite platforms, thereby enabling new architectural approaches for atmospheric monitoring.

CONOPS

After launch and deployment, MicroMAS2b will be power inhibited for 45 minutes, then execute autonomous solar panel and communications antenna deployment for 4 minutes and reach safe mode waiting for ground command. It will be then commanded through a progression of detumble and slew attitude control states to reach LVLH stabilized attitude. While in a stabilized attitude, the spacecraft will collect payload radiometer data while scanning over $\pm 56^\circ$ cross-track from nadir. The payload will cycle between data collection and standby power modes at 50% duty cycle to manage power consumption. In order to prevent EMI into the sensitive payload microwave channels, data will not be collected while the high power downlink radio is operating for nominal 8 minute pass near the ground station.

Materials

MicroMAS2b is a 3U CubeSat consisting of a 2U PC104 avionics stack/ADCS module connected to a 1U radiometer payload via a brushless scanner assembly and slip ring. It contains all standard electrical components, PCBs and solar cells. The structural housing consists of four Al 6061 side panels and four Al 7075 rails conforming to the PPOD 3U dimensional standards. Total mass is approximately 4.5 kg. There are no hazardous or exotic materials. Microwave electronics components are packaged in small (approx. 1-3 cu in) soldered unsealed waveguide housings. A thermal switch is packaged in a hermetically sealed stainless steel housing filled with dry nitrogen, tested to MIL-STD-202.

Hazards

There are no hazardous or exotic materials. However, a thermal switch is packaged in a hermetically sealed stainless-steel housing filled with dry nitrogen, tested to MIL-STD-202.

Batteries

The electrical power storage system consists of common ClydeSpace Ltd Lithium ion polymer chemistry batteries with over-charge/current protection circuitry and battery control with triple safety inhibits suitable for International Space Station manned spaceflight as per NASA JSC 20793 Rev B

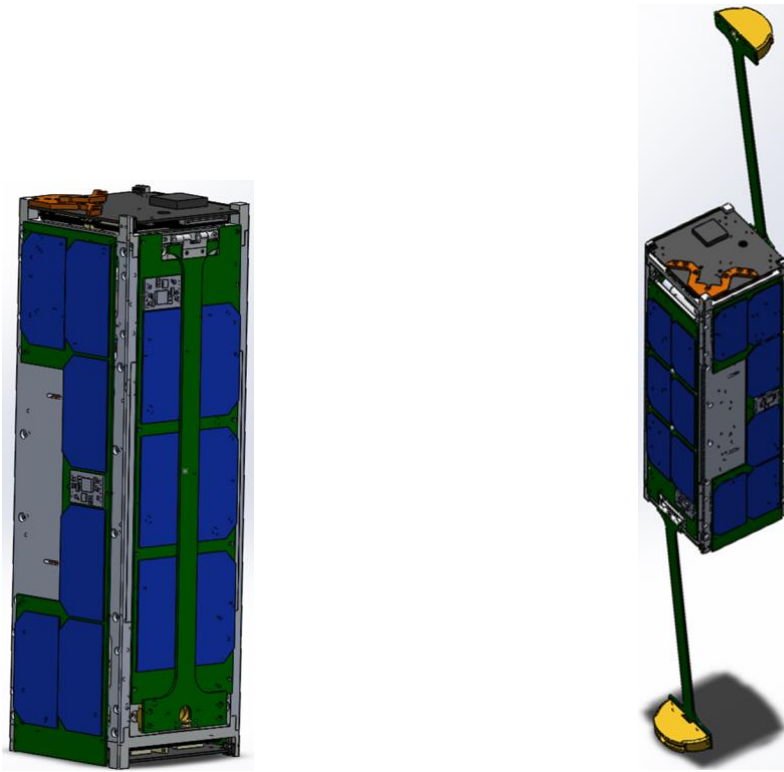


Figure 10: EXOCUBE Stowed/Deployed View

Overview

ExoCube2 will measure in-situ densities of selected ions and neutrals in the upper ionosphere and lower exosphere. These measurements will be used to characterize the climatology of the upper ionospheric and lower exospheric composition. They will help improve current empirical and climatological atmospheric models. The densities are measured using a gated time-of-flight mass spectrometer designed and built by NASA Goddard. A satellite bus to house the mass spectrometer was designed and built by Cal Poly. The bus includes an environmental chamber to protect the instrument and a 3-axis attitude determination control system (ADCS) that will maintain stable Nadir and Ram pointing necessary for accurate data measurement. The ADCS uses gravity gradient stabilization with deployable booms and a momentum wheel to stabilize the roll axis and Ram pointing. The mission life is expected to be 6 months to a year.

CONOPS

After deployment from the P-POD, the satellite will power on. Approximately 40 minutes later, antenna deployment will occur. Upon verification of antenna deployment, the beacon will be activated and the satellite will acquire with Cal Poly's ground station. The ground station will uplink the current time and TLEs. The detumble process will then begin. Magnetometers and solar sensors will determine orientation and magnetorquers will stabilize ExoCube2. Onboard GPS will acquire lock for position and time keeping. Once spin rates have been reduced, the PD controller and Kalman Filter will be activated and the booms will deploy. The camera on the $-Z$ panel will take pictures to verify boom deployment. Once Nadir pointing is acquired, the momentum wheel will begin spinning up. Around 4 hours later, the wheel will be at full speed and the satellite will reacquire Nadir and Ram pointing. The camera on the $-Z$ panel will take pictures to verify the

satellite is pointed in the correct direction. Once the correct orientation is verified, the science payload will be powered on. The mass spectrometer will take data over the Earth's poles and several ground stations throughout the mission. Every pass over a ground station (approx. every 12 hours), the satellite will downlink data from the instrument and uplink the current time for the clock and new TLEs to maintain accuracy of the orbital propagator.

Materials

The structure is made entirely of 6061-T6 Aluminum. The deployable booms are made of FR4, the tips are constructed from brass. The antennas are made of NiTi and Delrin. The satellite contains mostly standard commercial off the shelf materials, electrical components, PCBs, and solar cells. The cathode inside of the instrument is made of tungsten, but the tungsten is small enough that it burns up during re-entry.

Hazards

There are no pressure vessels, hazardous materials, or exotic materials.

Batteries

There are 4 1-cell batteries on the satellite. They are all Tenergy Li-Ion, 3.7 V 2600 mAh batteries. The UL listing number is MH48285. There is battery protection circuitry and over-charge protection circuitry. All batteries are connected in parallel.

PolarCube – Colorado Space Grant Consortium – 3U

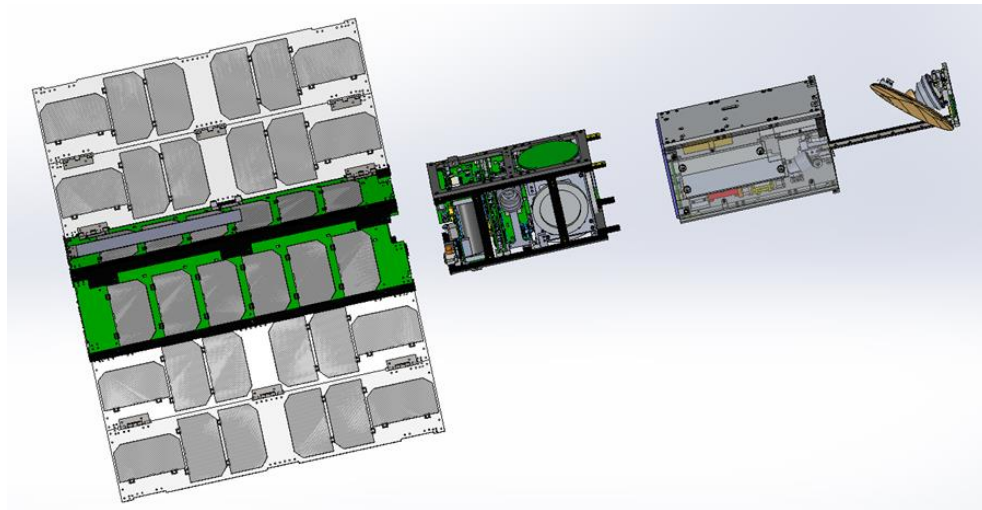


Figure 11: PolarCube Expand View

Overview

The PolarCube mission will collect Earth surface and atmospheric temperature data using a passive microwave radiometer operating at the 118.7503 GHz O₂ resonant frequency. To accomplish this, PolarCube is utilizing an existing 3U CubeSat bus, the Agile Low-cost Laboratory for Space Technology Acceleration and Research (ALL-STAR), designed and built entirely by students at COSGC. The objective is to collect brightness temperature spectra at high spatial resolution at a very low cost for remote sensing science and technology evaluation.

CONOPS

Upon deployment from the PPOD, PolarCube will power on EPS and begin a 60 minute software inhibit. After 60 minutes, EPS will trigger the frangibolt deployment and subsequently power on the ALL-STAR bus. PolarCube will then enter a bus commissioning phase. Once ground operators are satisfied with the bus operations, they will command the payload commissioning phase to begin. Once the payload has been commissioned, PolarCube will enter a minimum mission success phase where the payload will collect brightness temperature data over pre-determined orbit sectors, and will finally enter an open science collection phase until decommissioning and end of life operations.

Materials

PolarCube's primary structure is made of Aluminum 6061 with an anodized finish and Teflon coating on the rails. The system contains all standard commercial materials (IC's), FR-4 PCB's, brass RF components, and ITJ solar cells.

Hazards

There are no pressure vessels, hazardous, or exotic materials.

Batteries

The electrical power storage system consists of common lithium ion batteries with overcharge/current protection circuitry. UL Listing information is as follows MH48285.

TechEdSat-7 – NASA Ames – 3U

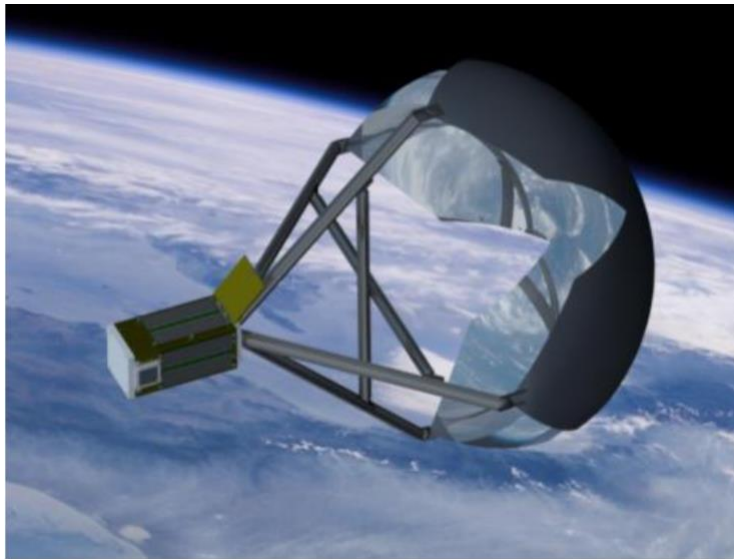


Figure 12: TechEdSat-7 Deployed View

Overview

The Technical Education Satellite 7 (TechEdSat-7) satellite will be integrated onto Virgin Orbit's LauncherOne. TechEdSat-7 will test and validate two different technologies in Low Earth Orbit (LEO): demonstration of the Exo-Brake and demonstration of the viability of the Iridium 9602 communication module.

The satellite will be inserted into orbit at an apogee of approximately 500 km, perigee of 500 km, with an inclination of 90 degrees. Transmission of data will begin 1 minute after deployment from the launch vehicle. The Exo-Brake will deorbit the satellite approximately 26 weeks after deployment concluding the mission.

TechEdSat-7 will fly on the Virgin Orbit CRS-13 mission, and will utilize the Xtenti FANTM RAIL separation system.

CONOPS

The satellite will be inserted into orbit at an apogee of approximately 500 km, perigee of 500 km, with an inclination of 90 degrees. Transmission of data will begin 1 minute after deployment from the launch vehicle. The Exo-Brake will deorbit the satellite approximately 26 weeks after deployment concluding the mission.

Materials

TechEdSat-7 is a 2U nanosatellite with dimensions of 10 cm x 10 cm x 21.7 cm and a total mass approximately equal to 2.5 kg. TechEdSat-7's payload carries a deployable Exo-Brake as a technology demonstration. The deployed Exo-Brake has a cross-sectional area of 1.25 m².

TechEdSat-7 will contain the following systems: one power board, one CUBIT RFID tag, one Crayfish board, one Iridium 9602 modem, one OEM 615 GPS, two Canon BP-930 batteries, two patch antennas, and one helical antenna.

Hazards

None, there are no propellants or pressurized areas.

Batteries

The power will be generated by solar panels and stored in two Lithium Ion batteries. The batteries that will be used are Canon BP-930 (supplied by the ISS Program Office). This battery is approved by the ISS for flight.

Prometheus: - USSOCOM / Los Alamos National Labs - 1.5U CubeSat

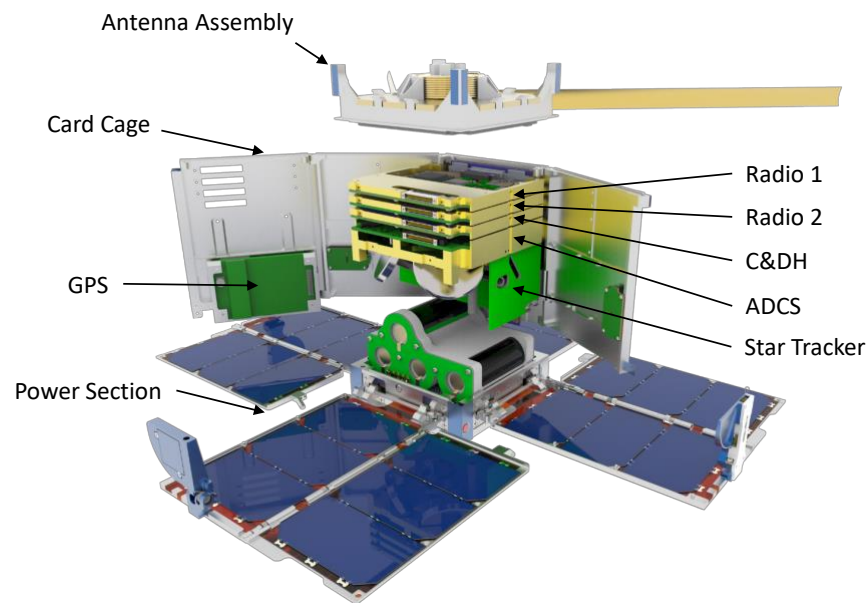


Figure 13: Prometheus CubeSat Expanded View

Overview

Prometheus is a CubeSat technology development and demonstration sponsored by USSOCOM. Los Alamos National Labs (LANL) is developing the Prometheus satellites with the dual objective of demonstrating an enhanced communications capability while also assessing the operational utility that can be realized with CubeSat technology.

CONOPS

Upon deployment from the PPOD, Prometheus will wait 45 minutes then will power up and go into beacon mode. Prometheus then awaits contact from the ground to establish link and requires ground command to activate any other capabilities, including the ADCS. The CubeSat will undergo significant test and checkout prior to performing mission operations.

Materials

The satellite structure is constructed from 6061 aluminum. Standard practice is all aluminum is either yellow iridite coated or hard anodized. Some portion, not including the rails, of the external surfaces have Sheldahl space grade thermal tapes applied to them (acrylic adhesives). Polyimide is the standard circuit board material used. The deployed helical antenna is made from phosphor bronze. The deployable monopole antennas are gold/nickel coated spring steel. All structural plastic components are FDM polycarbonate from Stratasys (TML = 0.17). Various internal components (fasteners, connectors, etc) are stainless steel. All materials used exhibit Total Mass Loss (TML) < 1% and Collected Volatile Condensable Materials (CVCM) < 0.1%. The batteries are LiFePO₄ chemistry. No exotic materials are used, no energetic materials are used. 3M Scotchweld 2216 is used throughout for potting and staking.

Hazards

There are no pressure vessels, hazardous or exotic materials.

Batteries

The Prometheus CubeSats power system includes solar cells, LiFePO₄ batteries for energy storage, and control electronics to manage battery charging and power availability to CubeSat systems. Four commercial A123 ANR26650M1-B batteries store energy to power the satellite systems (UL# BBCV2.MH45042). Each battery is rated at 2.5A-hr. Total energy storage capacity is 33 W-Hr. Total Lithium mass is estimated to be 3grams ($0.3 \times \text{Cell Capacity (A-hr)} \times \# \text{ of cells}$).

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-20 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-20 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))

The whole manifest of ELaNA-20 contains 3U or smaller CubeSats. Therefore, they are included in the 3U or smaller mentioned in 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 7.2 years maximum the ELaNa-20 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 12 CubeSats with the longest orbit lifetime is that of the INCA CubeSat with solar arrays deployed (37.5 X 11.5 X 11.5 cm with four deployed arrays each 37.5 cm X 11.5 cm):

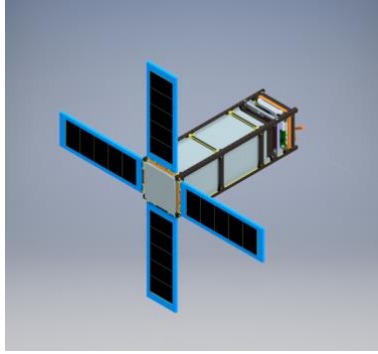


Figure 14: INCA Deployed Configuration

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

Equation 1: Mean Cross Sectional Area for Convex Objects

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

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 component dimensions used in these calculations

The INCA (3.83 kg) orbit at deployment is 500 km apogee altitude by 500 km perigee altitude, with an inclination of 90 degrees. With an area to mass ratio of 0.09 m²/kg, DAS yields 4.7 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-20 CubeSats see an average of 0.0 probability of collision. All CubeSats on ELaNa-20 were calculated to have a probability of collision of 0.0. Table 4 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.

CubeSat		CACTUS-1	CAPE-3	Q-PACE	MITEE	RadFXSat
Mass (kg)		2.8	1.3	4.2	4.0	1.31

Stowed	Mean C/S Area (m ²)	0.0459	.035	0.035	0.039	0.0188
	Area-to Mass (m ² /kg)	0.0164	0.0269	0.00833	0.00975	0.0144
	Orbital Lifetime (yrs)	5.2	4.7	6.2	5.9	5.3
	Probability of collision (10 ^X)	0.00000	0.00000	0.00000	0.00000	0.00000

Deployed **	Mean C/S Area (m ²)				0.0220	
	Area-to Mass (m ² /kg)				0.0055	
	Orbital Lifetime (yrs)				7.2	
	Probability of collision (10 ^X)				0.00000	

Table 3: CubeSat Orbital Lifetime & Collision Probability

CubeSat	PICS	INCA	MicroMAS-2b	EXOCUBE	PolarCube
Mass (kg)	2.7	3.83	4.5	3.2	3.9

Stowed	Mean C/S Area (m²)	0.0188	0.0979	0.039	0.0406	0.041
	Area-to Mass (m²/kg)	0.00697	0.0255	0.00868	0.0127	0.0105
	Orbital Lifetime (yrs)	6.6	4.7	6.1	5.5	5.8
	Probability of collision (10^X)	0.00000	0.00000	0.00000	0.00000	0.00000

Deployed	Mean C/S Area (m²)		0.147	0.107	0.136	0.11
	Area-to Mass (m²/kg)		0.0384	0.0238	0.0425	0.0282
	Orbital Lifetime (yrs)		4.3	4.8	4.2	4.6
	Probability of collision (10^X)		0.00000	0.00000	0.00000	0.00000

Table 4: CubeSat Orbital Lifetime & Collision Probability (cont.)

****Note: Blacked out areas represent CubeSats which do not have deployables**

CubeSat		TechEdSat-7	Prometheus
Mass (kg)		2.49	2.68

Stowed	Mean C/S Area (m²)	0.02241	0.0284
	Area-to Mass (m²/kg)	0.009	0.0106
	Orbital Lifetime (yrs)	4.9	4.4
	Probability of collision (10^X)	0.00000	0.00000

Deployed	Mean C/S Area (m²)	1.245	0.0748
	Area-to Mass (m²/kg)	0.500	0.0279
	Orbital Lifetime (yrs)	0.5	3.4
	Probability of collision (10^X)	0.00000	0.00000

Table 5: CubeSat Orbital Lifetime & Collision Probability (cont.)

****Note: Blacked out areas represent CubeSats which do not have deployables**

The probability of any ELaNa-20 spacecraft collision 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.

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-20 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-20 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 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 MiTEE in its deployed configuration as the worst case. The area-to-mass is calculated for is as follows:

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

Equation 3: Area to Mass

$$\frac{0.0222013 \text{ } m^2}{4 \text{ } kg} = 0.0055 \frac{m^2}{kg}$$

MiTEE 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.

DAS 2.1.1 Orbital Lifetime Calculations:

DAS inputs are: 500 km maximum apogee 500 km maximum perigee altitudes with an inclination of 90 degrees at deployment no earlier than December 2017. An area to mass ratio of 0.0055 m²/kg for the MiTEE CubeSat was used. DAS 2.1.1 yields a 7.2 years orbit lifetime for MiTEE in its deployed state.

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 to be flown on ELaNa-20 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. See Table 6 and Table 6.

Table 6: ELaNa-20 High Melting Temperature Material Analysis (1/2)

CubeSat	Name	Material	Mass (kg)	Demise Alt (km)	Kenetic Energy (J)
CACTUS-1	Mounting screws	Stainless Steel (generic)	.001	77.4	0
CACTUS-1	Nuts	Stainless Steel (generic)	.000128	77.8	0
CACTUS-1	Threaded rod	Stainless Steel (generic)	.01	78.0	0
CACTUS-1	Battery case	Aluminum 7075-T6	.160	75.8	0
CAPE-3	Magnetorquers	Iron	.003156	75.8	0
CAPE-3	Separation springs	Stainless Steel (generic)	.0014	76.6	0
CAPE-3	Weight ballast	Aluminum 6061-T6	.230	72.4	0
MiTEE	Metal magnetorquer	Nickel	.058	71.0	0
MiTEE	Deployment switch	Titanium (generic)	.0000005	78.0	0
MiTEE	Boom housing	Aluminum 6061-T6	.148	74.4	0
MiTEE	Langmuir probe	Titanium (generic)	.001	0.0	0
MiTEE	Antenna mounting probe	Aluminum 6061-T6	.158	74.7	0

Table 7: ELaNa-20 High Melting Temperature Material Analysis (2/2)

CubeSat	Name	Material	Mass (kg)	Demise Alt (km)	Kenetic Energy (J)
RadFXSat-2	PCB standoffs	Aluminum 6061-T6	.0005	77.5	0
PICS	Camera lens housing	Stainless Steel (generic)	.004	0.0	0
PICS	Antenna hinge 1	Aluminum 7075-T6	.00013	78.0	0
PICS	Antenna hinge 2	Aluminum 7075-T6	.00013	77.9	0
PICS	Bracket	Aluminum 6061-T6	.01018	76.9	0
INCA	Detector lid	Aluminum 6061-T6	.026	78.0	0
MicroMAS-2b	Payload balance ring	Aluminum 6061-T6	.166	75.9	0
MicroMAS-2b	Payload ballast	Tungsten	.001	0.0	3
MicroMAS-2b	Scanner housing	Titanium (generic)	.388	0.0	240
EXOCUBE	Reaction wheel	Aluminum 6061-T6	.0122	77.2	0
EXOCUBE	Battery bracket	Aluminum 6061-T6	.09325	76.1	0
EXOCUBE	Tip mass brackets	Aluminum 7075-T6	.001558	77.9	0
EXOCUBE	Rough pass through	Aluminum 7075-T6	.04905	74.8	0
EXOCUBE	Boom hinge	Aluminum 6061-T6	.00256	77.7	0
PolarCube	Battery bracket	Aluminum 6061-T6	.018	77.2	0
PolarCube	Star camera bracket	Aluminum 6061-T6	.0153	77.2	0
PolarCube	Isolator plate	Aluminum 6061-T6	.040	76.9	0
PolarCube	Frangibolt assembly	Aluminum 6061-T6	.0117	0.0	3
SHFT-2	ADCS	Aluminum 6061-T6	.895	68.3	0
SHFT-2	rails	Aluminum 7075-T6	.00399	77.9	0
TechEdSat-7 has no surviving components and can be seen inspected in Appendix					
Prometheus	Hinges	Stainless Steel (304)	0.04	0.0	2
Prometheus	Hinge Pins	Stainless Steel (304)	0.01912	77.4	0
Prometheus	SFS 1 to 1 Cable	Stainless Steel (304)	0.00357	77.5	0
Prometheus	Wheels & Pin Block	Stainless Steel (304)	0.2804	65.9	0

Table 8: ELaNa-20 Summary of Surviving High Temperature Material Components

CubeSat	Name	Material	Mass (g)	Demise Alt (km)	Kinetic Energy (J)
MiTEE	Langmuir probe	Titanium (generic)	.001	0	9
PICS	Camera lens housing	Stainless Steel (generic)	.004	0.0	0
MicroMAS-2b	Payload ballast	Tungsten	.001	0.0	3
MicroMAS-2b	Scanner housing	Titanium (generic)	.388	0.0	240
PolarCube	Frangibolt assembly	Aluminum 6061-T6	.0117	0.0	3
Prometheus	Hinges	Stainless Steel (304)	0.04	0.0	2

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 9: Requirement 4.7-1 Compliance by CubeSat

Name	Status	Risk of Human Casualty
CACTUS-1	Compliant	1:0
CAPE-3	Compliant	1:0
Q-PACE	Compliant	1:0
MiTEE	Compliant	1:0
RadFXSat-2	Compliant	1:0
PICS	Compliant	1:0
INCA	Compliant	1:0
MicroMAS-2b	Compliant	1:198200
EXOCUBE	Compliant	1:0
PolarCube	Compliant	1:0
TechEdSat-7	Compliant	1:0
Prometheus	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 CubeSats that have surviving components like MiTEE, PICS have a 1:0 probability as none of their components have more than 15J of energy. MicroMAS-2 has 1 component with greater than 15J of energy but the CubeSat's probability of risk of human casualty still exceeds the NASA requirement on an order of magnitude

All CubeSats launching under the ELaNa-20 mission are shown to be in compliance with Requirement 4.7-1 of NASA-STD-8719.14A.

Section 8: Assessment for Tether Missions

ELaNa-20 CubeSats will not be deploying any tethers.

ELaNa-20 CubeSats satisfy Section 8's requirement 4.8-1.

Section 9-14

ODAR sections 9 through 14 for the launch vehicle are not covered here.

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

/original signed by/

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Flight Design Analyst
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cc: VA-H/Mr. Carney
VA-H1/Mr. Beaver
VA-H1/Mr. Haddox
VA-G2/Mr. Treptow
SA-D2/Mr. Frattin
SA-D2/Mr. Hale
SA-D2/Mr. Henry
Analex-3/Mr. Davis
Analex-22/Ms. Ramos

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Appendix A. ELaNa-20 Component List by CubeSat: CACTUS-1

CUBESAT	Item Number	Name	Qty	Material	Body Type	Mass (g) (total)	Diameter / Width (mm)	Length (mm)	Height (mm)	High Temp	Melting Temp (F°)	Survivability
CACTUS-1	1	CACTUS - 1 3U Cubesat	1	-	Box	2838.193	-	-	-	-	-	-
CACTUS-1	2	Aerogel Monolith	2	Silica Aerogel	Box	7	50.8	50.8	12.7	No	-	Demise
CACTUS-1	3	Tab Base	1	Aluminum 7075	Flat Plate	296	113	364	3.5	No	-	Demise
CACTUS-1	4	Frame	1	Aluminum 7075	Box	391	101.5	364	100	No	-	Demise
CACTUS-1	5	End Mount (Comms side)	1	Aluminum 7075	Flat Plate	43	97	98.5	13.5	No	-	Demise
CACTUS-1	6	Hermes End Mount (Antenna)	1	Aluminum 7075	Flat Plate	44	97	98.5	13.5	No	-	Demise
CACTUS-1	7	Tape Antenna	2	Steel	Flat Plate	12.8	25.4	32	3	No	-	Demise
CACTUS-1	8	Aerogel Capture Bay (ACB)	2	Aluminum 7075	Box	160	75.54	125.54	42.2	No	-	Demise
CACTUS-1	9	Battery Case	1	Aluminum 7075	Box	99	86.74	91.2	39	Yes	-	Demise
CACTUS-1	10	Battery Case Lid / Burn Box	1	Aluminum 7075	Box	73	90.74	91.2	32	Yes	-	Demise
CACTUS-1	11	End Mount (ACB side)	1	Aluminum 7075	Box	44	97	98.5	13.5	No	-	Demise
CACTUS-1	12	Hermes End Mount (Interior)	1	Aluminum 7075	Flat Plate	44	97	98.5	13.5	No	-	Demise
CACTUS-1	13	RASC Locks	4	Aluminum 7075	Flat Plate	28	12	125.54	16.5	No	-	Demise
CACTUS-1	14	Batteries	7	Li-Ion	Cylinder	350	18.4	64.8	-	No	-	Demise
CACTUS-1	15	Pointing Magnet	1	NdFeB grade 42	Cylinder	20	9.525	38.1	-	No	-	Demise
CACTUS-1	16	Mounting Screws M3 x (4, 6, 8, 10)	64	Stainless Steel	Cylinder	64	3	Varies (4, 6, 8, 10)	-	Yes	2642°	Demise
CACTUS-1	17	Solar Panel PCB (Top and Bottom)	2	PCB FR-4	Flat Plate	156	100	264	1.6	No	-	Demise
CACTUS-1	18	Solar PCB (Left, Right Side)	2	PCB FR-4	Flat Plate	48	90	91	1.6	No	-	Demise
CACTUS-1	19	Small Solar PCB (Left, Right Side)	2	PCB FR-4	Flat Plate	22	40	90	1.6	No	-	Demise
CACTUS-1	20	Hermes Solar PCB (Sides)	2	PCB FR-4	Flat Plate	26	50	90	1.6	No	-	Demise
CACTUS-1	21	Hermes Solar PCB (Bottom)	1	PCB FR-4	Flat Plate	25	86.5	100	1.6	No	-	Demise
CACTUS-1	22	Antenna PCB	1	PCB FR-4	Flat Plate	18	60	97	1.6	No	-	Demise
CACTUS-1	23	Hermes Solar PCB (Top)	1	PCB FR-4	Flat Plate	15	50	100	1.6	No	-	Demise

CACTUS-1	24	Hermes Helix Antenna	1	Varies	Cylinder	14	18	48	-	No	-	Demise
CACTUS-1	25	Mylar Support Wire	4	Steel	Cylinder	6	1	72.54	-	No	-	Demise
CACTUS-1	26	Solar Panels	454	Solar Cell	Flat Plane	79.5	8	26.3	0.16	No	-	Demise
CACTUS-1	27	Nylon String (Antenna)	1	Nylon	Wire	0.15	1.0	Est. 330-380	-	No	-	Demise
CACTUS-1	28	Mylar sheets	N/A	PET Mylar	Flat Plate	1	N/A	N/A	0.01	No	-	Demise
CACTUS-1	29	M3 Weld Nuts	56	Stainless steel	Cylinder	56	7.5	3	-	Yes	2642°	Demise
CACTUS-1	30	M2 x (4,8) mm Screws	12	Stainless steel	Cylinder	12	2	Varies (4, 8)	-	No	-	Demise
CACTUS-1	31	Threaded Rod 1	2	Stainless Steel	Cylinder	10	3	95.4	-	No	-	Demise
CACTUS-1	32	Threaded Rod 2	2	Stainless steel	Cylinder	10	3	93.4	-	No	-	Demise
CACTUS-1	33	M3 Nuts	16	Stainless steel	Cylinder	8	5.5	2.4	-	Yes	2642°	Demise
CACTUS-1	34	M2 Nuts	8	Stainless steel	Cylinder	4	4.5	1.6	-	Yes	2642°	Demise
CACTUS-1	35	Hysteresis Rods	2	Permalloy 80	Cylinder	14	2	95	-	No	-	Demise
CACTUS-1	36	Bus Insulation (Top, Left, Right)	3	Aerogel Blanketing	Flat Plate	18	84.4	97	2	No	-	Demise
CACTUS-1	37	Battery Insulation (Front, Back)	2	Aerogel Blanketing	Flat Plate	10	80.2	82.74	2	No	-	Demise
CACTUS-1	38	Bus Insulation (Back)	1	Aerogel Blanketing	Flat Plate	6	93.5	95	2	No	-	Demise
CACTUS-1	39	Bus Insulation (Front)	1	Aerogel Blanketing	Flat Plate	6	88.5	93.5	2	No	-	Demise
CACTUS-1	40	Bus Insulation (Bottom)	1	Aerogel Blanketing	Flat Plate	5	84.4	97	2	No	-	Demise
CACTUS-1	41	Insulation packer (Battery Top and Bottom)	2	Aerogel Blanketing	Flat Plate	4	26.1	82.74	2	No	-	Demise
CACTUS-1	42	Insulation Packet (Battery sides)	2	Aerogel Blanketing	Flat Plate	2	26.1	80.2	2	No	-	Demise
CACTUS-1	43	RASC W/ coatings	2	PLA Plastic, RTV	Box	112	56	69	26.8	No	-	Demise
CACTUS-1	44	Hermes Battery Mount	2	ABS plastic	Box	35.2	22.25	73	21.5	No	-	Demise
CACTUS-1	45	Cactus Plastic Battery Housing	1	Thermoplastic Polyester, Aluminum	Box	26	76.2	78.74	22.1	No	-	Demise
CACTUS-1	46	Coaxial Cable	1	Copper, Plastic, Polyethylene	Wire	2	5	40	-	No	-	Demise
CACTUS-1	47	Wiring	N/A	28 AWG, Copper, Teflon	Cylinder	35	1.5	N/A	-	No	-	Demise
CACTUS-1	48	Solder	1	Tin/Lead	N/A	10	N/A	N/A	N/A	No	-	Demise

CACTUS-1	49	Nichrome Burn Wire	1	Nichrome	Rod / wire	0.003	0.16	200	-	No	-	Demise
CACTUS-1	50	TTL- jpeg camera	2	PCB FR4, Glass, Plastic	Block ?	22.3	32	32	24.75	No	-	Demise
CACTUS-1	51	BUS Boards (Power, Comms, Sensor, CPU)	4	PCB FR-4, Surface Mount Components	Flat Plane	248	90.17	95.885	12.75	No	-	Demise
CACTUS-1	52	Hermes Electrical PCB	1	PCB FR-4, Surface Mount Components	Flat Plane	25.4	90.17	95.88	1.6	No	-	Demise
CACTUS-1	53	Hermes Iridium Modem 9603	1	PCB FR-4, Surface Mount Components	Block	31	35.75	61	12.5	No	-	Demise
CACTUS-1	54	Hermes Raspberry Pi 0	1	PCB FR-4, Surface Mount Components	Flat Plane	11	31	65	4.5	No	-	Demise
CACTUS-1	55	Raspberry Pi Compute Module	1	PCB FR-4, Surface Mount Components	Flat Plane	5.76	30	67.6	1	No	-	Demise
CACTUS-1	56	5 mm LED (Dimensions not including wires)	4	Generic LED	Cylinder	1.08	5	5.6	-	No	-	Demise
CACTUS-1	57	Foot Switch	2	Plastic, steel	Box	2	15.2	20.1	6.4	No	-	Demise
CACTUS-1	58	734 RTV conformal coating (Electronics)	.75 Fluid oz.	Silicone Rubber MIL-A-46106	N/A	N/A	N/A	N/A	N/A	No	-	Demise
CACTUS-1	59	3145 RTV conformal coating (Structure)	.75 Fluid oz.	Silicone Rubber MIL-A-46146	N/A	N/A	N/A	N/A	N/A	No	-	Demise
CACTUS-1	60	Double Sided Tape	N/A	Polyimide Kapton	Flat Plate	12	N/A	N/A	0.01	No	-	Demise
CACTUS-1	61	Nylon spacer 16 mm	8	Nylon 66	Cylinder	4	4.5	16	-	No	-	Demise
CACTUS-1	62	Nylon spacer 18 mm	8	Nylon 66	Cylinder	4	4.5	18	-	No	-	Demise
CACTUS-1	63	Nylon spacer 14 mm	4	Nylon 66	Cylinder	2	4.5	14	-	No	-	Demise
CACTUS-1	64	Nylon spacer 22 mm	4	Nylon 66	Cylinder	2	4.5	22	-	No	-	Demise
CACTUS-1	65	Nylon spacer 19mm	4	Nylon 66	Cylinder	2	4.5	19	-	No	-	Demise
CACTUS-1	66	Nylon M3 Nut	2	Nylon 66	Cylinder	1	5.5	2.4	-	No	-	Demise

Appendix B. ELaNa-20 Component List by CubeSat: CAPE-3

CUBESAT	Item Number	Name	Qty	Material	Body Type	Mass (g) (total)	Diameter / Width (mm)	Length (mm)	Height (mm)	High Temp	Melting Temp (F°)	Survivability
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CAPE-3	0	CubeSat	1	Aluminum 6061	Cube	1330	100	113.5	100	No	-	Demise
CAPE-3	1	Frame	1	Aluminum 6061	Cube	180	100	113.5	100	No	-	Demise
CAPE-3	2	Battery Cells	4	Lithium Ion	Cylinder	45	26	70	n/a	No	-	Demise
CAPE-3	3	Solar Cells	12	Crystalline Silicon	Flat Plate	2.24	39.5	68.9	n/a	No	-	Demise
CAPE-3	4	Deployment Switches	2	Silver alloy gold plated	Box	0.28	6.1	8.1	2.7	No	-	Demise
CAPE-3	5	RBF Pin	1	Stainless Steel	Cylinder	n/a	n/a	n/a	n/a	No	-	Demise
CAPE-3	6	Screws/Bolts	X	Stainless Steel	Cylinder	0.6	3	11	n/a	No	-	Demise
CAPE-3	7	Long Antenna	4	Nitinol	Thin wire	0.87	0.5	508	n/a	No	-	Demise
CAPE-3	8	Short Antenna	4	Nitinol	Thin wire	0.25	0.5	178	n/a	No	-	Demise
CAPE-3	9	Antenna Platforms	2	Delrin	Flat Plate	40	100	100	6	No	-	Demise
CAPE-3	10	Motherboard	1	PCB	Flat Plate	40	97	97	1.6	No	-	Demise
CAPE-3	11	Comm board	2	PCB	Flat Plate	40	97	97	1.6	No	-	Demise
CAPE-3	12	Comm board	1	PCB	Flat Plate	40	97	97	1.6	No	-	Demise
CAPE-3	13	Battery Board	1	PCB	Flat Plate	30	97	97	1.6	No	-	Demise
CAPE-3	14	Power Board	1	PCB	Flat Plate	40	97	97	1.6	No	-	Demise
CAPE-3	15	Exterior PCBs	4	PCB	Flat Plate	30	97	97	1.6	No	-	Demise
CAPE-3	16	Separation Springs	2	Stainless Steel	Cylinder	1.4	0.07	0.6	n/a	Yes	2642°	Demise
CAPE-3	17	Cabling/wiring	X	copper, rubber	wire	variable	variable	variable	variable	No	-	Demise
CAPE-3	18	Cell Housing	1	Cotton lacing cord	Rectangular	n/a	2.38	n/a	0.397	No	-	Demise
CAPE-3	19	PCB Connecting Rods	4	Stainless Steel	Cylindrical Rod	6	3	100	n/a	No	-	Demise
CAPE-3	20	Mezzanine Connectors	10	Thermoplastic	Rectangle	1.163	8	51.5	4.86	No	-	Demise
CAPE-3	21	Reaction Wheel	1	DC Motor	Cube	55	28	31	26	No	-	Demise
CAPE-3	22	Magnetorque Core	2	Iron	Cylindrical	3.156	3.2	50	n/a	Yes	2800°	Demise
CAPE-3	23	Magnetorque Wire	2	Copper Wire	Wire	0.318	0.12	7854	n/a	No	-	Demise
CAPE-3	24	Control Board	1	PCB	Square	45	97	97	1.6	No	-	Demise
CAPE-3	25	Payload Board	1	PCB	Square	50	97	97	1.6	No	-	Demise

CAPE-3	26	Crystals	2	Triboluminescent	Paste	variable	variable	variable	variable	No	-	Demise
CAPE-3	27	Camera	1	Plastic/glass	Cylindrical	6.862	10	10	10	No	-	Demise
CAPE-3	28	Geiger Counter	1	sensor	Box	3.55	16	28	6	No	-	Demise
CAPE-3	29	LED's	2	semiconductor	Cylindrical	0.25	5	9	n/a	No	-	Demise
CAPE-3	30	Weight Ballast	X	Aluminum 6061	rectangles	230	variable	variable	variable	Yes	1205°	Demise

Appendix C. Elana-20 Component List by CubeSat: EXOCUBE

CUBESAT	Item Number	Name	Qty	Material	Body Type	Mass (g) (total)	Diameter / Width (mm)	Length (mm)	Height (mm)	High Temp	Melting Temp (F°)	Survivability
EXOCUBE	1	ExoCube++ 3U CubeSat	1	Various	Box	3864	100	100	340.5	No	-	Demise
EXOCUBE	2	CubeSat Structure	1	Black Anodized Aluminum 6061	Box	1228.87	100	100	340.5	No	-	Demise
EXOCUBE	3	Antenna	2	Nitinol Wire	Cylinder	2.7	0.15	80	N/A	No	-	Demise
EXOCUBE	4	Antenna Route	1	Delrin	Box	4.73	64.48	64.4	3.4	No	-	Demise
EXOCUBE	5	Solar Cell	24	Eglass	Box	7.45	69	40	1	No	-	Demise
EXOCUBE	6	X Panel	2	FR-4 Multilayer PCB	Box	91.67	83	289	1.6	No	-	Demise
EXOCUBE	7	Y Panel	2	FR-4 Multilayer PCB	Box	87.12	83	334	1.6	No	-	Demise
EXOCUBE	8	Reaction Wheel	1	Aluminum 6061, Nitronic 60 (UNS S21800) SS, Delrin, Samarium Cobalt, SS 416	Box	122	40.64	40.64	19.05	Yes	2795°	Demise
EXOCUBE	9	Magnetorquer Route	3	Delrin	Box	3.5	82	51	4	No	-	Demise
EXOCUBE	10	Magnetorquer Wire	3	Copper	Cylinder	9	3	260	N/A	No	-	Demise
EXOCUBE	11	GPS Patch	1	Ceramic	Box	20	25.1	25.1	5.2	No	-	Demise
EXOCUBE	12	Batteries	4	Lithium Ion	Cylinder	45	19.16	66	N/A	No	-	Demise
EXOCUBE	13	Battery Bracket	1	Aluminum 6061	Box	93.25	81	89.85	28.15	Yes	1205°	Demise
EXOCUBE	14	-Z System Board w/ Components	1	FR-4 Multilayer PCB	Box	60	83	100	13.8	No	-	Demise
EXOCUBE	15	-Z Payload Interface and Battery Board	1	FR-4 Multilayer PCB	Box	50	83	83	3	No	-	Demise
EXOCUBE	16	+Z Payload Extension Board	1	FR-4 Multilayer PCB	Box	50	83	83	5.15	No	-	Demise
EXOCUBE	17	+Z Panel	1	FR-4 Multilayer PCB	Box	30	100	100	2.5	No	-	Demise
EXOCUBE	18	-Z Panel	1	FR-4 Multilayer PCB	Box	30	100	100	2.5	No	-	Demise
EXOCUBE	19	Tip Mass Brackets	2	7075-T6, Plate (SS)	Box	15.58	31.57	79.47	5	Yes	2795°	Demise
EXOCUBE	20	Rough Pass Through	1	Aluminum 6061	Cylinder	49.05	31.75	36.66	30.23	Yes	1205°	Demise
EXOCUBE	21	Heat Shrink	1	RNF-100 Polyolefin Heat Shrink	Tube	1	63.5	25.4	0.5	No	-	Demise

EXOCUBE	22	Staking Compound	1	3M Scotch Weld 2216	Rectangular	50	N/A	N/A	N/A	No	-	Demise
EXOCUBE	23	Kapton Tape	1	Kapton Tape	Tape	0	Various	Various	0.05	No	-	Demise
EXOCUBE	24	Sep/Actuating Switches	5	Plastic (PBT)	Rectangular	2	6	8	7	No	-	Demise
EXOCUBE	25	Boom Mass	2	Brass Alloy 360	Rectangular	200.69	33.5	67.8	16.8	No	-	Demise
EXOCUBE	26	Boom Truss	2	FR-4 Multilayer PCB	Box	27.3	68	299.4	2	No	-	Demise
EXOCUBE	27	Kit Kat	2	Aluminum 6061	Rectangular	3.01	11.4	28.05	5.18	No	-	Demise
EXOCUBE	28	Boom Spring	2	AISI 316 Annealed SS Bar	Cylinder	1	6.1	20	N/A	No	-	Demise
EXOCUBE	29	Screw - Representative	152	Stainless Steel 316	Cylinder	0.87	2.8	10	N/A	No	-	Demise
EXOCUBE	30	Boom Hinge	2	Aluminum 6061	Box	2.56	15	46	6.5	Yes	1205°	Demise
EXOCUBE	31	Goddard Instrument	1	FR-4 Multilayer PCB, Stainless Steel, Aluminum 6061 Chromate Conversion, Ultem,	Box	400	74	75	1.59	No	-	Demise
EXOCUBE	32	GPS Board	1	FR-4 Multilayer PCB	Box	24	45.72	71.12	11.09	No	-	Demise
EXOCUBE	33	Battery Board	1	FR-4 Multilayer PCB	Box	50	58.51	78.51	8.12	No	-	Demise
EXOCUBE	34	Solar Angle Sensor Board	4	FR-4 Multilayer PCB	Box	20	20	30	1.6	No	-	Demise

Appendix D. Elana-20 Component List by CubeSat: INCA

CUBESAT	Item Number	Name	Qty	Material	Body Type	Mass (g) (total)	Diameter / Width (mm)	Length (mm)	Height (mm)	High Temp	Melting Temp (F°)	Survivability
INCA	2	Deployable Solar Panels	1	Aluminum 7075	Box	154	100	341.8	100	No	-	Demise
INCA	3	Fixed Solar Panels	4	PCB	Flat Plate	39.4	82	332	3	No	-	Demise
INCA	4	Neutron Detector Case	4	PCB	Flat Plate	40	82	250	3	No	-	Demise
INCA	5	Neutron Detector Lid	1	Aluminum 6061	Box	855	88	223	86	Yes	1205°	Demise
INCA	6	Scintillators Crystals	1	Aluminum 6061	Flat Plate	26	88	223	3	No	-	Demise
INCA	7	Scintillators Holders	2	P-Terfinal	Cylinder	966	51		42	No	-	Demise
INCA	8	Veto Boards	2	Aluminum	Box	245	72	72	76	No	-	Demise
INCA	9	Battery Pack	4	EJ-212	Flat Plate	235	69	219	3	No	-	Demise
INCA	10	Beagle Bone	1	Aluminum 6061 and Lithium	Box	247				No	-	Demise
INCA	11	Link Star Radio	1	PCB	Flat plate	40	86	53	~10	No	-	Demise
INCA	12	Intrepid XY	1	PCB	Flat plate	unkno wn	Unknown	Unknown	Unkno wn	No	-	Demise
INCA	13	Novatel OEM-615 GPS	4	PCB	Flat plate	32	103	83	~5	No	-	Demise
INCA	14	Intrepid Systems Board	1	PCB	Flat plate	22	71	46	12	No	-	Demise
INCA	15	Intrepid -Z	1	PCB	Flat plate	104	94	83	~2	No	-	Demise
INCA	16	Sun Sensor	1	PCB	Flat plate	96	91	91	~5	No	-	Demise
INCA	17	Miscellaneous Nuts and Screws	1	PCB	-	-	-	-	-	No	-	Demise
INCA	18	Missilaneous Wires	Unknown	Steel	-	-	-	-	-	No	-	Demise

Appendix E. Elana-20 Component List by CubeSat: MicroMAS-2b

CUBESAT	Item Number	Name	Qty	Material	Body Type	Mass (g) (total)	Diameter / Width (mm)	Length (mm)	Height (mm)	High Temp	Melting Temp (F°)	Survivability
MicroMAS-2b	1	Payload Antenna/Gband Mixer	1	Al 6061	Box	115	80		20	No	-	Demise
MicroMAS-2b	2	Payload G RFE	1	Al, Au coated	Box	30	80	50	30	No	-	Demise
MicroMAS-2b	3	Payload W/F RFE	1	Al, Au coated	Box	42				No	-	Demise
MicroMAS-2b	4	IF Processor	1	PCB FR4, Dupont 9K7 LTCC	Box	118	68	58	25	No	-	Demise
MicroMAS-2b	5	Payload Interface Module	1	PCB FR4	Board	16	70	60	10	No	-	Demise
MicroMAS-2b	6	Payload Voltage Regulator Module	1	PCB FR4	Board	20	65	35	10	No	-	Demise
MicroMAS-2b	7	Payload Dielectric Resonant Oscillator	1		Box	54	32	41	16	No	-	Demise
MicroMAS-2b	8	Payload Heaters/Thermostat	1	stainless steel, hermetically sealed dry nitrogen	Cylinder	10	16	-	13	No	-	Demise
MicroMAS-2b	9	Payload Structures, fasteners	n/a	Al 6061 passivated; tungsten; fasteners: stainless steel 304L	Various plates	275	100	100	100	No	6191°	Survives
MicroMAS-2b	10	Payload Harnesses	n/a		Cables	40	-	-	-	No	-	Demise
MicroMAS-2b	11	Payload Balance Ring	1	Al 6061	Various plates	166	80	-	10	Yes	1205°	Demise
MicroMAS-2b	12	Payload Ballast	10	tungsten	screw	1	3	25		Yes	6191°	Survives
MicroMAS-2b	13	Bus Avionics TIB/Gyro	1	PCB: FR4	Board	111	96	90	16	No	-	Demise
MicroMAS-2b	14	Bus Avionics Processor	1	PCB: FR4	Board	104	96	90	11	No	-	Demise
MicroMAS-2b	15	Bus Avionics BIB	1	PCB: FR4	Board	54	96	90	8	No	-	Demise
MicroMAS-2b	16	Bus Avionics Radio	1	Housing: Al	Board	138	68	79	15	No	-	Demise

MicroMAS-2b	17	Bus Radio UHF Filter	1		Box	36	35	14	10	No	-	Demise
MicroMAS-2b	18	Bus Radio UHF Antenna	1	Antenna: spring steel; cables: FEP	Plate	30	8	178	-	No	-	Demise
MicroMAS-2b	19	Bus Avionics EPS	1	PCB: FR4	Board	150	90	85	11	No	-	Demise
MicroMAS-2b	20	Bus Avionics Battery	1	PCB: FR4; cells: Li cobalt oxide	Board	173	95	86	15	No	-	Demise
MicroMAS-2b	21	Bus Avionics ADCS Housing	1	Housing: Al 6061; MQT: electromagnet ferrite 66; PCB: FR4	Box	638	100	100	56	No	-	Demise
MicroMAS-2b	22	Bus Avionics ADCS reaction wheels	3	Neodymium magnet, stainless steel case, ceramic balls	Box	160	40	20	20	No	-	Demise
MicroMAS-2b	23	Bus Solar Panel Assembly	4	PCB: FR4 PCB; cells: GaInP2/GaAs/Ge; Hinges: Al 6082	Board	250	82	326	1.6	No	-	Demise
MicroMAS-2b	24	Bus Solar Panel Harness Set	1	PTFE	Cables	30	-	-	-	No	-	Demise
MicroMAS-2b	25	Bus Thermal Control	1	RTD: alumina; Wires: PTFE	Cable	50	-	-	-	No	-	Demise
MicroMAS-2b	26	Bus Housing Assembly, fasteners	1	Rails: Al 7075 anodized; Sides: Al 6061 alodined; Fasteners: stainless steel 304L	Various plates	328	-	200	90	No	-	Demise
MicroMAS-2b	27	Bus Wiring	n/a	ETFE-SB	Cables	39	-	-	-	No	-	Demise
MicroMAS-2b	28	Scanner Housing	1	Housing, shaft: Al 6061; Hub: titanium; Bearings: stainless steel balls, Braycote 601 lubricant; Encoder grating: soda lime glass	Cylinder	388	73	-	42	Yes	3034°	Survives
MicroMAS-2b	29	Scanner Motor	1	Rotor: stainless steel 455; Stator: neodymium boron iron magnet	Cylinder	163	68	-	25	No	-	Demise

Appendix F. ELaNa-20 Component List by CubeSat: MITEE

CUBESAT	Item Number	Name	Qty	Material	Body Type	Mass (g) (total)	Diameter / Width (mm)	Length (mm)	Height (mm)	High Temp	Melting Temp (F°)	Survivability
MiTEE	1	MiTEE 3U Cubesat	-	-	-	-	-	-	-	-	-	-
MiTEE	2	CubeSat Main Walls	2	6061 Aluminum	Box	98	100	10	340	No	-	Demise
MiTEE	3	Cubesat Side Walls	2	6061 Aluminum	Box	290	100	10	340	No	-	Demise
MiTEE	4	Langmuir Probe	1	Oriented Rhenium, Titanium, Molybdeum	Cylinder	50	4	53	4	Yes	3034°	Yes
MiTEE	5	Langmuir Probe Deployment Mechanism	1	6061 Aluminum	Hinge	10	12	95	15	No	-	Demise
MiTEE	6	Antennae	4	302 Steel	Tape	20	1.5	17	1	No	-	Demise
MiTEE	7	Radio Board	1	PCB	Board	60	93	97	10	No	-	Demise
MiTEE	8	Radio	1	Aluminum	Box	52	32	62	9	No	-	Demise
MiTEE	9	Langmuir Probe Board	1	PCB	Board	60	93	97	16	No	-	Demise
MiTEE	10	Metal Core Magnetorquer	2	Nickel-Alloy	Cylinder	58	25	55	13	Yes	2651°	Demise
MiTEE	11	Air Core Magnetorquer	1	PLA	Square Coil	58	70	70	20	No	-	Demise
MiTEE	12	Magnetorquer Board	1	PCB	Board	18	93	97	35	No	-	Demise
MiTEE	13	ADCS PCB	1	PCB	Board	60	93	97	13	No	-	Demise
MiTEE	14	CDH PCB	1	PCB	Board	60	93	97	8	No	-	Demise
MiTEE	15	EPS/Plasma PCB	1	PCB	Board	60	93	97	8	No	-	Demise
MiTEE	16	EPS Battery PCB	1	PCB	Board	430	93	97	35	No	-	Demise
MiTEE	17	Batteries	4	Lithium Ion	Cylinder	45	18	65	18	No	-	Demise
MiTEE	18	HVPS PCB	1	PCB	Board	75	93	97	16	No	-	Demise
MiTEE	19	Constant Current Power Supply PCB	1	PCB	Board	68	93	97	19	No	-	Demise
MiTEE	20	Thermionic Cathode	2	Stainless Steel ¹	Concave Repellor	5	10	13	9	No	-	Demise
MiTEE	21	Boom Tape	4	Stainless Steel	Tape	0.7	20	1	50	No	-	Demise

MiTEE	22	Boom Housing	1	6061-T6 Aluminum	Box	148	60.5	50	41.8	Yes	1205°	Demise
MiTEE	23	Anode End Body	1	6061 Aluminum	Box	50	80	80	20	No	-	Demise
MiTEE	24	Deployment Switch	2	Titanium	Cylinder	2	5	5	26	Yes	3034°	Demise
MiTEE	25	Solar Panel PCB	4	PCB	Board	138	80	340	2	No	-	Demise
MiTEE	26	Solar Cell	24	InGaP/InGaAs/Ge Solar Cell	Flat Cell	3	80	23	0.5	No	-	Demise
MiTEE	27	Photodiode	13	Silicon	Sensor	1	1	3	0.4	No	-	Demise
MiTEE	28	Backplane PCB	1	PCB	Board		62	200	2	No	-	Demise
MiTEE	29	Backplane Connectors	18	Polyester and Copper	Header Connector	1	6	23	8	No	-	Demise
MiTEE	30	Fasteners	70	Stainless Steel	Bolt	< 1	5	5	Various	No	-	Demise
MiTEE	31	Cabling	4	Copper	Cylinder	1	2	10	2	No	-	Demise
MiTEE	32	Wedgelocks	18	6063 Aluminum	Box	2	6	74	6	No	-	Demise
MiTEE	33	Antenna Mounting Plate	1	6061 Aluminum	Plate	158	100	100	19	Yes	1205°	Demise

Appendix G. ELaNa-20 Component List by CubeSat: PICS

CUBESAT	Item Number	Name	Qty	Material	Body Type	Mass (g) (total)	Diameter / Width (mm)	Length (mm)	Height (mm)	High Temp	Melting Temp (F°)	Survivability
PICS	1	PICs-A/B Identical 1U CubeSats	1	Aluminum 6061	Box	1209.4	116	116	116	No	-	Demise
PICS	2	CubeSat Structure	1	Aluminum 6061	Box	330	102.5	100	110	No	-	Demise
PICS	3	Antennae	4	Copper 101	Cylinder	4.5	3	69	-	No	-	Demise
PICS	4	Solar Harvester Board	6	Fiberglass FR4	Box	35	83	100	2	No	-	Demise
PICS	5	Solar Cell	12	GaAs	Box	2.2	40	69	0.14	No	-	Demise
PICS	6	Separation Switch	2	PBT	Box	3	13	7	6	No	-	Demise
PICS	7	Separation Spring	2	Steel	Cylinder	3	3	13	-	No	-	Demise
PICS	8	Camera Lens	6	Glass	Cylinder	3	14	8	-	No	-	Demise
PICS	9	Camera Lens Housing	6	Stainless Steel	Cylinder	4	19	4	-	Yes	2642°	Yes
PICS	10	Antenna Hinge Side 1	4	Aluminum 7075	Box	3	26.5	6	6	Yes	1205°	Demise
PICS	11	Antenna Hinge Side 2	4	Aluminum 7075	Box	3	13.8	5.7	4.45	Yes	1205°	Demise
PICS	12	Antenna Hinge Spring	4	Stainless Steel 301	Cylinder	1	6	4	-	No	-	Demise
PICS	13	Antenna Inhibit Wire	4	Nylon	Wire	1	0.3048	10	-	No	-	Demise
PICS	14	Antenna Deployment Burn Wire	4	Nichrome	Wire	1	0.0762	7	-	No	-	Demise
PICS	15	CubeSat Feet	8	Aluminum 6061	Box	1.25	8	8.5	8.5	No	-	Demise
PICS	16	Bracket	4	Aluminum 6061	Box	10.18	60	8	8	Yes	1205°	Demise
PICS	17	Camera Mount	6	Aluminum	Box	14.6	4	50	48.4	No	-	Demise
PICS	18	Mounting Rods	4	Aluminum 1100-O	Cylinder	1	2.4	72	-	No	-	Demise
PICS	19	Hex Standoff	8	Aluminum	Cylinder	1	5.5	15.5	-	No	-	Demise
PICS	20	Solar Harvester Connectors	6	Nylon 66	Box	0.218	3.2	15.5	4.2	No	-	Demise
PICS	21	Camera	6	Fiberglass FR4	Box	25	35	25	22	No	-	Demise
PICS	22	Camera Housing	6	Aluminum	Box	15	16	16	16	No	-	Demise

PICS	23	Camera Board	6	Fiberglass FR4	Box	10	35	25	1.65	No	-	Demise
PICS	24	Radio	1	Fiberglass Isola FR408	Box	50	45	45	8	No	-	Demise
PICS	25	Antenna Board	1	Fiberglass FR4	Box	15	88	88	1.65	No	-	Demise
PICS	26	Battery Boards	4	Fiberglass FR4	Box	10	51	51	2	No	-	Demise
PICS	27	C&DH Board	1	Fiberglass FR4	Box	40	88	88	3	No	-	Demise
PICS	28	FPGA SoM	1	Fiberglass FR4	Box	11	30	57	1.6	No	-	Demise
PICS	29	Phillips Screw with Lock Washer	20	Stainless Steel 18-8	Cylinder	0.24	4.7	6.3	-	No	-	Demise
PICS	30	Phillips Screw with Lock Washer	18	Stainless Steel 18-8	Cylinder	0.27	4.7	7.9	-	No	-	Demise
PICS	31	Flat Head Phillips Screw	16	Stainless Steel 18-8	Cylinder	0.35	5.4	8	-	No	-	Demise
PICS	32	Metric Phillips Machine Screw	4	Stainless Steel 18-8	Cylinder	0.02	3.2	11.3	-	No	-	Demise
PICS	33	Zinc Plated Steel Hex Nut	1	Steel, Class 8, Zinc Plated	Cylinder	0.04	3.7	1.3	-	No	-	Demise
PICS	34	Metric Flat Head Phillips Machine Screw	4	Steel, Zinc Plated	Cylinder	0.193	4.7	5	-	No	-	Demise
PICS	35	Metric Cheese Head Slotted Machine Screw	4	Steel, Zinc Plated	Cylinder	0.074	2.6	5.9	-	No	-	Demise
PICS	36	Socket Head Cap Screw	24	Steel, Black Oxide Alloy	Cylinder	0.13	3	6.6	-	No	-	Demise
PICS	37	Wires	180	Copper	Wire	0.03	0.321	40	-	No	-	Demise
PICS	38	Thermal Strap/Sink	3	Aluminum 6061	Box	3	30	5	-	No	-	Demise
PICS	39	Batteries	4	LiPo	Box	17	34	48	5.5	No	-	Demise
PICS	40	Passive Electro-magnetic Stabilization Coils	5	Copper	Cylinder	4	5	30		No	-	Demise
PICS	41	Camera Connectors	6	Nylon 66	Box	0.2002	3.2	14.25	4.2	No	-	Demise

Appendix H.

ELaNa-20 Component List by CubeSat: POLARCUBE

CUBESAT	Item Number	Name	Qty	Material	Body Type	Mass (g) (total)	Diameter / Width (mm)	Length (mm)	Height (mm)	High Temp	Melting Temp (F°)	Survivability
POLARCUBE	1	PolarCube 3U CubeSat	1	Aluminum 6061	Box	-	-	-	-	No	-	Demise
POLARCUBE	2	Bus Deployed Solar Panel	4	FR-4, GaAs	Plate	75	84	340	2	No	-	Demise
POLARCUBE	3	Bus Exo-Frame (Rails)	4	Aluminum 6061	Plate	55.9	98.5	340.5	8.5	No	-	Demise
POLARCUBE	4	Bus Exo-frame Solar Panel	4	FR-4, GaAs	Plate	55	84	340	2	No	-	Demise
POLARCUBE	5	Bus X PEZ Frame	2	Aluminum 6061	Plate	35.4	82.5	165.1	6.1	No	-	Demise
POLARCUBE	6	Bus Y PEZ Frame	2	Aluminum 6061	Plate	27.7	82.5	165.1	13.3	No	-	Demise
POLARCUBE	7	Payload PEZ Frame	4	Aluminum 6061	Plate	79	82.5	195.1	13.3	No	-	Demise
POLARCUBE	8	Payload Reflector	1	Aluminum 6061	Disk	40	94.56	75.69	34.99	No	-	Demise
POLARCUBE	9	Payload Reflector Housing	1	Aluminum 6061	Plate	45	72.09	69.43	20.32	No	-	Demise
POLARCUBE	10	Payload Deployment Rail	1	Steel	Rod	37.69	7	158.88	5	No	-	Demise
POLARCUBE	11	Bus Tx Antenna	1	Brass, FR-4	Can	13	60	32.6	-	No	-	Demise
POLARCUBE	12	Bus Rx Antenna Bracket	2	Aluminum 6061	Block	7.4	22	26	10	No	-	Demise
POLARCUBE	13	Bus solar panel hinge	12	Steel 304	Plate	3.4	7.8	31.8	3	No	-	Demise
POLARCUBE	14	Bus Rx Antenna Axle	2	FR-4, Copper	Plate	10	10	200	0.76	No	-	Demise
POLARCUBE	15	Bus Deployment Claws -Z	4	Aluminum 6061	Block	1.8	10.8	13.8	12.3	No	-	Demise
POLARCUBE	16	Bus Rx Antenna	2	Copper	Rod	1.4	1	200	-	No	-	Demise
POLARCUBE	17	Bus Deployment Claws +Z	4	Aluminum 6061	Block	0.2	6.1	8.9	8.7	No	-	Demise
POLARCUBE	18	Bus CDH board	1	FR-4, Copper	Plate	62	74.2	169.2	11.6	No	-	Demise
POLARCUBE	19	Bus EPS Main board	1	FR-4, Copper	Plate	56	78.3	82.5	12.4	No	-	Demise
POLARCUBE	20	Bus COM RF board	1	FR-4, Copper	Plate	50	78.3	82.5	11.3	No	-	Demise
POLARCUBE	21	Bus EPS Li-ion cell	4	Li-Ion	Rod	46	18.4	66.5	-	No	-	Demise
POLARCUBE	22	Bus ACS Main board	1	FR-4, Copper	Plate	45	78.3	82.5	5.1	No	-	Demise
POLARCUBE	23	Bus COM Digital board	1	FR-4, Copper	Plate	44	78.3	82.5	8.7	No	-	Demise

POLARCUBE	24	Bus Reaction Wheel	3	Aluminum 6061	Disk	21.2	57.2	5.1	-	No	-	Demise
POLARCUBE	25	Bus ACS Star Camera board	1	FR-4, Copper	Plate	25	44.5	82.6	6.3	No	-	Demise
POLARCUBE	26	Bus GPS board	1	FR-4, Copper	Plate	18	46	71	13	No	-	Demise
POLARCUBE	27	Bus EPS battery bracket	2	Aluminum 6061	Box Frame	18	26.5	80.7	12	Yes	1205°	Demise
POLARCUBE	28	Bus Star Camera Bracket	1	Aluminum 6061	Plate	15.3	22	82.5	10.5	Yes	1205°	Demise
POLARCUBE	29	Bus ACS Motor Driver board	1	FR-4, Copper	Plate	15.2	40.6	54.6	8.7	No	-	Demise
POLARCUBE	30	Bus Magnetic Torque Rod	3	Steel, Copper	Rod	12.5	12	50	-	No	-	Demise
POLARCUBE	31	Bus RWM Bracket	3	Aluminum 6061	Plate	10.4	60	66.8	1.6	No	-	Demise
POLARCUBE	32	Payload Board Enclosures	1	Aluminum 6061	Box	277.54	86.03	103.63	50.8	No	-	Demise
POLARCUBE	33	RAD_RF_Oscillator	1	Brass	Box	176.72	28.7	60.69	22.1	No	-	Demise
POLARCUBE	34	RAD_RF_Tuner	1	Brass	Box	5	19.05	31.45	19.05	No	-	Demise
POLARCUBE	35	RAD_RF_PIN-SwitchDiode	1	Brass	Box	63	18.39	30.95	5.99	No	-	Demise
POLARCUBE	37	RAD_RF_Mixer	1	Brass	Box	72	30.48	31.75	20.32	No	-	Demise
POLARCUBE	38	Isolater Plate	1	Aluminum 6061	Plate	40	85.52	86.03	3.05	Yes	1205°	Demise
POLARCUBE	39	Payload IF Board	1	FR-4, Copper	Plate	46	66.95	103.89	8.7	No	-	Demise
POLARCUBE	40	Payload VA Board	1	FR-4, Copper	Plate	52	66.95	103.89	8.7	No	-	Demise
POLARCUBE	41	Payload Digital Board	1	FR-4, Copper	Plate	43	80.77	81.99	8.7	No	-	Demise
POLARCUBE	42	Payload Adapter Board	1	FR-4, Copper	Plate	30	73.79	73.79	8.7	No	-	Demise
POLARCUBE	43	Bus frangibolt assembly	1	Aluminum 6061, Titanium	Tube	11.7	21	25	22.8	Yes	3034°	Yes
POLARCUBE	44	Bus Star Camera Lens & Frame	1	Glass & Steel	Disk/Rod	10.8	22	18.9	-	No	-	Demise
POLARCUBE	45	Bus Star Camera Baffle	1	Aluminum 6061	Tube	10.1	25.2	27.2	-	No	-	Demise
POLARCUBE	46	Bus GPS wire harness	1	Copper	Wires	8.5				No	-	Demise
POLARCUBE	47	Bus EPS wire harness 1	1	Copper	Ribbon	6	25	350	2	No	-	Demise
POLARCUBE	48	Bus Deployment Spring	2	Spring Steel	Coiled Sheet	3.5	12.9	8.2	-	No	-	Demise
POLARCUBE	49	Bus RF Cabling	3	Copper	Wire	3				No	-	Demise
POLARCUBE	50	Bus Standoffs	12	Steel (304, 316)	Rod	3	3.7	6.5	-	No	-	Demise

POLARCUBE	51	Bus Tx Antenna Bracket	2	Aluminum 6061	Plate	2.8	16.8	36.4	7.6	No	-	Demise
POLARCUBE	52	Bus Reaction Wheel Motor	3	Multiple (Steel)	Rod	2.5	6	20	-	No	-	Demise
POLARCUBE	53	Bus board clips 1	15	Aluminum 6061	Block	1.8	7.6	18.2	6.8	No	-	Demise
POLARCUBE	54	Bus EPS wire harness 2	2	Copper	Ribbon	1.5	20	50	4	No	-	Demise
POLARCUBE	55	Bus Dep Spring Spool	2	Aluminum 6061	Tube	1.5	9	8.2	-	No	-	Demise
POLARCUBE	56	Bus SS Fasteners	298	Steel (304, 316)	Rod	1	#0, #2, #4	.125 - .5"	-	No	-	Demise
POLARCUBE	57	Bus board clips 2	6	Aluminum 6062	Block	0.9	5.7	10.8	6.4	No	-	Demise
POLARCUBE	58	Bus Spring Plunger	2	Steel 316	Rod	0.5	3	10.6	-	No	-	Demise

Appendix I. ELaNa-20 Component List by CubeSat: Q-PACE

CUBESAT	Item Number	Name	Qty	Material	Body Type	Mass (g) (total)	Diameter / Width (mm)	Length (mm)	Height (mm)	High Temp	Melting Temp (F°)	Survivability
Q-PACE	1	QPACE 3U CubeSat	-	6061-T6 (SS)	Box	453.67	-	-	-	No	-	Demise
Q-PACE	2	QPACE Structure	-	6061-T6 (SS)	Box	66.43	453.67	99.262	99.002	No	-	Demise
Q-PACE	3	Super Structure Rails	4	6061-T6 (SS)	Flat Plate	8.88	66.43	17.89	17.89	No	-	Demise
Q-PACE	4	Solar Panels		-	Flat Plate		8.88	92.075	79.375	No	-	Demise
Q-PACE	5	S-Band Patch Antenna	1	-	Flat Plate	3	17.98	93.98	93.98	No	-	Demise
Q-PACE	6	Quintbass Guitar Antenna String	1	-	-	3	700	0.91	0.91	No	-	Demise
Q-PACE	7	Rail Mount Fasteners	4	6061-T6 (SS)	Box					No	-	Demise
Q-PACE	8	Battery System	1	-	-	-	-	-	-	No	-	Demise
Q-PACE	9	Batteries	6	Lithium Ion	Cylinder	24.04	29	40.64	40.64	No	-	Demise
Q-PACE	10	Battery PCB	1	PCB	Box	40	24.04	83	83	No	-	Demise
Q-PACE	11	GoPro Hero3+ Black	1	Various	Box	71	40	41	60	No	-	Demise
Q-PACE	12	CCDR - system		-		45	71	-	-	No	-	Demise
Q-PACE	13	Raspberry Pi	1	PCB	Box	45	45	83	83	No	-	Demise
Q-PACE	14	Interface Eletronics	1	PCB	Box		45	83	83	No	-	Demise
Q-PACE	15	WTC/PD PCB	1	PCB	Box	42	42	83	83	No	-	Demise
Q-PACE	16	MPPT/ Charger PCB	1	PCB	Box	42	42	83	83	No	-	Demise
Q-PACE	17	Experiment Control Electronic PCB	1	PCB	Box	147	42	83	83	No	-	Demise
Q-PACE	18	Comms/RF Module	1	PCB	Box	include d in structur e	147	89	89	No	-	Demise
Q-PACE	19	ETC Structure	1	6061-T6 (SS)	Box	14.5	included in structure	-	-	No	-	Demise
Q-PACE	20	12 V Push Solenoids		Alloy Steel	Box		14.5	14	13	No	-	Demise

Q-PACE	21	4 Wire Mimi Stepper Motor	1	Alloy Steel	Box	2.4		4.5	6	No	-	Demise
Q-PACE	22	4 Wire Mimi Stepper Motorw/ Gear	1	6061-T6 (SS)	Box	40	2.4	11	6	No	-	Demise
Q-PACE	23	Glass Plate	1	Glass	Flat Plate		40	2.5	2.1	No	-	Demise
Q-PACE	24	Cabling	various	PCB	-	453.67	-	-	-	No	-	Demise

Appendix J. ELaNa-20 Component List by CubeSat: RadFXSat-2

CUBESAT	Item Number	Name	Qty	Material	Body Type	Mass (g) (total)	Diameter / Width (mm)	Length (mm)	Height (mm)	High Temp	Melting Temp (F°)	Survivability
RadFXSat-2	1	<i>RadFXSat-2, updated August 30, 2016.</i>	-	-	box (1U)	-	-	-	-	-	-	Demise
RadFXSat-2	2	CubeSat Walls	2	Aluminum 5052 H32	sheet w/ bends	32.	200.	108.	1.	-	-	Demise
RadFXSat-2	3	Solar Panels (+Z, -Z)	2	Fiberglass	sheet	42.	97.	97.	1.6	-	-	Demise
RadFXSat-2	4	Solar Panels (+X, -X, +Y, -Y)	4	Fiberglass	sheet	43.	81.	108.	1.6	-	-	Demise
RadFXSat-2	5	Rail Ends	8	Aluminum 6061	stepped box	4.	21.	21.	10.	-	-	Demise
RadFXSat-2	6	Antenna	1	Nitinol	wire	1.	0.5	165.	-	-	-	Demise
RadFXSat-2	7	Antenna	1	Nitinol	wire	1.	0.5	530.	-	-	-	Demise
RadFXSat-2	8	Antennae Posts	2	Copper	cylinder	1.	5.	4.	-	-	-	Demise
RadFXSat-2	9	Antennae Posts	2	Fiberglass	cylinder	1.	5.	4.	-	-	-	Demise
RadFXSat-2	10	Antennae Posts	4	Delrin	cylinder	1.	5.	4.	-	-	-	Demise
RadFXSat-2	11	PCB Stack mounts	12	Delrin	box	1.	14.	14.	7.	-	-	Demise
RadFXSat-2	12	PCB Stack screws	4	stainless steel	cylinder	1.3	2.8	98.	-	-	-	Demise
RadFXSat-2	13	VUC PCB	1	Fiberglass	sheet	38.	95.	95.	1.6	-	-	Demise
RadFXSat-2	14	REM PCBs	3	Fiberglass	sheet	45.	95.	95.	1.6	-	-	Demise
RadFXSat-2	15	Batteries	6	NiCad "A" battery	cylinder	31.	17.	49.	-	-	-	Demise
RadFXSat-2	16	Hysteresis Rods	2	Permalloy	cylinder	4.8	3.2	70.	-	-	-	Demise
RadFXSat-2	17	Battery PCB (excl Batt,Hyst,Tan)	1	Fiberglass	sheet	50.	95.	95.	1.6	-	-	Demise
RadFXSat-2	18	MPPT PCB (excl Lead,Tan)	1	Fiberglass	sheet	49.	95.	95.	1.6	-	-	Demise
RadFXSat-2	19	IHU PCB (excl Tan)	1	Fiberglass	sheet	46.	95.	95.	1.6	-	-	Demise
RadFXSat-2	20	ICR PCB (pop excl RF Shield)	1	Fiberglass	sheet	48.	95.	95.	1.6	-	-	Demise

RadFXSat-2	21	RX/TX PCB (pop excl RF Shield,Tan)	1	Fiberglass	sheet	44.	95.	95.	1.6	-	-	Demise
RadFXSat-2	22	RF Shields	2	Copper	sheet	18.	80.	80.	0.5	-	-	Demise
RadFXSat-2	23	PCB Standoffs	20	Aluminum 6061	hollow cylinder	0.5	6.4	8.2	-	Yes	1205°	Demise
RadFXSat-2	24	PCB Standoffs	8	Copper	hollow cylinder	0.8	4.8	8.2	-	-	-	Demise
RadFXSat-2	25	PCB Standoffs	8	Delrin	hollow cylinder	0.3	6.4	8.2	-	-	-	Demise
RadFXSat-2	26	Magnet	1	Neodymium	cylinder	5.3	6.4	19.	-	-	-	Demise
RadFXSat-2	27	Fasteners, cabling, misc	1	varies	-	33.	-	-	-	-	-	Demise
RadFXSat-2	28	Lead ballast	1	Lead	sheet	210.	74.9	74.9	3.1	-	-	Demise
RadFXSat-2	29	Tantalum radiation shield	2	Tantalum	sheet	1.8	9.	24.	0.5	-	-	Demise
RadFXSat-2	30	Tantalum radiation shield	1	Tantalum	sheet	1.9	15.	15.	0.5	-	-	Demise
RadFXSat-2	31	Tantalum radiation shield	1	Tantalum	sheet	1.1	9.	15.	0.5	-	-	Demise
RadFXSat-2	32	Tantalum radiation shield	1	Tantalum	sheet	0.8	6.	15.	0.5	-	-	Demise
RadFXSat-2	33	Tantalum radiation shield	2	Tantalum	sheet	0.9	8.	13.	0.5	-	-	Demise
RadFXSat-2	34	Tantalum radiation shield	2	Tantalum	sheet	0.6	7.	10.	0.5	-	-	Demise
RadFXSat-2	35	Tantalum radiation shield	2	Tantalum	sheet	0.3	4.	9.	0.5	-	-	Demise
RadFXSat-2	36	Tantalum radiation shield	1	Tantalum	sheet	0.4	6.	8.	0.5	-	-	Demise
RadFXSat-2	38	Tantalum radiation shield	4	Tantalum	sheet	0.3	5.	6.	0.5	-	-	Demise
RadFXSat-2	39	Tantalum radiation shield	5	Tantalum	sheet	0.2	5.	5.	0.5	-	-	Demise
RadFXSat-2	40	Tantalum radiation shield	6	Tantalum	sheet	0.2	4.	5.	0.5	-	-	Demise
RadFXSat-2	41	Tantalum radiation shield	2	Tantalum	sheet	0.1	4.	4.	0.5	-	-	Demise
RadFXSat-2	42	Tantalum radiation shield	9	Tantalum	sheet	0.1	3.	3.	0.5	-	-	Demise
RadFXSat-2	43	Tantalum radiation shield	6	Tantalum	sheet	0.1	2.	3.	0.5	-	-	Demise
RadFXSat-2	44	Tantalum radiation shield	8	Tantalum	sheet	0.	2.	2.	0.5	-	-	Demise

Appendix K. ELaNa-20 NASA Ames Submitted ODAR - TechEdSat-7

See next page:

	<i>TechEdSat-7</i> <i>Orbital Debris Assessment Report (ODAR)</i>	T7MP-06- XS001 Rev 2	
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TechEdSat-7
Orbital Debris Assessment Report (ODAR)
&
End of Mission Plan (EOMP)

In accordance with NPR 8715.6A, this report is presented as compliance with the required reporting format per NASA-STD-8719.14, APPENDIX A.

Report Version: 2 (11/09/2017)

DAS Software Used in This Analysis: DAS v2.1.1

	<i>TechEdSat-7</i> <i>Orbital Debris Assessment Report (ODAR)</i>	T7MP-06- XS001 Rev 2	
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	<i>TechEdSat-7</i> <i>Orbital Debris Assessment Report (ODAR)</i>	T7MP-06- XS001 Rev 2	
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Record of Revisions				
REV	DATE	AFFECTED PAGES	DESCRIPTION OF CHANGE	AUTHOR (S)
0	10/24/2017	All	Initial Draft	Meredith Campbell
1	10/27/2017	All	New mass an launch date	Meredith Campbell
2	11/9/2017	All	Update information on Revision of ODAR Report 8719.14B	Ali Guarneros Luna

	<i>TechEdSat-7</i> <i>Orbital Debris Assessment Report (ODAR)</i>	T7MP-06- XS001 Rev 2	
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Self-assessment and OSMA assessment of the ODAR using the format in Appendix A.2 of NASA-STD-8719.14:

A self-assessment is provided below in accordance with the assessment format provided in Appendix A.2 of NASA-STD-8719.14. In the final ODAR document, this assessment will reflect any inputs received from OSMA as well.

Orbital Debris Self-Assessment Report Evaluation: TechEdSat-7 Mission

Reqm't #	Launch Vehicle					Spacecraft				Comments
	Compliant	N/A	Not Compliant	Incomplete	Standard Non-Compliant	Compliant	N/A	Not Compliant	Incomplete	
4.3-1.a 25 years						X				No Debris Released in LEO. See note 1.
4.3-1.b <100 object year limit						X				No Debris Released in LEO. See note 1.
4.3-2 GEO +/- 200Km						X				No Debris Released in GEO. See note 1.
4.4-1 < 0.001 Explosion Risk				X		X				There is no explosive hazard.
4.4-2 Passive Energy Source				X		X				There is no explosive hazard.
4.4-3 Limit Long-Term Risk				X		X				No planned breakups.
4.4-4 Limit BU Short term Risk				X		X				No planned breakups. 1.
4.5-1 <0.001 10cm Impact Risk				X		X				See note 1.
4.5-2 Postmission Disposal Risk						X				
4.6-1(a) Atmosphere Energy Option				X		X				See note 1.
4.6-1(b) Storage Orbit				X		X				See note 1.
4.6-1(c) Direct Retrieval				X		X				See note 1.
4.6-2 GEO Disposal				X		X				See note 1.
4.6-3 MEO Disposal				X		X				See note 1.
4.6-4 Disposal Reliability				X		X				See note 1.
4.6-5 Summary of DeOrbit				X		X				See note 1.
4.7-1 Ground Population Risk				X		X				See note 1.
4.8-1 Tethers Risk						X				No tethers used.

Notes:

1. All of the other portions of the launch stack are non-NASA and TechEdSat-7 is not the lead.

Pre-Launch EOMP Evaluation: TechEdSat Mission

Reqm't #	Spacecraft				EOMP Comments
	Compliant	N/A	Not Compliant	N/A	
4.3-1.a 25 years	☒	☐	☐	☐	
4.3-1.b <100 object year limit	☒	☐	☐	☐	
4.3-2 GEO +/- 200Km	☒	☐	☐	☐	
4.4-1 < 0.001 Explosion Risk	☒	☐	☐	☐	
4.4-2 Passive Energy Source	☒	☐	☐	☐	Passive RF systems. No planned breakups. Very low probability of breakup or debris generation due to explosion.
4.4-3 Limit Long-Term Risk	☒	☐	☐	☐	No planned breakups.
4.4-4 Limit BU Short term Risk	☒	☐	☐	☐	
4.5-1 <0.001 10cm Impact Risk	☒	☐	☐	☐	
4.5-2 Postmission Disposal Risk	☒	☐	☐	☐	
4.6-1(a) Atmosphere Energy Option	☒	☐	☐	☐	
4.6-1(b) Storage Orbit	☒	☐	☐	☐	N/A. No ability to maneuver to higher orbit.
4.6-1(c) Direct Retrieval	☒	☐	☐	☐	N/A. Atmospheric re-entry.
4.6-2 GEO Disposal	☒	☐	☐	☐	N/A. Not in GEO
4.6-3 MEO Disposal	☒	☐	☐	☐	N/A. Orbit not between LEO and GEO.
4.6-4 Disposal Reliability	☒	☐	☐	☐	No operation is required to execute atmospheric re-entry
4.6-5 Summary of DeOrbit	☒	☐	☐	☐	
4.7-1 Ground Population Risk	☒	☐	☐	☐	
4.8-1 Tethers Risk	☒	☐	☐	☐	

Assessment Report Format:

ODAR Technical Sections Format Requirements:

This ODAR follows the format in NASA-STD-8719.14, Appendix A.1 and includes the content indicated at a minimum in each section 2 through 8 below for the TechEdSat-7 satellite. Sections 9 through 14 apply to the launch vehicle ODAR and are not covered here.

ODAR Section 1: Program Management and Mission Overview

Mission Directorate: ARC Code R Office

Engineer Director: David Korsmeyer, ARC

Mission Design Division, Division Chief: Charles Richey, ARC

Project Manager/Senior Scientist: Marcus Murbach

Schedule of mission design and development milestones from NASA mission selection through proposed launch date, including spacecraft PDR and CDR (or equivalent) dates*:

Mission Selection:	August 2017
Mission Preliminary Design Review:	August 2017
Mission Critical Design Review:	January 2018
Launch:	April 2018
Begin Operation:	April 2018

Mission Overview:

The Technical Education Satellite 7 (TechEdSat-7) satellite will be integrated onto Virgin Orbit's LauncherOne. TechEdSat-7 will test and validate two different technologies in Low Earth Orbit (LEO): demonstration of the Exo-Brake and demonstration of the viability of the Iridium 9602 communication module.

The satellite will be inserted into orbit at an apogee of approximately 500 km, perigee of 500 km, with an inclination of 90 degrees. Transmission of data will begin 1 minute after deployment from the launch vehicle. The Exo-Brake will deorbit the satellite approximately 26 weeks after deployment concluding the mission.

TechEdSat-7 will fly on the Virgin Orbit CRS-13 mission, and will utilize the Xtenti FANTM RAIL separation system. There are no propellants.

Launch vehicle and launch site: Virgin Orbit LauncherOne, Mojave Air & Space Port (MHV) with air launch over the Pacific Ocean

Proposed launch date: April, 2018

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Mission duration: 26 weeks

Launch and deployment profile, including all parking, transfer, and operational orbits with apogee, perigee, and inclination:

TechEdSat-7 will be launched on a Virgin Orbit LauncherOne launch vehicle using the Xtenti FANTM RAIL separation system.

The TechEdSat-7 orbit is defined as follows:

Apogee: 500 km

Perigee: 500 km

Inclination: 90 degrees.

TechEdSat-7 has no propulsion and therefore does not actively change orbits. TechEdSat-7 will deploy the Exo-Brake, slow down, lose altitude, and then disintegrate upon atmospheric re-entry approximately 26 weeks after deployment. If the Exo-Brake fails to deploy the satellite will re-enter in 256 weeks.

Interaction or potential physical interference with other operational Spacecraft:

The main risks of this satellite are the Canon BP-930 battery used by the spacecraft (flown in and certified by the ISS program) and the possibility of the TechEdSat-7 impacting another deployment. Since the TechEdSat-7 is a 3.5U CubeSat being launched from the system, and NanoRacks has shown that the likelihood of any CubeSat impacting the ISS is very minimal (validated by the ISS Program Office).

ODAR Section 2: Spacecraft Description

Physical description of the spacecraft:

TechEdSat-7 is a 2U nanosatellite with dimensions of 10 cm x 10 cm x 21.7 cm and a total mass approximately equal to 2.5 kg. TechEdSat-7's payload carries a deployable Exo-Brake as a technology demonstration. The deployed Exo-Brake has a cross-sectional area of 1.25 m².

TechEdSat-7 will contain the following systems: one power board, one CUBIT RFID tag, one Crayfish board, one Iridium 9602 modem, one OEM 615 GPS, two Canon BP-930 batteries, two patch antennas, and one helical antenna.

- The Iridium 9602 modem will have one patch antenna.
- The OEM615 GPS shares a dual patch antenna with the Iridium 9602 modem.
- The power board will control the deployment of the Exo-Brake.

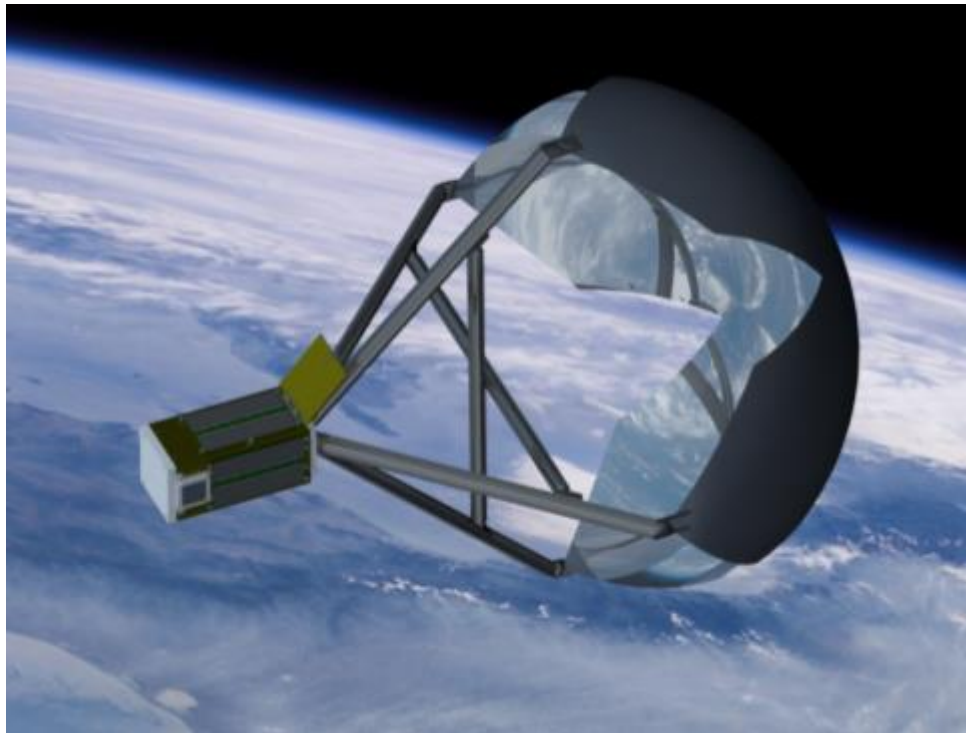


Figure 1: TechEdSat-7 Fully Deployed View

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Total satellite mass at launch, including all propellants and fluids: 2.5 kg

Dry mass of satellite at launch, excluding solid rocket motor propellants: 2.5 kg

Description of all propulsion systems (cold gas, mono-propellant, bi-propellant, electric, nuclear):

There will be no propulsion systems on TechEdSat-7.

Identification, including mass and pressure, of all fluids (liquids and gases) planned to be on board and a description of the fluid loading plan or strategies, excluding fluids in sealed heat pipes.

Not applicable, there will be no fluids or gasses on board.

Fluids in Pressurized Batteries:

None. TechEdSat-7 uses unpressurized standard COTS Lithium Ion battery cells.

Description of attitude control system and indication of the normal attitude of the spacecraft with respect to the velocity vector:

TechEdSat-7 does not have any attitude control system, but it does include an IMU to determine the orientation of the satellite (any attitude control comes from the aerodynamics of the Exo-Brake).

Description of any range safety or other pyrotechnic devices:

None. The TechEdSat-7 satellite will be launched powered off and a Remove-Before-Flight (RBF) pin is used to prevent accidental activation.

Description of the electrical generation and storage system:

The power will be generated by solar panels and stored in two Lithium Ion batteries. The batteries that will be used are Canon BP-930 (supplied by the ISS Program Office). See attached data sheet (Appendix B). This battery is approved by the ISS for flight. The dimensions of the battery are 4 x 7 x 3.8 cm and the weight is 0.18 kg.

Identification of any other sources of stored energy not noted above:

None.

Identification of any radioactive materials on board:

None.

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ODAR Section 3: Assessment of Spacecraft Debris Released during Normal Operations

Identification of any object (>1 mm) expected to be released from the spacecraft any time after launch, including object dimensions, mass, and material:

None. There are no intentional releases.

Rationale/necessity for release of each object:

N/A.

Time of release of each object, relative to launch time:

N/A.

Release velocity of each object with respect to spacecraft:

N/A.

Expected orbital parameters (apogee, perigee, and inclination) of each object after release:

N/A.

Calculated orbital lifetime of each object, including time spent in Low Earth Orbit (LEO):

N/A.

Assessment of spacecraft compliance with Requirements 4.3-1 and 4.3-2 (per DAS v2.1)

4.3-1, Mission Related Debris Passing Through LEO:

COMPLIANT. No debris released >1mm, while passing through LEO.

4.3-2, Mission Related Debris Passing Near GEO:

COMPLIANT. No debris released will transverse GEO.

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

Potential causes of spacecraft breakup during deployment and mission operations:

There is no credible scenario that would result in spacecraft breakup during normal deployment and operations.

Summary of failure modes and effects analyses of all credible failure modes, which may lead to an accidental explosion:

In-mission failure of a battery cell protection circuit could lead to a short circuit resulting in overheating and a very remote possibility of battery cell explosion. The battery safety systems discussed in the FMEA (see requirement 4.4-1 below) describe the combined faults that must occur for any of nine (9) independent, mutually exclusive failure modes that could lead to a battery explosion.

Detailed plan for any designed spacecraft breakup, including explosions and intentional collisions:

There are no planned breakups other than during atmospheric entry for disposal.

List of components which shall be passivated at End of Mission (EOM) including method of passivation and amount which cannot be passivated:

None.

Rationale for all items which are required to be passivated, but cannot be due to their design:

TechEdSat-7 will be in orbit for 26 weeks with successful deployment of the Exo-Brake based on the DAS analysis shown in this report. If the Exo-Brake fails to deploy, TechEdSat-7 will be in orbit for 256 weeks based on the DAS analysis shown in this report. Therefore, no post-mission passivation will be performed, as the satellite will burn up on re-entry at the end of the mission.

Assessment of spacecraft compliance with Requirements 4.4-1 through 4.4-4:

Requirement 4.4-1: Limiting the risk to other space systems from accidental explosions during deployment and mission operations while in orbit about Earth or the Moon, or Mars, or in the vicinity of Sun-Earth or Earth-Moon Lagrange Points:

For each spacecraft and launch vehicle orbital stage employed for a mission, the program or project shall demonstrate, via failure mode and effects analyses or equivalent analyses, that the integrated probability of explosion for all credible failure modes of each spacecraft and launch vehicle does not exceed 0.001 (excluding small particle impacts) (Requirement 56449).`

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Compliance statement:

Required Probability: 0.001.

Expected Probability: 0.000.

Supporting Rationale and FMEA details:

Payload Pressure Vessel Failure:

TechEdSat-7 is vented per ISS safety standards. It is not a sealed container.

Battery explosion:

Effect: All failure modes below might result in battery explosion with the possibility of orbital debris generation. However, in the unlikely event that a battery cell does explosively rupture, the small size, mass, and potential energy, of these small batteries is such that while the spacecraft could be expected to vent gases, most debris from the battery rupture should be contained within the vessel due to the lack of penetration energy. Note also that this same battery combination has been tested extensively, and now flown several times with no noted anomaly.

Probability: Very Low. It is believed to be less than 0.1% given that multiple independent (not common mode) faults must occur for each failure mode to cause the ultimate effect (explosion).

Failure mode 1: Battery Internal short circuit.

Mitigation 1: Complete proto-qualification and environmental acceptance tests of the Canon BP-930 battery by JSC ISS program. The acceptance tests are shock, vibration, thermal cycling, and vacuum tests followed by maximum system rate-limited charge and discharge to prove that no internal short circuit sensitivity exists.

Combined faults required for realized failure: Environmental testing **AND** functional charge/discharge tests must both be ineffective in discovery of the failure mode.

Failure Mode 2: Internal thermal rise due to high load discharge rate.

Mitigation 2: Each cell includes a positive temperature coefficient (PTC) variable resistance device that ensures high rate discharge is limited to acceptable levels if thermal rise occurs in the battery.

Combined faults required for realized failure: The PTC must fail **AND** spacecraft thermal design must be incorrect **AND** external over current detection and protection must fail for this failure mode to occur.

Failure Mode 3: Overcharging and excessive charge rate.

Mitigation 3: The satellite bus battery charging circuit design eliminates the possibility of the batteries being overcharged if circuits function nominally. This circuit has been proto-qualification tested for survival in shock, vibration, and thermal-vacuum environments. The charge circuit disconnects the incoming current when battery voltage indicates normal full charge at 8.4 V. If this circuit fails to operate, continuing charge can cause gas generation. The batteries include overpressure release vents that allow gas to escape, virtually eliminating any explosion hazard.

Combined faults required for realized failure:

- 1) **For overcharging:** The charge control circuit must fail to function **AND** the PTC device must fail (or temperatures generated must be insufficient to cause the PTC device to modulate) **AND** the overpressure relief device must be inadequate to vent generated gasses at acceptable rates to avoid explosion.
- 2) **For excessive charge rate:** The maximum charging rate from a single solar panel when in AM 1.5 G conditions (on Earth, perpendicular to the sun) is 200 mA. The maximum charge rate our battery can accept is 3 A. The battery is a proto-qualified Canon BP-930 from the JSC ISS program, and has four US18650S cells. The battery itself has two parallel strings of 2 cells connected in series, and thus having 4 cells. Due to solar panel current limits and their direction-facing arrangement on the satellite, there is no physical means of exceeding charging rate limits, even if only a single string from the battery was accepting charge. For this failure mode to become active one string must fail to accept a charge **AND** the charge control circuit on the remaining string fails. The overpressure relief vent keeps the battery cells from rupturing, and is thus limited to worst-case effects of overcharging.

Failure Mode 4: Excessive discharge rate or short circuit due to external device failure or terminal contact with conductors not at battery voltage levels (due to abrasion or inadequate proximity separation).

Mitigation 4: This failure mode is negated by a) proto-qualification tested short circuit protection on each external circuit, b) design of battery packs and insulators such that no contact with nearby board traces is possible without being caused by some other mechanical failure, c) obviation of such other mechanical failures by proto-qualification and acceptance environmental tests (shock, vibration, thermal cycling, and thermal-vacuum tests).

Combined faults required for realized failure: The PTC must fail **AND** an external load must fail/short-circuit **AND** external over-current detection and disconnect function must fail to enable this failure mode.

Failure Mode 5: Inoperable vents.

Mitigation 5: Battery vents are not inhibited by the battery holder design or the spacecraft.

Combined effects required for realized failure: The manufacturer fails to install proper venting and ISS environmental stress screening fails to detect failed vents.

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Failure Mode 6: Crushing.

Mitigation 6: This mode is negated by spacecraft design. There are no moving parts in the proximity of the batteries.

Combined faults required for realized failure: A catastrophic failure must occur in an external system **AND** the failure must cause a collision sufficient to crush the batteries leading to an internal short circuit **AND** the satellite must be in a naturally sustained orbit at the time the crushing occurs.

Failure Mode 7: Low level current leakage or short-circuit through battery pack case or due to moisture-based degradation of insulators.

Mitigation 7: These modes are negated by a) battery holder/case design made of non-conductive plastic, and b) operation in vacuum such that no moisture can affect insulators.

Combined faults required for realized failure: Abrasion or piercing failure of circuit board coating or wire insulators **AND** dislocation of battery packs **AND** failure of battery terminal insulators **AND** failure to detect such failures in environmental tests must occur to result in this failure mode.

Failure Mode 8: Excess temperatures due to orbital environment and high discharge combined.

Mitigation 8: The spacecraft thermal design will negate this possibility. Thermal rise has been analyzed in combination with space environment temperatures showing that batteries do not exceed normal allowable operating temperatures, which are well below temperatures of concern for explosions.

Combined faults required for realized failure: Thermal analysis **AND** thermal design **AND** mission simulations in thermal-vacuum chamber testing **AND** the PTC device must fail **AND** over-current monitoring and control must all fail for this failure mode to occur.

Failure Mode 9: Polarity reversal due to over-discharge caused by continuous load during periods of negative power generation vs. consumption.

Mitigation 9: In nominal operations, the spacecraft EPS design negates this mode because the processor will stop when voltage drops too low, below 7 V. This disables ALL connected loads, creating a guaranteed power-positive charging scenario. The spacecraft will not restart or connect any loads until battery voltage is above the acceptable threshold. At this point, only the safe mode processor is enabled and charging the battery commences. Once the battery reaches 90% of the peak voltage (around 7.5 V), it will switch to nominal mode and will be able to receive ground commands for continuing mission functions.

Combined faults required for realized failure: The microcontroller must stop executing code **AND** significant loads must be commanded/stuck "on" **AND** power margin analysis must be wrong **AND** the charge control circuit must fail for this failure mode to occur.

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Failure Mode 10: Excess battery temperatures due to post mission orbital environment and constant solar panel overcharge while satellite is powered off.

Mitigation 10: Selection of the ISS-approved Canon BP-930 battery packs (GSE from the NASA/Johnson Space Center). These battery packs have battery protection circuits, which prevent over-charge and over-heating. They are lot-tested and supplied as GSE (Government Furnished Equipment) from the NASA/Johnson Space Center. In terms of the orbit environment, the previous TechEdSat-1, TechEdSat-3, and TechEdSat-4, TechEdSat-5 (using the same packaging and battery pack) showed no signs of overheating from environmental heating.

Requirement 4.4-2: Design for passivation after completion of mission operations while in orbit about Earth or the Moon:

Design of all spacecraft and launch vehicle orbital stages shall include the ability to deplete all onboard sources of stored energy and disconnect all energy generation sources when they are no longer required for mission operations or post mission disposal or control to a level which cannot cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft. The design of depletion burns and ventings should minimize the probability of accidental collision with tracked objects in space (Requirement 56450).

Compliance statement:

TechEdSat-7 will be in orbit for 24 weeks with successful deployment of the Exo-Brake. If the Exo-Brake fails to deploy, TechEdSat-7 will be in orbit for approximately 253 weeks based on the DAS analysis shown in this report. Therefore, no post-mission passivation will be performed, as the satellite will burn up on re-entry at the end of the mission. Therefore, the TechEdSat-7 battery will meet the above requirement.

Requirement 4.4-3. Limiting the long-term risk to other space systems from planned breakups for Earth, lunar, Mars, Sun-Earth Lagrange Point, and Earth-Moon Lagrange Point missions:

Planned explosions or intentional collisions shall:

- a. For LEO-crossing missions, be conducted at an altitude such that for orbital debris fragments larger than 10 cm the object-time product does not exceed 100 object-years. For example, if the debris fragments greater than 10cm decay in the maximum allowed 1 year, a maximum of 100 such fragments can be generated by the breakup.
- b. Not generate debris larger than 1 mm that remains in Earth, lunar, or Mars orbits or in the vicinity of Sun-Earth or Earth-Moon Lagrange points longer than one year

Compliance statement:

This requirement is not applicable. There are no planned breakups.

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Requirement 4.4-4: Limiting the short-term risk to other space systems from planned breakups for Earth, lunar, Mars, Sun-Earth Lagrange Point, and Earth-Moon Lagrange Point missions:

Immediately before a planned explosion or intentional collision, the probability of debris, orbital or ballistic, larger than 1 mm colliding with any operating spacecraft within 24 hours of the breakup shall be verified to not exceed 10⁻⁶.

Compliance statement:

This requirement is not applicable. There are no planned breakups.

ODAR Section 5: Assessment of Spacecraft Potential for On-Orbit Collisions

Assessment of spacecraft compliance with Requirements 4.5-1 and 4.5-2 (per DAS v2.1, and calculation methods provided in NASA-STD-8719.14, section 4.5.4):

Requirement 4.5-1. Limiting debris generated by collisions with large objects when in Earth orbit: For each spacecraft and launch vehicle orbital stage in or passing through LEO, the program or project shall demonstrate that, during the orbital lifetime of each spacecraft and orbital stage, the probability of accidental collision with space objects larger than 10 cm in diameter does not exceed 0.001. For spacecraft and orbital stages near GEO, the time-integrated probability -when they are in the GEO protection zone -of accidental collision with space objects larger than 10 cm in diameter shall not exceed 0.001 (Requirement 56506).

Large Object Impact and Debris Generation Probability: 0.000000; COMPLIANT.

Requirement 4.5-2. Limiting debris generated by collisions with small objects when operating in Earth: For each spacecraft, the program or project shall demonstrate that, during the mission of the spacecraft, the probability of accidental collision with orbital debris and meteoroids sufficient to prevent compliance with the applicable post mission disposal requirements does not exceed 0.01 (Requirement 56507).

Small Object Impact and Debris Generation Probability: 0.000000; COMPLIANT

ODAR Section 6: Assessment of Spacecraft Postmission Disposal Plans and Procedures

6.1 Description of spacecraft disposal option selected: Two cases will be considered for this section. The first case is called “Nominal Deployment” in which the Exo-Brake successfully

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deploys and de-orbits the satellite. The second case is called “No Deployment” in which the Exo-Brake fails to deploy and the satellite de-orbits naturally due to atmospheric friction.

Case 1: *Nominal Deployment* The satellite will de-orbit due to the deployed Exo-Brake. There is no propulsion system and burn at re-entry.

Case 2: *Failed Deployment* The satellite will de-orbit naturally by atmospheric re-entry. There is no propulsion system and burn at re-entry.

6.2 Plan for any spacecraft maneuvers required to accomplish post mission disposal: None.

6.3 Calculation of area-to-mass ratio after post mission disposal, if the controlled reentry option is not selected:

Case 1: *Nominal Deployment*

Spacecraft Mass: 2.5 kg

Cross-sectional Area: 1.25 m²

Area to mass ratio: $1.25/2.5 = 0.5 \text{ m}^2/\text{kg}$

Case 2: *Failed Deployment*

Spacecraft Mass: 2.5 kg

Cross-sectional Area: 0.0217 m²

Area to mass ratio: $0.0217/2.5 = 0.00868 \text{ m}^2/\text{kg}$

6.4 Assessment of spacecraft compliance with Requirements 4.6-1 through 4.6-4 (per DAS v 2.1 and NASA-STD-8719.14 section):

Requirement 4.6-1. Disposal for space structures passing through LEO: A spacecraft or orbital stage with a perigee altitude below 2000 km shall be disposed of by one of three methods: (Requirement 56557)

a. Atmospheric reentry option:

- Leave the space structure in an orbit in which natural forces will lead to atmospheric reentry within 25 years after the completion of mission but no more than 35 years after launch; or
- Maneuver the space structure into a controlled de-orbit trajectory as soon as practical after completion of mission.

b. Storage orbit option: Maneuver the space structure into an orbit with perigee altitude greater than 2000 km and ensure its apogee will be below GEO altitude - 200 km for 100 years.

c. Direct retrieval: Retrieve the space structure and remove it from orbit within 10 years after completion of mission.

Analysis:

Case 1: Nominal Deployment

TechEdSat-7 satellite reentry is COMPLIANT using Method “a.” TechEdSat-7 will re-enter in 0.504 years (approximately 26 weeks) after launch with orbit history shown in Figure 2.

Case 2: Failed Deployment

TechEdSat-7 satellite reentry is COMPLIANT using Method “a.” TechEdSat-7 will re-enter in 4.928 years (approximately 256 weeks) after launch with orbit history as shown in Figure 3.

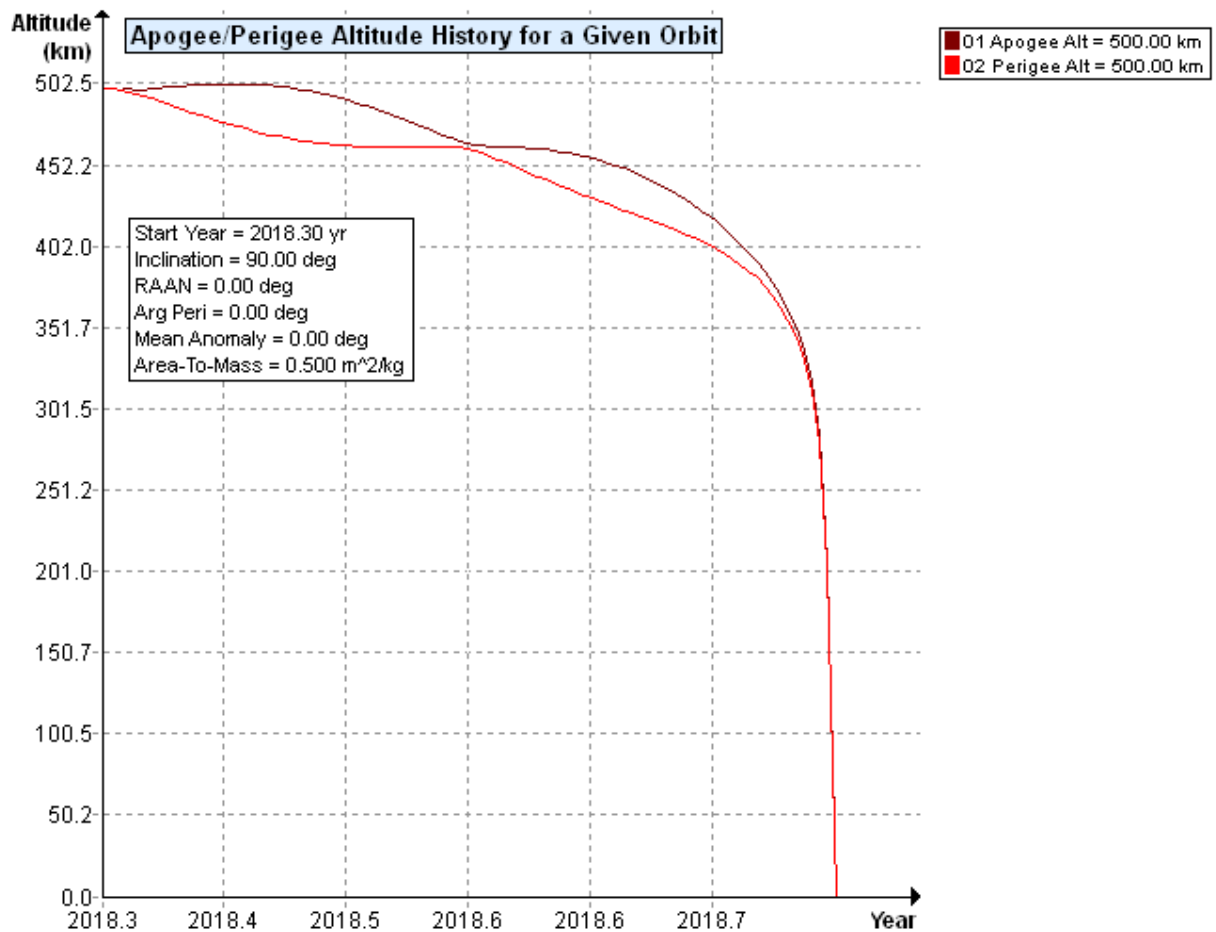


Figure 2: TechEdSat-7 Orbit History for Case 1: Nominal Deployment

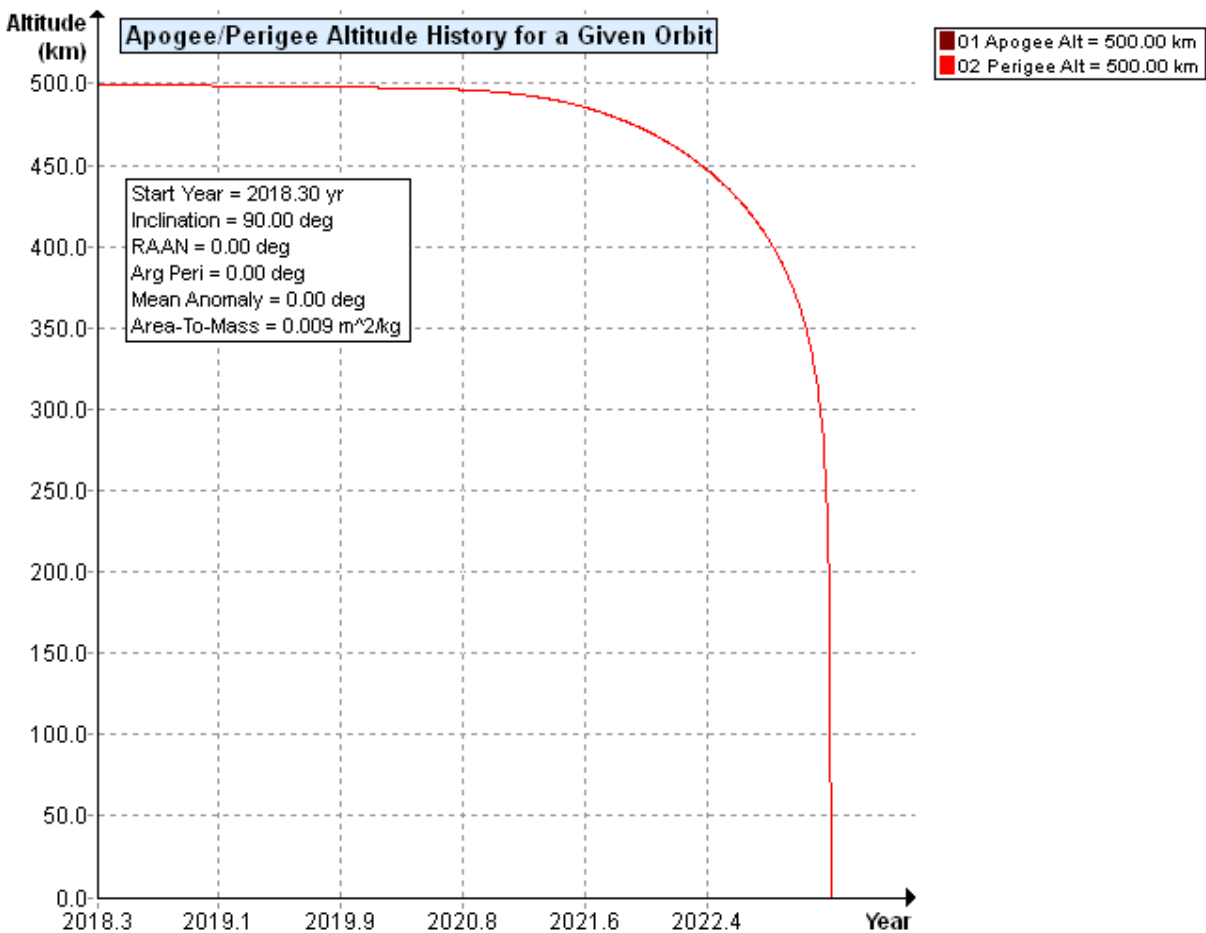


Figure 3: TechEdSat-7 Orbit History for Case 2: Failed Deployment

Requirement 4.6-2. Disposal for space structures near GEO. A spacecraft or orbital stage in an orbit near GEO shall be maneuvered at EOM to a disposal orbit above GEO with a predicted minimum perigee of GEO +200 km (35,986 km) or below GEO with a predicted maximum apogee of GEO –200 km (35,586 km) for a period of at least 100 years after disposal.

Analysis: Not applicable. TechEdSat-7 orbit is in LEO.

Requirement 4.6-3. Disposal for space structures between LEO and GEO.

- A spacecraft or orbital stage shall be left in an orbit with a perigee greater than 2000 km above the Earth's surface and apogee below GEO altitude -200 km for 100 years.
- A spacecraft or orbital stage shall not use nearly circular disposal orbits near regions of high value operational space structures, such as the Global Navigation Satellite Systems near the semi-synchronous altitudes

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Analysis: Not applicable. TechEdSat-7 orbit is in LEO.

Requirement 4.6-4. Reliability of Post mission Disposal Operations in Earth Orbit: NASA space programs and projects shall ensure that all post mission disposal operations to meet Requirements 4.6-1, 4.6-2, and/or 4.6-3 are designed for a probability of success as follows:

- a. Be no less than 0.90 at EOM.
- b. For controlled reentry, the probability of success at the time of reentry burn must be sufficiently high so as not to cause a violation of Requirement 4.7-1 pertaining to limiting the risk of human casualty.

Analysis:

Case 1: Nominal Deployment

TechEdSat-7 de-orbiting relies on the Exo-Brake de-orbiting device. Release of the Exo-Brake will result in de-orbiting in approximately 26 weeks with no disposal or de-orbiting actions required.

Case 2: Failed Deployment

TechEdSat-7 de-orbiting does not rely on de-orbiting devices. Release with a downward, retrograde vector will result in de-orbiting in approximately 5 years with no disposal or de-orbiting actions required.

ODAR Section 7: Assessment of Spacecraft Reentry Hazards

Assessment of spacecraft compliance with Requirement 4.7-1:

Requirement 4.7-1. Limit the risk of human casualty: The potential for human casualty is assumed for any object with an impacting kinetic energy in excess of 15 joules:

- a. For uncontrolled reentry, the risk of human casualty from surviving debris shall not exceed 0.0001 (1:10,000) (Requirement 56626).

Summary Analysis Results: DAS v2.1 reports that TechEdSat-7 is compliant with the requirement. It predicts that no components on board has more than 15 joules of impact kinetic energy. The majority of TechEdSat-7 including its components and the Exo-Brake will burn up on re-entry. As seen in the analysis outputs below, the highest impact kinetic energies is 0 Joules. Also, there are no titanium components that will be used on TechEdSat-7.

10 27 2017; 16:50:56PM *****Processing Requirement 4.7-1
Return Status : Passed

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*****INPUT*****

Item Number = 1

name = TES7
 quantity = 1
 parent = 0
 materialID = 8
 type = Box
 Aero Mass = 2.500000
 Thermal Mass = 2.500000
 Diameter/Width = 0.100000
 Length = 0.217000
 Height = 0.100000

name = Door Assembly
 quantity = 1
 parent = 1
 materialID = 8
 type = Flat Plate
 Aero Mass = 0.083000
 Thermal Mass = 0.083000
 Diameter/Width = 0.100000
 Length = 0.100000

name = Ejection Plate Assembly
 quantity = 1
 parent = 1
 materialID = 77
 type = Box
 Aero Mass = 0.145000
 Thermal Mass = 0.145000
 Diameter/Width = 0.100000
 Length = 0.100000
 Height = 0.044000

name = Lower Stack Assembly
 quantity = 1
 parent = 1
 materialID = 8
 type = Box
 Aero Mass = 1.512000
 Thermal Mass = 1.140000
 Diameter/Width = 0.100000
 Length = 0.100000
 Height = 0.050000

name = Battery
 quantity = 2
 parent = 4
 materialID = 70

```

type = Box
Aero Mass = 0.186000
Thermal Mass = 0.186000
Diameter/Width = 0.040000
Length = 0.075000
Height = 0.040000

name = Upper Stack Assembly
quantity = 1
parent = 1
materialID = 58
type = Box
Aero Mass = 0.142500
Thermal Mass = 0.031500
Diameter/Width = 0.030000
Length = 0.030000
Height = 0.015000

name = Crayfish
quantity = 1
parent = 6
materialID = 23
type = Flat Plate
Aero Mass = 0.035000
Thermal Mass = 0.035000
Diameter/Width = 0.100000
Length = 0.100000

name = Adam 12 Power Board
quantity = 1
parent = 6
materialID = 4
type = Flat Plate
Aero Mass = 0.076000
Thermal Mass = 0.076000
Diameter/Width = 0.300000
Length = 0.400000

name = Solar Panel
quantity = 4
parent = 1
materialID = 23
type = Flat Plate
Aero Mass = 0.053000
Thermal Mass = 0.053000
Diameter/Width = 0.100000
Length = 0.157500

name = Structure
quantity = 1

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parent = 1
materialID = 8
type = Box
Aero Mass = 0.370000
Thermal Mass = 0.370000
Diameter/Width = 0.100000
Length = 0.217000
Height = 0.100000
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name = ExoBrake
quantity = 1
parent = 1
materialID = 44
type = Flat Plate
Aero Mass = 0.135500
Thermal Mass = 0.135500
Diameter/Width = 1.250000
Length = 1.250000
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*****OUTPUT*****
Item Number = 1
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name = TES7
Demise Altitude = 77.995979
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
```

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name = Door Assembly
Demise Altitude = 76.112137
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
```

```
*****
name = Ejection Plate Assembly
Demise Altitude = 77.550102
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
```

```
*****
name = Lower Stack Assembly
Demise Altitude = 65.798409
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
```

```
*****
name = Battery
Demise Altitude = 64.908737
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
```

name = Upper Stack Assembly
Demise Altitude = 73.529701
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

name = Crayfish
Demise Altitude = 73.024727
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

name = Adam 12 Power Board
Demise Altitude = 73.255264
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

name = Solar Panel
Demise Altitude = 77.472542
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

name = Structure
Demise Altitude = 76.177994
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

name = ExoBrake
Demise Altitude = 77.988823
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

===== End of Requirement 4.7-1 =====

Requirements 4.7-1b and 4.7-1c below are non-applicable requirements because TechEdSat-7 does not use controlled reentry.

4.7-1, b) **NOT APPLICABLE.** For controlled reentry, the selected trajectory shall ensure that no surviving debris impact with a kinetic energy greater than 15 joules is closer than 370 km from foreign landmasses, or is within 50 km from the continental U.S., territories of the U.S., and the permanent ice pack of Antarctica (Requirement 56627).

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4.7-1 c) **NOT APPLICABLE.** For controlled reentries, the product of the probability of failure of the reentry burn (from Requirement 4.6-4.b) and the risk of human casualty assuming uncontrolled reentry shall not exceed 0.0001 (1:10,000) (Requirement 56628).

ODAR Section 8: Assessment for Tether Missions

Requirement 4.8-1. Mitigate the collision hazards of space tethers in protected regions of space: Intact and remnants of severed tether systems in Earth, lunar, or Mars orbit, in the Sun-Earth Lagrange Points, or in the Earth-Moon Lagrange Points shall limit the generation of orbital debris from on-orbit collisions with other operational spacecraft.

Not applicable. There are no tethers in the TechEdSat-7 mission.

ODAR Sections 9-14: Launch Vehicle

Since the TechEdSat-7 launch vehicle is managed by Virgin Orbit the orbital debris assessment for the launch vehicle will be performed by Virgin Orbit. The following note from NPR 8715.6A, Paragraph P.2.2, is applied, *“Note: It is recognized that NASA has no involvement or control in the design or operation of Federal Aviation Administration (FAA)-licensed launches or foreign or Department of Defense (DoD)-furnished launch services, and, therefore, these are not subject to the requirements in this NPR for the launch portion.”*

END of ODAR for TechEdSat-7.

Appendix A: Acronyms

AFRL	Air Force Research Lab
ARC	Ames Research Center
Arg peri	Argument of Perigee
CDR	Critical Design Review
cm	centimeter
COTS	Commercial Off-The-Shelf (items)
DAS	Debris Assessment Software
EOM	End Of Mission
ESMD	Exploration Systems Mission Directorate
FRR	Flight Readiness Review
GEO	Geosynchronous Earth Orbit
ITAR	International Traffic In Arms Regulations
kg	kilogram
km	kilometer
LEO	Low Earth Orbit
Li-Ion	Lithium Ion
m^2	Meters squared
ml	milliliter
mm	millimeter
N/A	Not Applicable.
ODAR	Orbital Debris Assessment Report
TechEdSat-7	Technical Education Satellite-6
ORR	Operations Readiness Review
OSMA	Office of Safety and Mission Assurance
PDR	Preliminary Design Review
PL	Payload
P-POD	Poly Picosatellite Orbital Deployer
PSIa	Pounds Per Square Inch, absolute
PSRR	Pre-Ship Readiness Review
RAAN	Right Ascension of the Ascending Node
SESLO	Space environment survivability of live organisms (payload)
SMA	Safety and Mission Assurance
Ti	Titanium
USAF	United States Air Force
UTJ	Ultra Triple Junction
yr	year

Appendix B: Battery Data Sheet

MATERIAL SAFETY DATA SHEET

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SECTION 1 IDENTIFICATION OF THE SUBSTANCE/MIXTURE AND OF THE COMPANY/UNDERTAKING

Product Name:	Lithium Ion Battery
Product Code:	BP-930
Company Name:	Canon Inc.
Address:	30-2, Shimomaruko 3-Chome, Ohta-ku, Tokyo 146-8501, Japan
Use of the Product:	Battery for Video camera
Supplier:	
Address:	
Phone number:	

With regard to air transport, the International Civil Aviation Organization (ICAO) Packing Instruction 965 Part 1 complies with the Recommendation as is; further, the International Air Transport Association (IATA) adopts ICAO Packing Instruction 965 Part 1. In addition, the regulations of the US Department of Transportation for land, sea and air transportation are based on the UN Recommendations.

SECTION 2 MATERIALS AND INGREDIENTS INFORMATION

IMPORTANT NOTE: The battery pack uses four US 18650S lithium-ion rechargeable cells and control circuit on the PWB. The cells are connected in 2 parallel strings of 2 cells in series. The battery pack should not be opened or burned since the following ingredients contained within the cells could be harmful under some circumstance if exposed or misused. The cells contain neither metallic lithium nor lithium alloy.

Cathode:	Lithium-Cobalt Dioxides (active material)
	Polyvinylidene Fluoride (binder)
	Graphite (conductive material)
Anode:	Graphite (active material)
	Polyvinylidene Fluoride (binder)
Electrolyte:	Organic Solvent (non-aqueous liquid)
	Lithium Salt
Others:	Heavy metals such as Mercury, Cadmium, Lead, and Chromium are not used in the cells.
Enclosure:	Plastic (PC)

SECTION 3 FIRE HAZARD DATA

In case of fire, use CO₂ or dry chemical extinguishers.

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SECTION 4 HEALTH HAZARD DATA

Under normal condition of use, these chemicals are contained in sealed can. Risk of exposure occurs only if the cells are mechanically abused.

- | | |
|---------------|---|
| Inhalation: | Contents of an opened cell can cause respiratory irritation.
Remove to fresh air immediately and call a doctor. |
| Skin Contact: | Contents of an opened cell can cause skin irritation.
Wash skin with soap and water. |
| Eye Contact: | Contents of an opened cell can cause eye irritation.
Immediately flush eyes thoroughly with water for at least 15 minutes. Seek medical attention. |

SECTION 5 PRECAUTIONS FOR SAFE HANDLING AND USE

- | | |
|--------------|---|
| Storage: | Store within the recommended limit of -20 degrees C to 45 degrees C (-4 degrees F to 113 degrees F), well-ventilated area.
Do not expose to high temperature (60 degrees C/140 degrees F). Since short circuit can cause burn hazard or safety vent to open, do not store with metal jewelry, metal covered tables, or metal belt. |
| Handling: | Do not disassemble, remodel, or solder. Do not short + and - terminals with a metal. Do not open the battery pack. |
| Charging: | Charge within the limits of 0 degrees C to 40 degrees C (32 degrees F to 104 degrees F) temperature.
Charge with specified charger designed for this battery pack. |
| Discharging: | Discharge within the limits of -10 degrees C to 50 degrees C (14 degrees F to 122 degrees F) temperature. |
| Disposal: | Dispose in accordance with applicable federal, state and local regulation. |
| Caution: | Attach the cover to the battery pack to prevent short circuits.
Do not disassemble. Do not incinerate. Do not expose to temperature above 140 degrees F. |

SECTION 6 SPECIAL PROTECTION INFORMATION

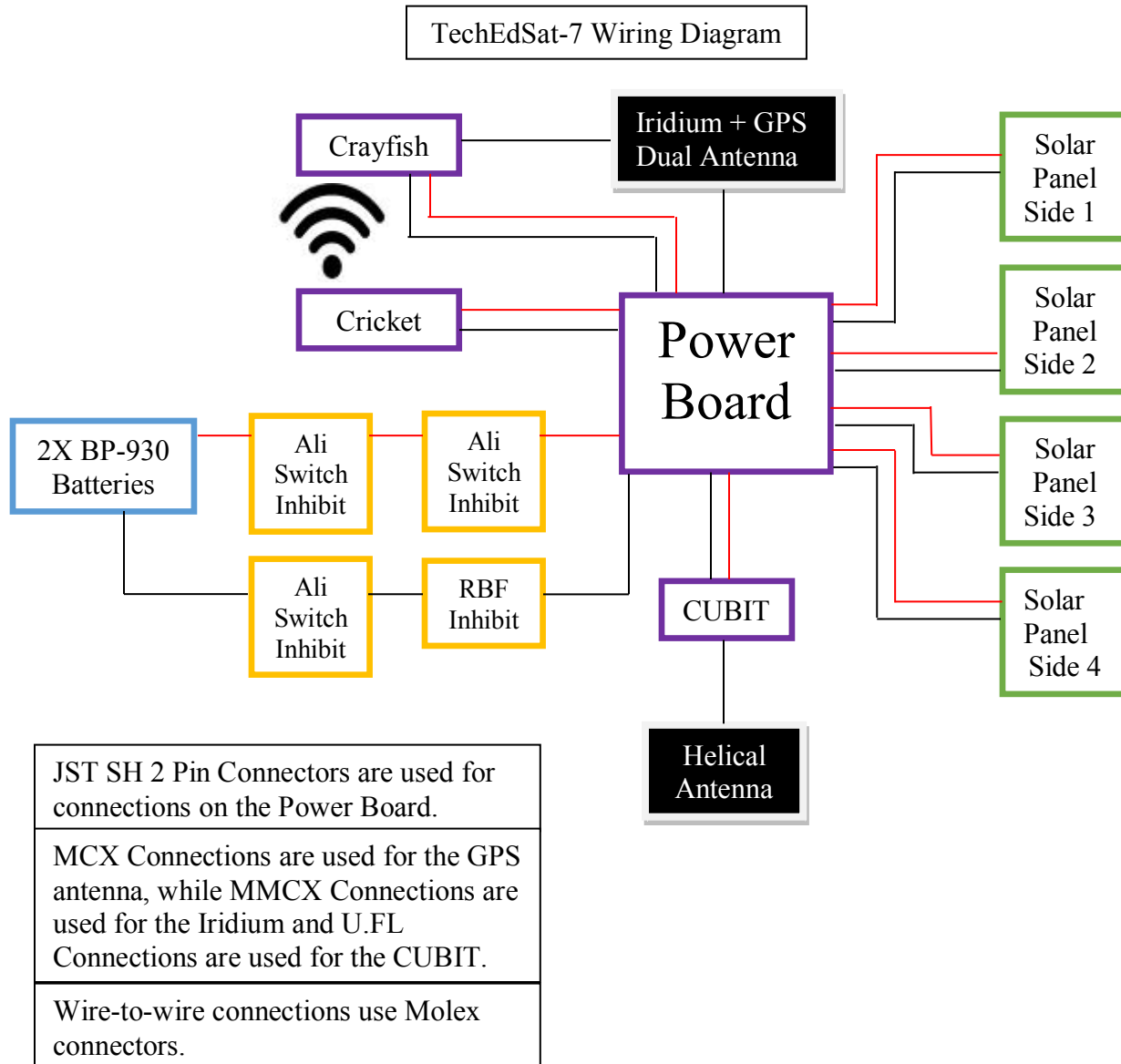
- | | |
|-------------------------|---------------------------------|
| Respiratory Protection: | Not necessary under normal use. |
| Ventilation: | Not necessary under normal use. |
| Eye Protection: | Not necessary under normal use. |
| Protective Gloves: | Not necessary under normal use. |

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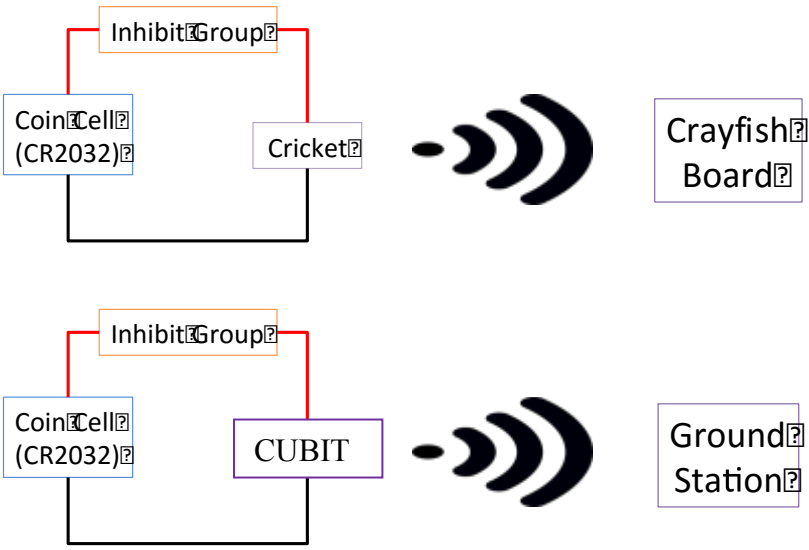
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Appendix C: Wiring Schematics



Second Cricket and CUBIT Wiring Diagram



Appendix L. ELaNa-20 Component List by CubeSat: Prometheus

CUBESAT	Item Number	Name	Body Type	Material	Qty	Mass (g) (total)	Diameter/ Width (mm)	Length (mm)	Height (mm)	High Temp	Melting Temp (F°)	Survivability
Prometheus	1 Power	Power Housing	Box	Aluminum 6061	1	161.55	100	100	25	No	-	Demise
Prometheus	2 Power	Power Board	Box	Polyimide & Misc	1	91.53	92	92	22.5	No	-	Demise
Prometheus	3 Power	Mono Holder Arms	Box	Aluminum 6061	2	31.30	60	40	10	No	-	Demise
Prometheus	4 Power	Hot Tip Arms	Box	Aluminum 6061	2	21.24	60	40	10	No	-	Demise
Prometheus	5 Power	Hinges	Box	Steel 304 304	8	40.00	150	70	2	Yes	2642°	See Table 8
Prometheus	6 Power	Hinge Pins	Box	Steel 304	4	19.12	10	2	2	Yes	2642°	See Table 8
Prometheus	7 Power	Battery Cage and PCBs	Box	Poly Carbonate, Polyimide, & Misc	1	53.30	95	45	70	No	-	Demise
Prometheus	8 Power	Batteries	Cylinder	Li Ion Electrolyte	4	304.00	26	-	65	No	-	Demise
Prometheus	9 Power	Safe Arm Plug	Box	Plastic, Polyimide, & Misc	1	5.70	45	2	1	No	-	Demise
Prometheus	10 Power	Solar Panel	Box	Aluminum 6061 (mostly), Kapton, Semiconductor	4	500.12	15	7	2	No	-	Demise
Prometheus	11 SFS	SFS Proc and Frame	Box	Aluminum 6061 & Polyimide	1	35.46	4	20	2	No	-	Demise
Prometheus	12 SFS	SFS 1 to 1 Cable	Box	Steel 304 connector shells	1	3.57	10	10	80		2642°	See Table 8
Prometheus	13 SFS	SFS Sensor and Frame	Box	Aluminum 6061 and Glass	1	13.35	20	10	5	No	-	Demise
Prometheus	14 ADCS	ADCS Module w/o Wheels	Box	Aluminum 6061, Polyimide, & Misc.	1	274.60	98	98	42	No	-	Demise
Prometheus	15 ADCS	Wheels & Pin Block	Box	Steel 304	4	280.40	44.5	-	5.7	Yes	2642°	See Table 8
Prometheus	16 ADCS	Sun Sensors	Box	Aluminum 6061, Glass, Polyimide, & Misc	3	25.02	25	15	6	No	-	Demise
Prometheus	17 ADCS	Magnetometer	Flat Plate		2	6.00	15	15	-	No	-	Demise

Prometheus Continued

CUBESAT	Item Number	Name	Qty	Material	Body Type	Mass (g) (total)	Diameter/ Width (mm)	Length (mm)	Height (mm)	High Temp	Melting Temp (F°)	Survivability
Prometheus	18 Card Cage	Card Cage +X Side	Box	Aluminum 6061	1	34.95	110	100	2	No	-	Demise
Prometheus	19 Card Cage	Card Cage -X Side	Box	Aluminum 6061	1	31.05	110	100	2	No	-	Demise
Prometheus	20 Card Cage	Card Cage +Y Side	Box	Aluminum 6061	1	57.04	110	100	2	No	-	Demise
Prometheus	21 Card Cage	Card Cage -Y Side	Box	Aluminum 6061	1	45.16	110	100	2	No	-	Demise
Prometheus	22 Card Cage	Back Cover	Box	Aluminum 6061	1	15.31	90	60	1.5	No	-	Demise
Prometheus	23 Card Cage	Dig Radio Module	Box	Aluminum, Polyimide, & Misc	2	132.70	96	93	7.5	No	-	Demise
Prometheus	24 Card Cage	GPS Frame	Box	Aluminum 6061	1	6.89	70	50	5	No	-	Demise
Prometheus	25 Card Cage	GPS PCB	Box	Polyimide & Misc	1	21.96	70	50	1.6	No	-	Demise
Prometheus	26 Card Cage	C&DH Module	Box	Aluminum, Polyimide, & Misc	1	60.60	96	93	7.5	No	-	Demise
Prometheus	27 Card Cage	Backplane PCB	Box	Polyimide & Misc	1	48.03	116	62	5	No	-	Demise
Prometheus	28 RF	Analog Radio PCB	Box	Polyimide & Misc	1	51.85	90	90	1.6	No	-	Demise
Prometheus	29 RF	RF Housing	Box	Aluminum 6061	1	92.51	20	100	100	No	-	Demise
Prometheus	30 RF	RF Cover	Box	Aluminum 6061	1	32.23	90	90	1	No	-	Demise
Prometheus	31 RF	Antenna PCB and Helical	Cylinder	Polyimide & Misc & Gold plated phospher bronze	1	72.30	3	-	300	No	-	Demise
Prometheus	32 RF	LB Elements	Box	Gold plated Spring Steel 304	2	7.94	300	150	0.5	No	-	Demise
Prometheus	33 RF	RF Cables	Cylinder	Copper & Teflon	2	4.00	20	-	50	No	-	Demise
Prometheus	34 RF	Helical Center Stow Support	Box	Polycarbonate	1	10.53	44.5	-	5.7	No	-	Demise
Prometheus	35 RF	Helical Outer Stow Support	Box	Polycarbonate	5	3.15	14	11	12	No	-	Demise
Prometheus	36 Misc	3M Scotchweld 2216 (Staking)	Box	Nonconductive epoxy	N/A	N/A	-	-	-	No	-	Demise
Prometheus	37 Misc	Silver Epoxy (EPOTEK H20E)	Box	Conductive epoxy containing Ag	1	<0.1	1	10	10	No	-	Demise
Prometheus	38 Misc	Lubricant (Braycote 601EF)	Box	Vacuum-rated grease (perfluorinated polyether)	1	<0.1	1	10	10	No	-	Demise
Prometheus	39 Misc	Thermal Tape (Mylar/Sheldahl, 100XC Kapton)	Box	Black Kapton film	4	6.00	0.1	100	150	No	-	Demise
Prometheus	40 Misc	Staking, screws, etc.	Box	2216, Steel 304, etc.	-	#REF!	-	-	-	No	-	Demise