NC STATE UNIVERSITY

Mechanical and Aerospace Engineering

Aerospace Engineering Capstone
Senior Design 2024-2025

Personnel - CLEOSATRA

Nick Lawton
Project Manager
Payload Lead

Will Bodnar
Thermal Control and Survivability Lead

Eve Whitman
Structures/Materials Lead
Testing/Safety Lead

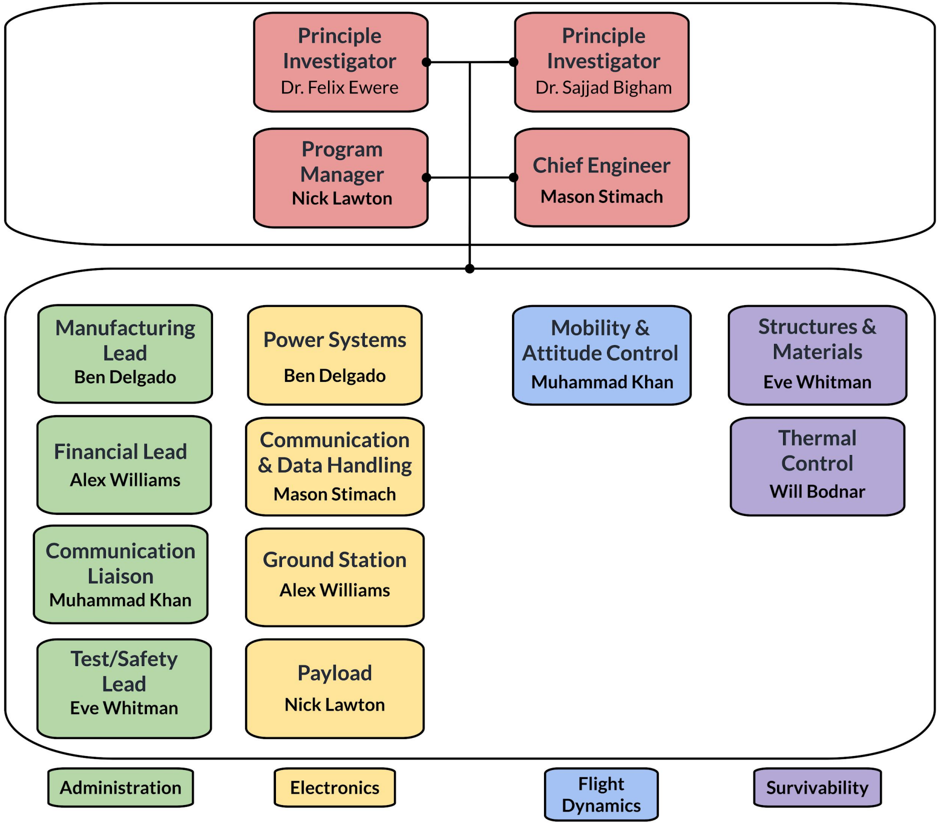
Ben Delgado
Power Systems Lead
Manufacturing Lead

Mason Stimach
Communication Lead
Systems Engineer

Alex Williams
Ground Station Lead
Financial Lead

Muhammad Khan
Mobility/Attitude Control Lead
Communication Liaison

Organizational Structure



Setting the scene

Satellites take in large amounts of data, and the amount keeps growing. Current computational constraints prevent large data processing. Computational constraints are partially due to the rad-hard components. [11]

Clearing the way for *any electronic* to be used in space requires a means to overcome these constraints.

Startups [12] are entering the space, governments want more and more constellations [13] which will be constrained by the current bottlenecks, and universities are rapidly investigating solutions in this field [14].

Mission Overview

“The space industry needs a way to provide reliable radiation protection for electronics without changing the underlying electronic component from its COTS design”

Objectives: CLEOSATRA

- Will serve as a 3U computational satellite
- Will employ an effective radiation shield made from existing rad-hard techniques and newer materials
- Will provide adequate radiation protect for COTS electronic components
- Will measure effectiveness of the shield by providing a shielded and unshielded reference processor

Research Goals

CLEOSATRA aims to redefine how electronics are shielded from radiation in space, while establishing a reliable commercial 3U-cubesat architecture.

Experimental configuration:

- Two commercial processors will mirror sensor-data capture
  - Only one computer will be shielded from radiation
- Radiation detectors will be placed next to the processors to measure incident energy levels encountered by each computer.
- The goal is to compare the performance of the radiation-shielded computer with the unshielded design through tracking errors caused by radiation.

Stakeholders

- Dr. Sajjad Bigham
- NCSU
- NCSU Nuclear Engineering Department
- UNP
- NASA
- AFRL
- DoD

Radiation Environment

Orbit: Circular, 1000 km altitude, 43° inclination

Radiation Models:

- Proton Model: AP-8 (Solar Minimum)
- Electron Model: AE-8 (Solar Maximum)
- SAPPHIRE models

Key Radiation Risks

- **Protons:** 0.10 - 1.00 MeV.
- **Electrons:** 0.04 - 0.20 MeV, with critical surface charging risks.
- **GCRs:** 10.00 - 50.00 MeV/nuc and 100.00 - 500.00 MeV/nuc for heavy ions.

Radiation Environment

- Proton flux Model: AP-8 (Solar Minimum)

Integral:

Energy Range (MeV)	Average Flux (cm^2/s)	Fluence (cm^2)	Comments
0.10 - 0.30	4000 - 4100	1.38×10^{11} - 1.61×10^{11}	High flux; crucial low-energy range
0.30 - 1.00	3000 - 3800	8.64×10^{10} - 5.76×10^{10}	Moderate; still significant
1.00 - 10.00	2500 - 900	3.79×10^{10} - 7.89×10^{9}	Decreasing; noticeable dip
10.00 - 100.00	300 - 20	8.30×10^{8} - 7.99×10^{7}	Sharp decline in flux
100.00 - 400.00	< 20	$< 1.23 \times 10^{8}$	Lowest flux, but important to note

Differential:

Energy Range (MeV)	Average Flux ($cm^2/MeV/s$)	Fluence (cm^2/MeV)	Comments
0.10 - 0.50	8000 - 2300	2.59×10^{11} - 7.45×10^{10}	Critical low-energy range
0.50 - 2.00	1900 - 300	5.96×10^{10} - 1.04×10^{10}	Noticeable but lesser
2.00 - 10.00	150 - 20	3.53×10^{9} - 1.16×10^{8}	Smaller fluxes, but consistent
10.00 - 100.00	< 10	$< 7.99 \times 10^{7}$	Minimal exposure expected

Radiation Environment

- Electron flux Model: AE-5 (Solar Maximum)

Integral Electron Flux:

Energy Range (MeV)	**Average Flux (cm^2/s)**	**Fluence (cm^2)**	**Comments**
0.04 - 0.20	1.80×10^6 - 5.92×10^5	5.93×10^{13} - 1.67×10^{13}	High flux; critical low-energy band
0.20 - 0.50	4.79×10^5 - 3.06×10^6	1.66×10^{13} - 9.66×10^{12}	Noticeable increase; moderate risk
0.50 - 1.00	7.94×10^3 - 1.84×10^2	2.47×10^{11} - 5.17×10^{10}	Sharp decline in flux

Radiation Environment

- Solar Particle Event flux Model: SAPPHIRE model

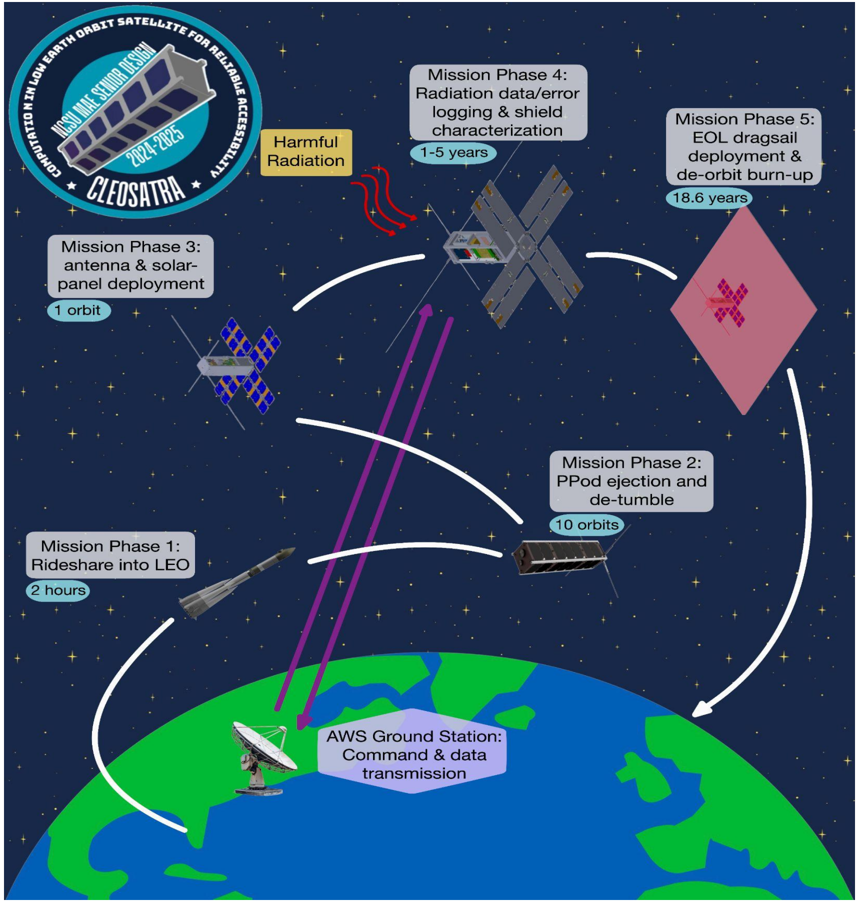
Proton Fluence:

Energy Range (MeV)	**Total Fluence (cm^2)**	**Comments**
0.10 - 2.00	1.88×10^4	Critical for solar event shielding
2.00 - 10.00	1.88×10^4	Lesser but consistent
100.00 - 1000.00	Decreases significantly	Only occasional exposure expected

Cosmic Ray:

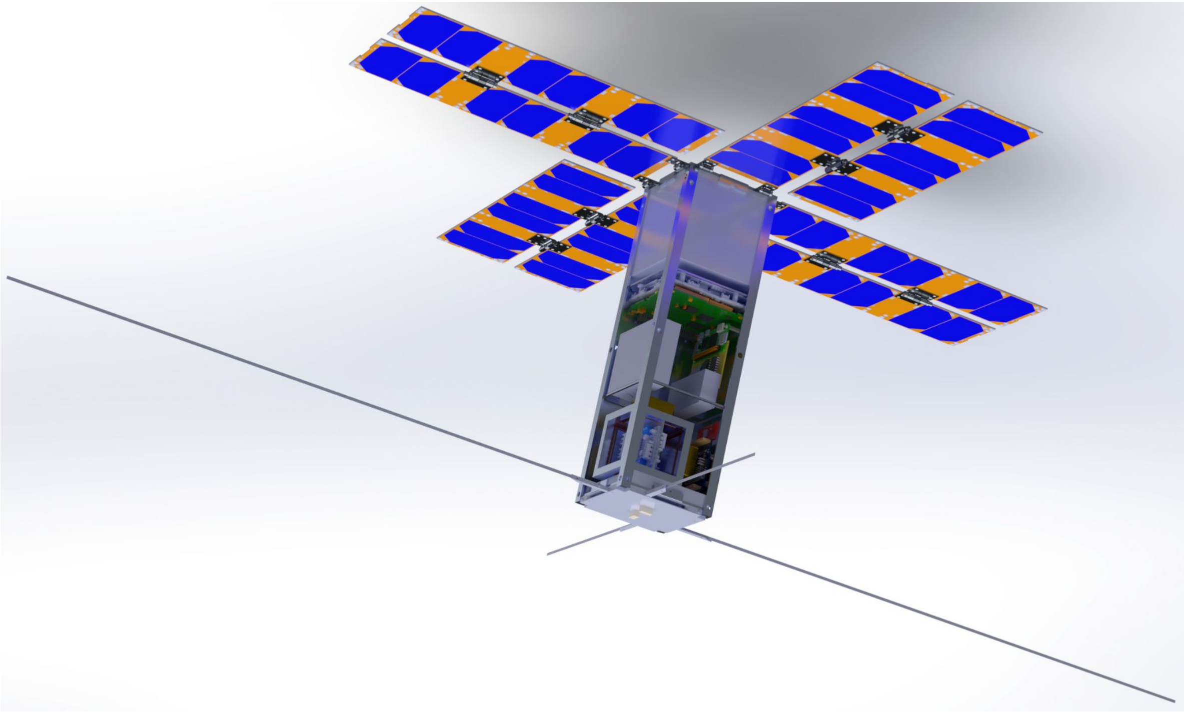
Energy Range (MeV/nuc)	**Average Flux (cm^2/MeV/s)**	**Comments**
1.00 - 3.00	Higher baseline	Noticeable in low energy
10.00 - 50.00	Medium exposure	Regular exposure, moderate risk
100.00 - 500.00	Lower exposure but present	Less frequent, sporadic bursts

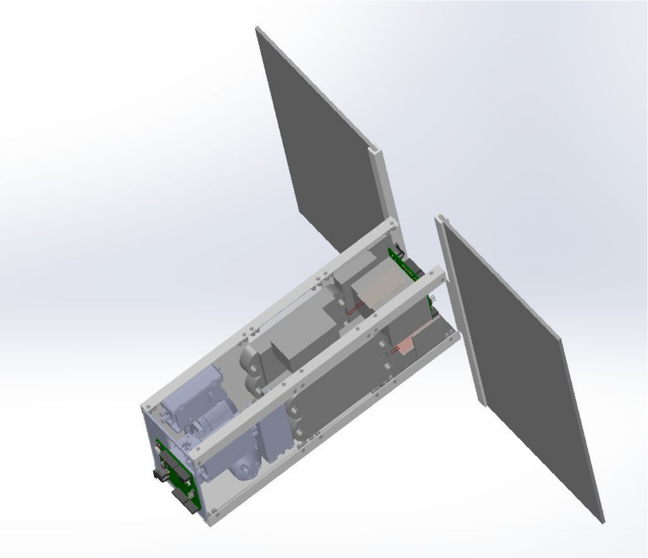
CONOPS


COMPUTATIO N IN LOW EARTH ORBIT SATELLITE FOR RELIABLE ACCESSIBILITY
NCSU MAE SENIOR DESIGN
2024-2025
CLEOSATRA
Harmful Radiation
Mission Phase 4: Radiation data/error logging & shield characterization
1-5 years
Mission Phase 5: EOL dragsail deployment & de-orbit burn-up
18.6 years
Mission Phase 3: antenna & solar-panel deployment
1 orbit
Mission Phase 2: PPod ejection and de-tumble
10 orbits
Mission Phase 1: Rideshare into LEO
2 hours
AWS Ground Station: Command & data transmission

Design Solution

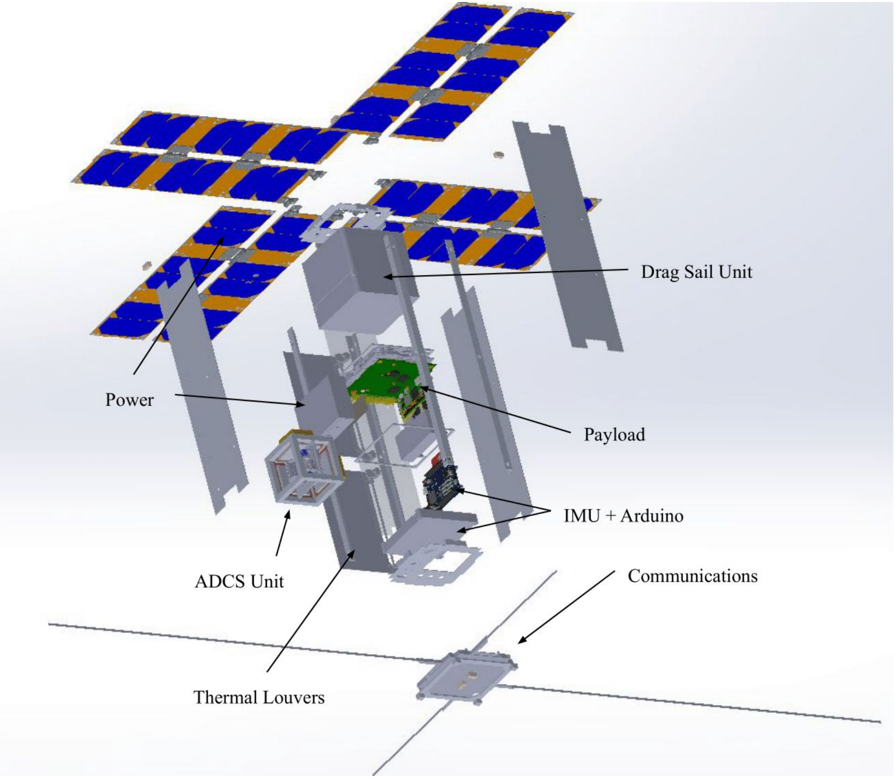
CAD Model

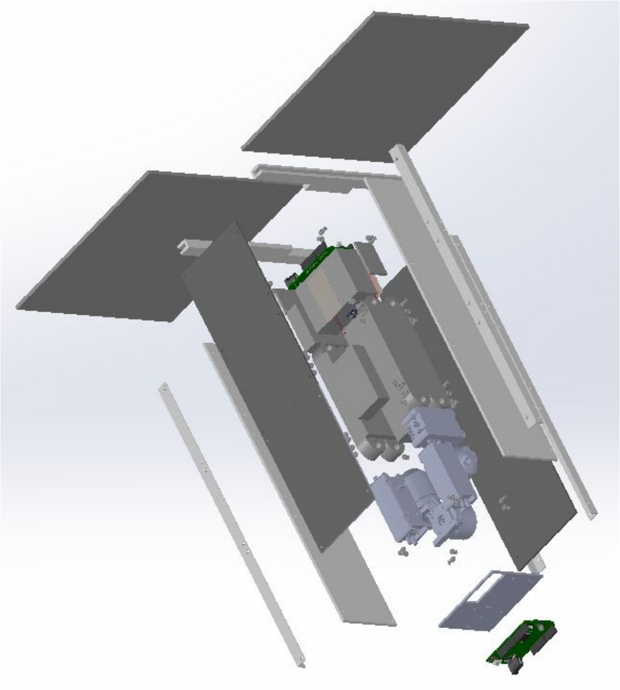




*Panels are hidden for ease of viewing

Exploded View



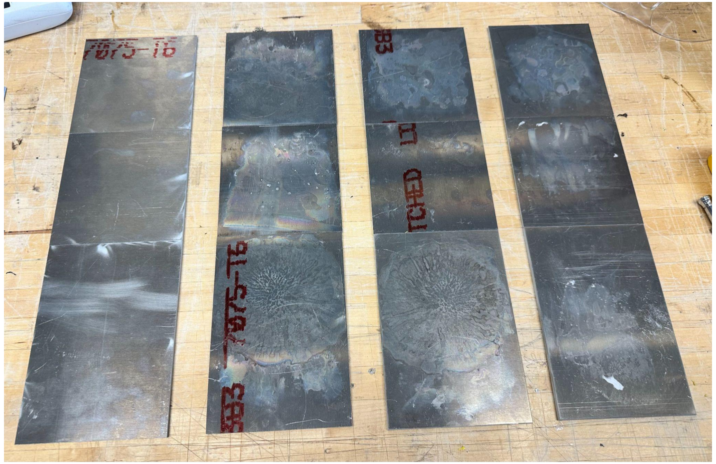


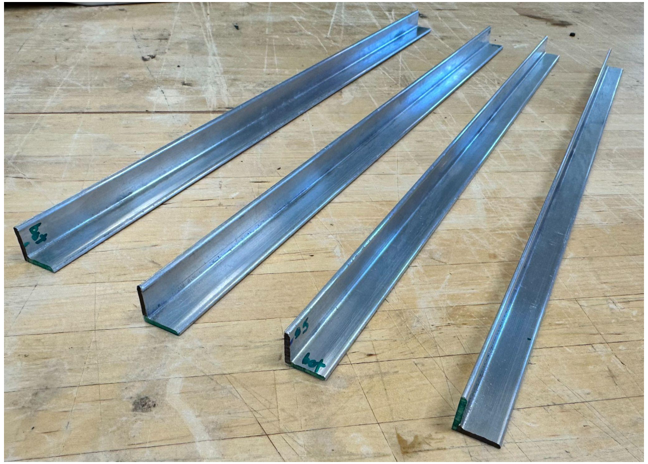
Structures

- **Gran Systems 3U Structure:**
  - Aluminum 6061-T6
  - 100 x 100 x 340 mm
  - 580 g
  - Temperature Range of −50°C to +120°C

Structures - Prototype

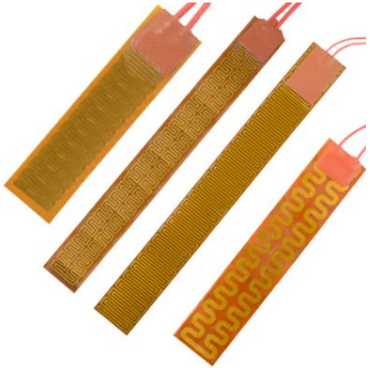
- **Frame:** Aluminum 7075 90° Angle Brackets
  - 100 x 100 x 340 mm
  - 18-8 Stainless Steel Socket Head Screws
- **Panels:** Aluminum 7075 Sheets

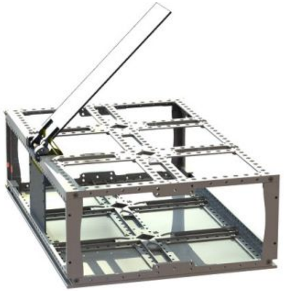


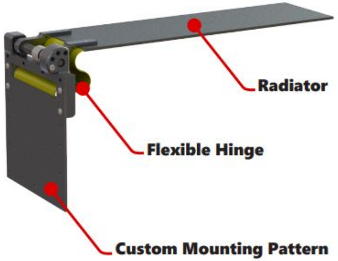


Thermal

- **External coating:** A276 Polyurethane
  - absorbs or reflect radiation
    - absorbance: 0.23
    - emittance: 0.88-0.91
- **Internal coating:** Z306 Polyurethane
  - facilitates heat transfer between components
    - absorbance: 0.95
    - emittance: 0.90
- **Kapton Flexible Heater**
  - regulates battery temperature
- **Deployable Radiator**
- **Temperature Sensors:** 2x PT100-500

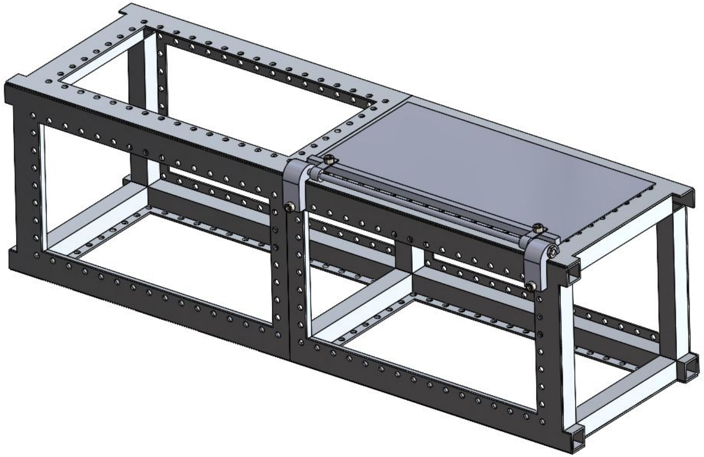


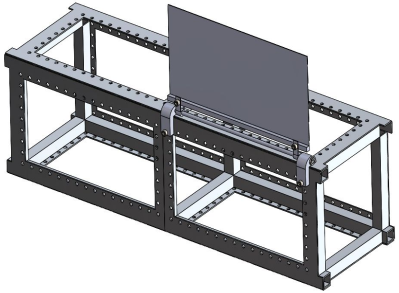




Thermal Louver

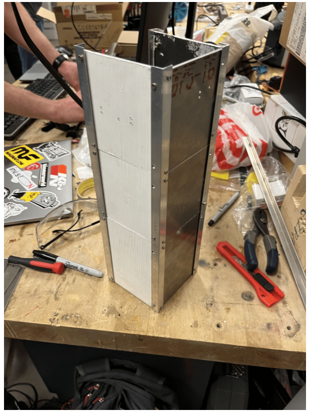
- High-efficiency embedded heat pipe radiator with high conduction hinge
- Active deployment via actuator and coil spring mechanism
  - 0-180°
- TRL 6
- Up to 1 square meter of heat rejection at 100W
- -20°C to +45°C

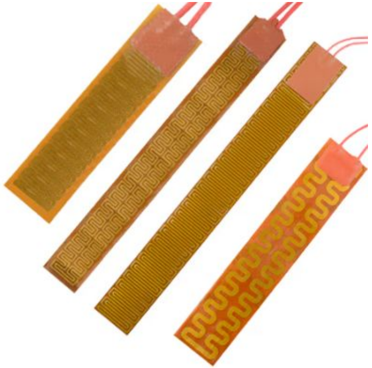


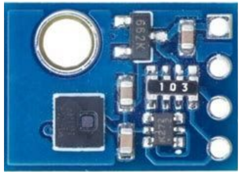


Thermal - Prototype

- **External coating:** Cool Cat Thermal, White Matte Coating
- **Kapton Flexible Heater:** PI Heating Elements Film Strip Heater Adhesive Polyimide Heater Plate
- **Temperature sensor:** 2x AHT21

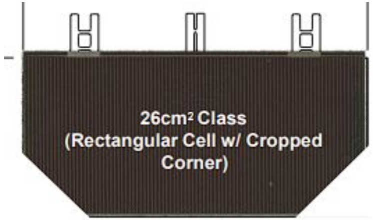


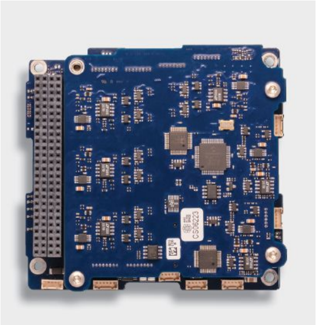




Power

- **Solar Arrays:** 4x Spectrolab 6U Deployable Arrays,
  - Triple junction cells.
  - 30.7% BOL, 26.7% EOL Efficiency
  - 150 g per panel, 1.2 kg in total
- **Electronic Power System,** Starbuck Nano Plus from AAC Clyde:
  - Provides capacity and redundancy for up to 12U cubesats
  - Support deployable panels
  - Most-flown EPS for cubesats





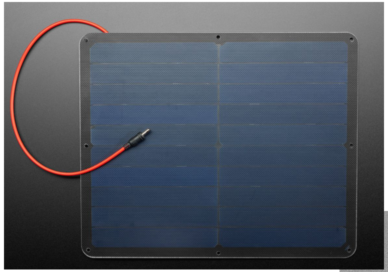
Product	NANO-PLUS
Integrated Battery	No
Intended Use	3- 12U CubeSat with deployable panels
Mass (typical)	148 g
Length	95.89 mm
Width	90.17 mm
Height*	20.82 mm

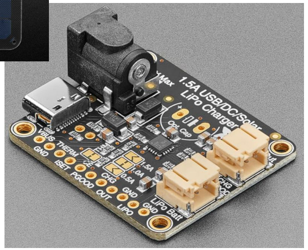
Power

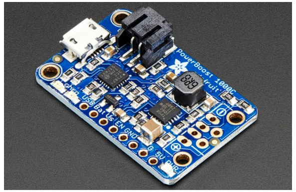
- **Lithium-ion batteries:** LG MJ1 18650 cylindrical lithium-ion cell
  - Minimum 15Wh battery capacity
  - 2 sets of 2 Cells in series for redundancy
  - Each Cell:
    - 3.64v
    - 3500 mAh
    - 49 grams
    - 10A discharge, 3.4A charge
    - 400 cycles

Power - Prototype

- **Solar Panels:** 2x 10w 5v Solar Panels
  - Charge the system using solar
- **Solar Charger:** 2x Adafruit bq24074 charger
  - Regulate solar panel charge with MPPT.
  - Outputs 4.4v, input 10V, max current load 1.5A
- **Batteries:** 2x 1s lithium ion (3.7v) 6600 mAh
  - Batteries will each be independently connected different solar arrays to provide redundancy
- **DC-DC Boost converters:**
  - Step up to 5v & 12v

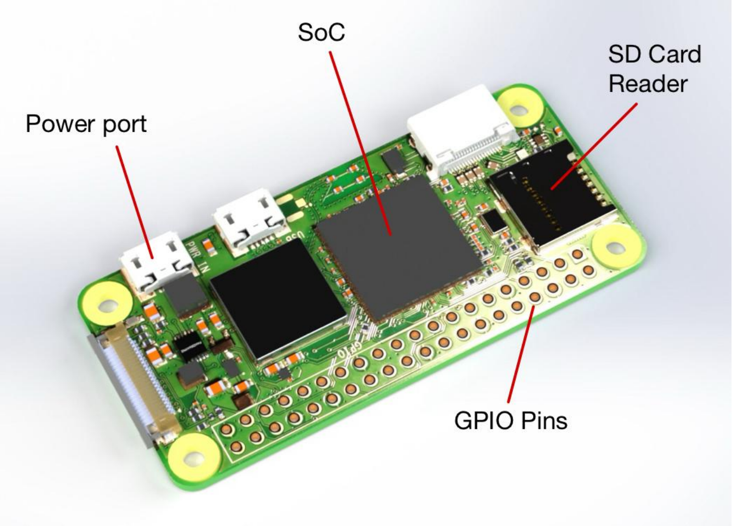


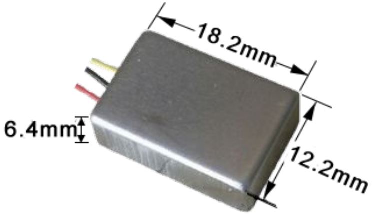




Payload

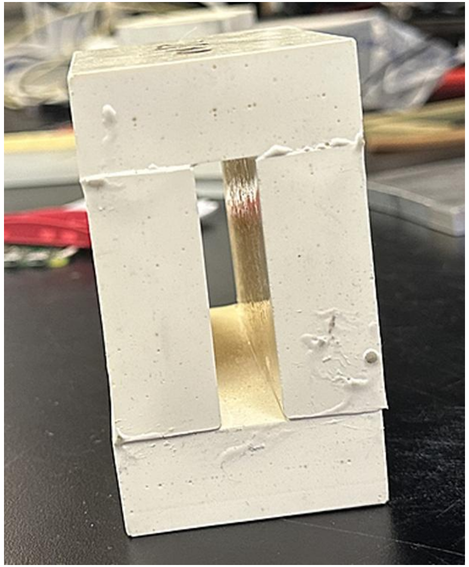
- **Processors:** 2x Raspberry Pi Zero 2 W's
  - Quad-core Arm A53 CPU
  - Video GPU
  - GPIO Communication
  - Over-voltage protection
- **Watchdog:** Arduino Beetle
  - Resets frozen processors
- **Multiplexor/Level Converter:** CD4053
  - Logic level shifting
- **Radiation Sensor:** SemeaTech Mini Gamma
  - Detects 30 keV ~ 3 MeV
  - 4,000 pulse counts/h

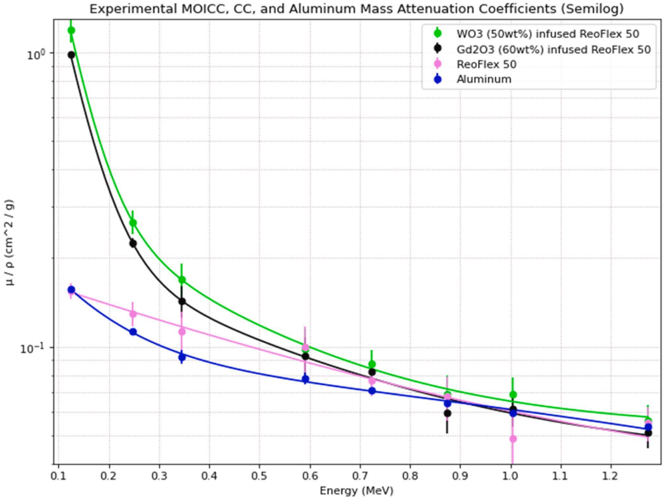




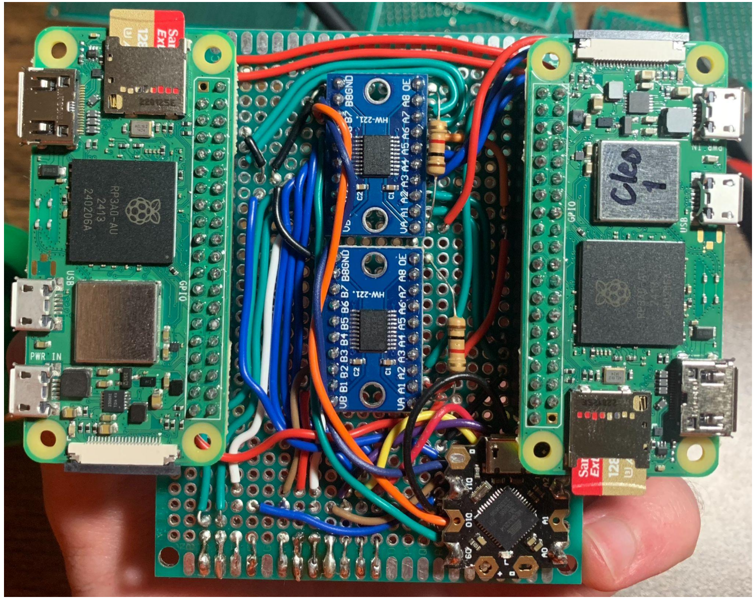
Payload

- **Radiation Shielding:** Conformal Coating doped with heavy metals
  - Developed by the NCSU Nuclear Engineering Dept.
  - Utilizing WO3





Payload



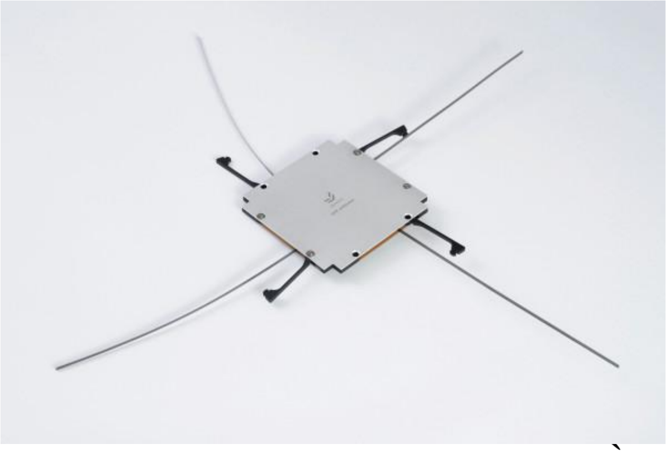
Processor communication circuit

Error Detection Algorithm:

- **Checksum memory scans**
  - Blocks tested via encryption
- **System health checks**
  - Task manager
  - Memory
  - CPU
- **Watchdog timer**
  - Resets frozen processor
  - Internal & External for redundancy

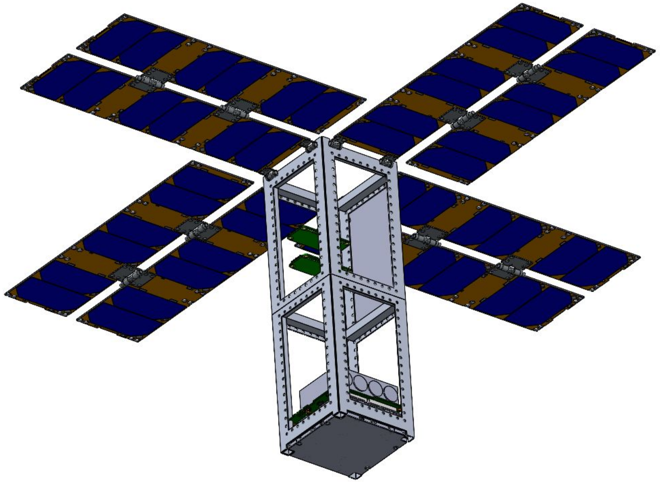
Data and Communications

- **UHF Transceiver:** EnduroSat UHF Transceiver II
  - Frequency Range: 400 - 403 MHz or 430 - 440 MH
  - Tx Power: 1W (up to 2W)
  - Mass: 94g
  - Data Rate: Up to 19.2 kbps
- **UHF Antenna:** EnduroSat UHF Antenna III
  - Deployable
  - Frequency Range: 400 - 438 MHz
  - Polarization: Circular
  - Mass: 85g
  - Gain: >0 dBi (Omnidirectional)

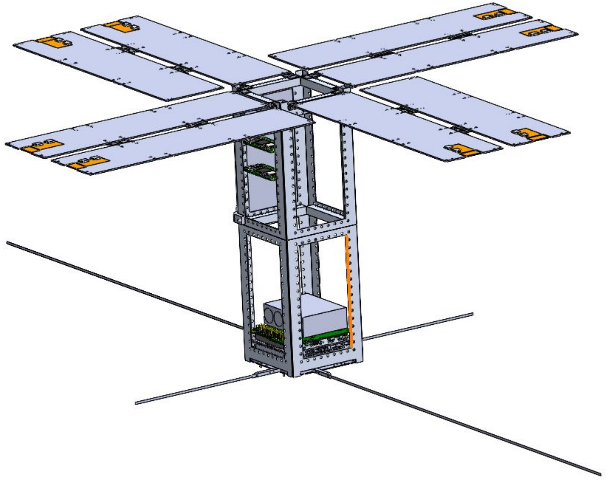


Data and Communications

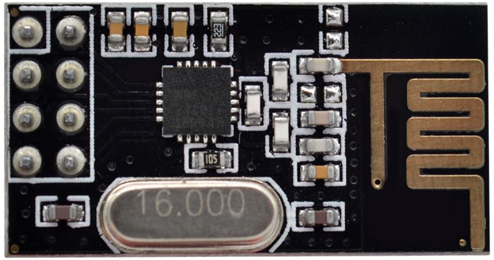
Stowed Antenna



Deployed Antenna



Communications - Prototype



- **Transceiver:** NRF24L01
  - Compact antenna
  - Frequency Range: 2.4-2.5GHz
  - Data Rate: 2Mbps
  - Input Power Range: 1.9 ~ 3.6V
  - Power Consumption: 9.0mA 6dBm
  - SPI Interface (Serial Peripheral Interface)
- **Controller:** Arduino Uno R4 Minima
  - Controls communication between main Raspberry Pi and
    - GPIO Communication

Mobility & Attitude Control

Reaction Wheels: 3x RocketLab's RW-0.003

- Aligned with the x, y, or z-axis to control internal torque
  - Nominal Torque: 0.003 Nm
  - Peak: 0.005 Nms at 5V

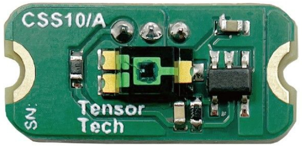
Magnetorquers: 3x EXA MT01 Compact Magnetorquer

- Desaturates reaction wheels and control external torque
  - Nominal Magnetic Moment: >0.19 Am^2
  - Torque produced depends on the strength of the surroun magnetic field

Mobility & Attitude Control

IMU with magnetometer: Space Inventor IMU-P4

- Includes 2 sets of gyroscopes, accelerometers, 3-axi magnetometers, and temperature sensors



Coarse Sun Sensors: 8x TensorTech CSS-10

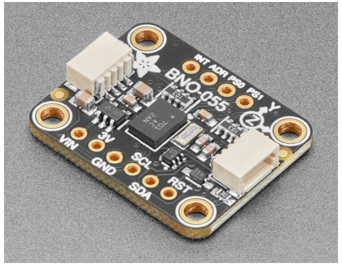
- 2x on each panel
- Accuracy within 5 degrees

Fine Sun Sensors: 4x TensorTech FSS-15

- 1x on each panel
- Accuracy within 0.1 degrees

Attitude Control - Prototype

- **Reaction Wheels:** Brass flywheels connected to 12V BLDC motor
  - Hall sensor to monitor RPM
- **IMU:** Adafruit 9-DOF Absolute Orientation IMU Fusion Breako
  - Includes: magnetometer, gyroscope, and accelerometer



Ground Station

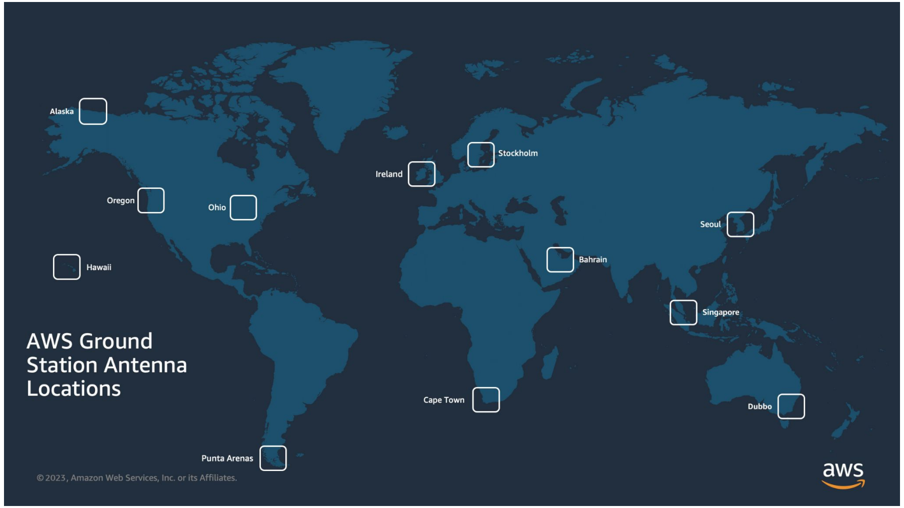
AWS Ground Station Service

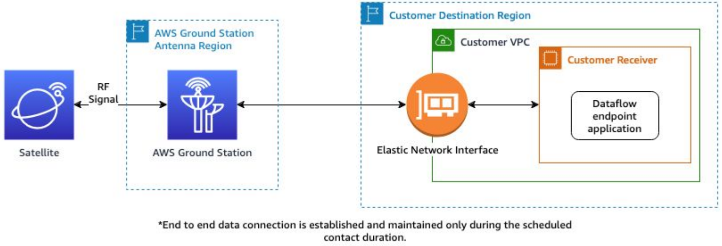
Global Access: Provides 9+ ground stations worldwide with UHF, S-band, and X-band support, enabling frequent access to CubeSat data.

Cost-Effective: Pay-per-minute model, allowing us to avoid the high upfront and maintenance costs of building and operating a dedicated ground station.

Cloud Integration: Direct pipeline to AWS services (S3, EC2, and more) for data storage, processing, and AI/ML applications on telemetry, and payload data.

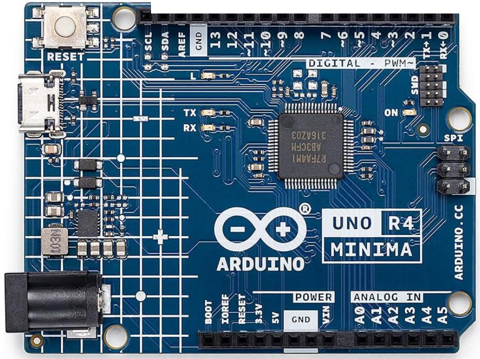
Flexibility: AWS Ground Station offers on-demand satellite communication with dynamic scheduling, ensuring efficient resource use

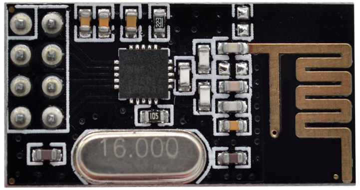




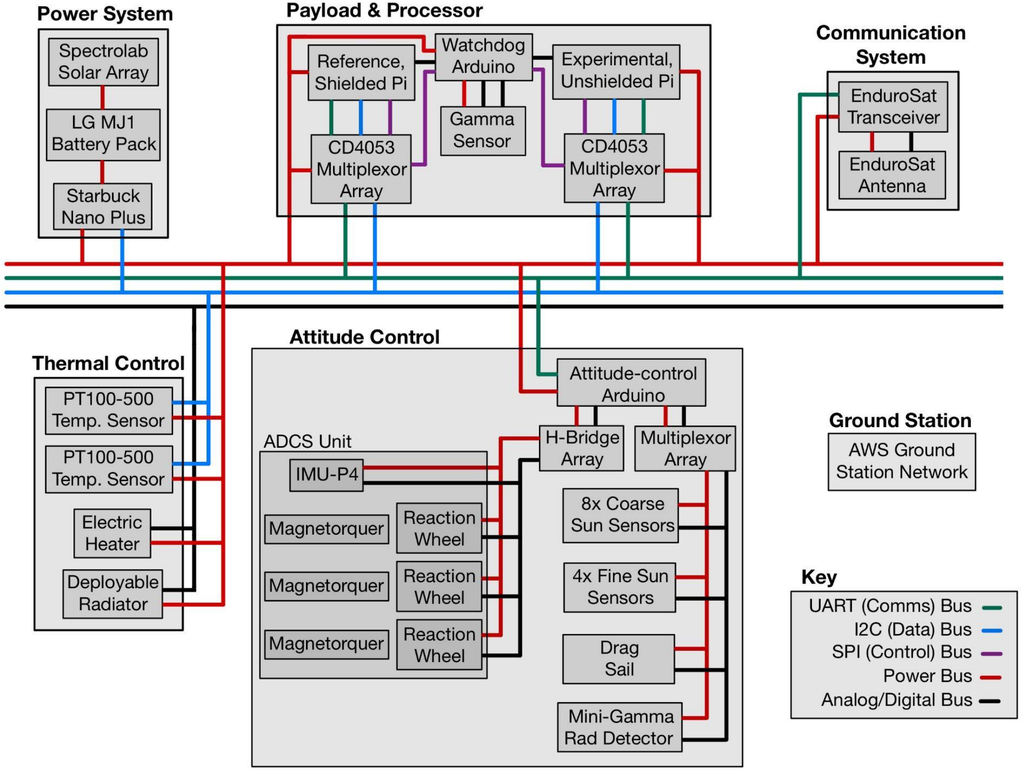
Ground Station - Prototype

- **Transceiver:** NRF24L01
  - Frequency Range: 2.4-2.5GHz
  - Data Rate: 2Mbps
- **Controller:** Arduino Uno R4 Minima
  - Controls communication between main Raspberry Pi and
- **PC:** Laptop with NRF24 Library
  - Primary interface with Arduino
  - power source
  - Used for programming, monitoring, and logging ground station to satellite communication

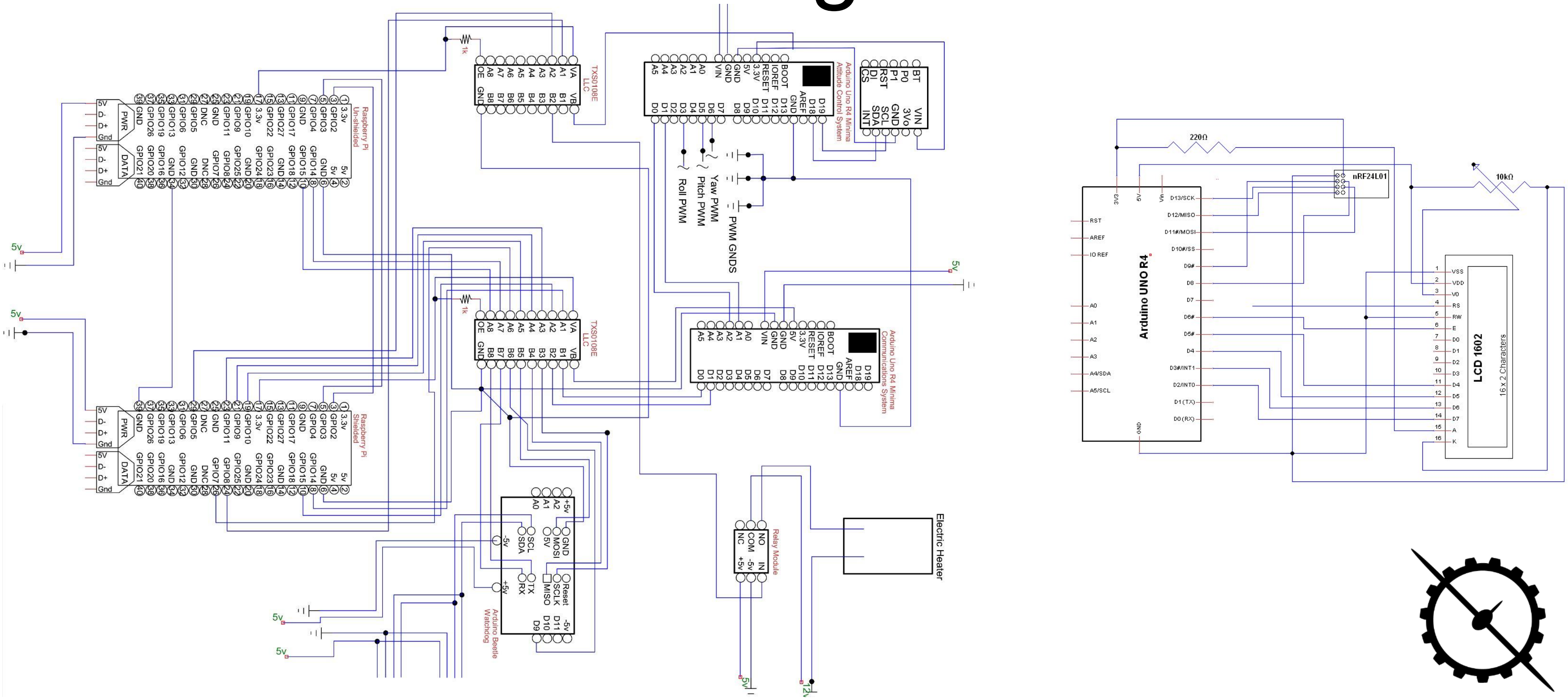




Functional Block Diagram



CLEOSATRA Wiring Schematic

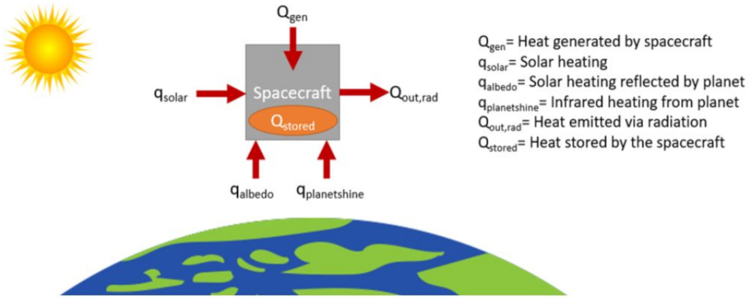


Evidence of Feasibility

Thermal

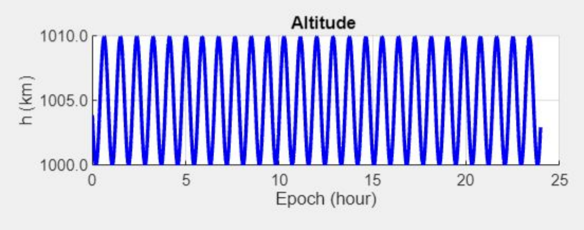
- Governing Equation:
  - Orbiting Spacecraft heating problem:

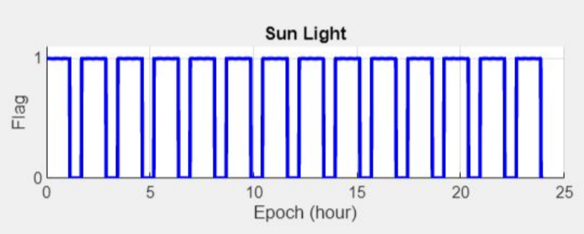
    $q_{solar} + q_{albedo} + q_{IR} + Q_{gen} = Q_{stored} + Q_{out,rad}$
- Heat Sources:
  - α = 0.23, absorption for AZ276
  - Solar Radiation
    - G_s = 1361 W/m^2
    - $q_{solar} = \alpha G_s A_s \cos(\theta)$, [W]
  - Albedo Radiation
    - a = 0.3
    - $q_{albedo} = G_s \alpha A_{alb} F_e(a)\cos(\varphi)$, [W]
  - IR Radiation
    - G_{IR} = 250 W/m^2
    - ε = 0.88, emissivity for AZ276
    - $q_{IR} = \varepsilon G_{IR} A_{IR} F_e$, [W]
- LEO Data Values:
  - -65°C to 125°C
- Q_{gen} values based on internal heat generated by spacecraft components, and electric heater
- Q_{stored} values based on internal heat stored by spacecraft, not radiated or dissipated out

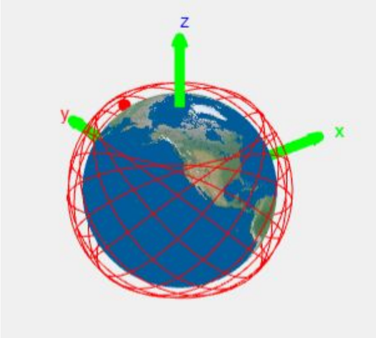


Thermal

- Ansys STK Simulation, Matlab CubeSat Thermal Power Tool:
- Single Day orbit: January 2nd, 2027

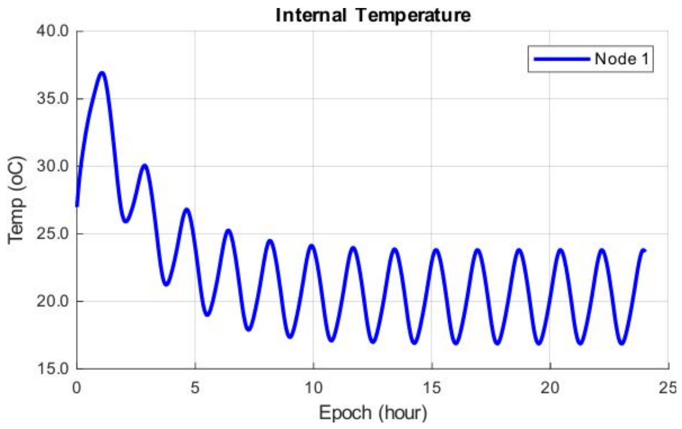


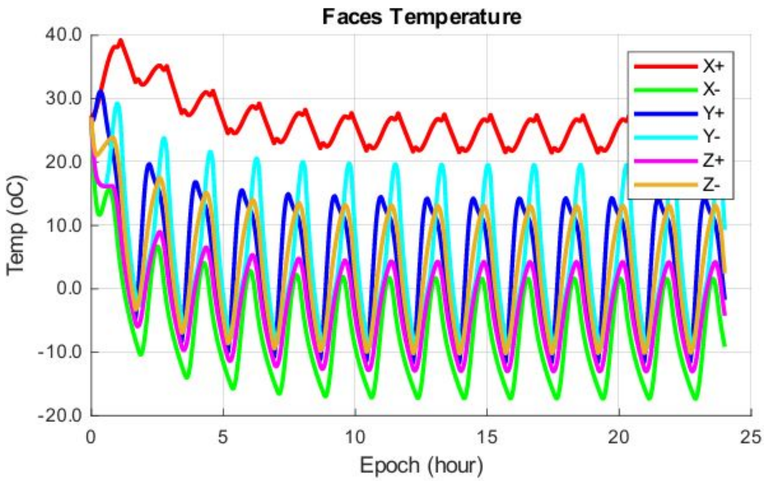




Thermal

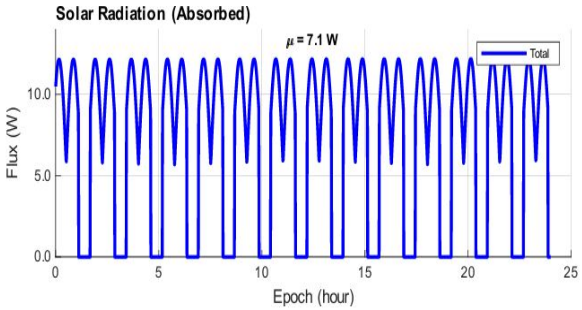
Maximum temperature range allowed: 0-50 Celcius for systems range, 20-40 Celsius for Power System requirements

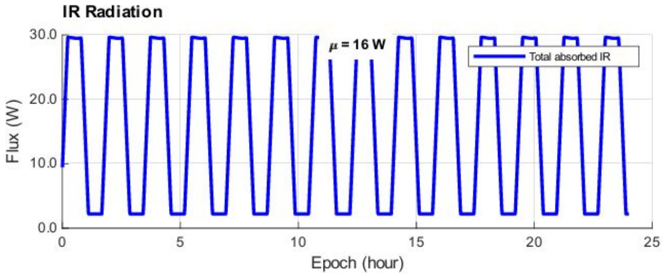


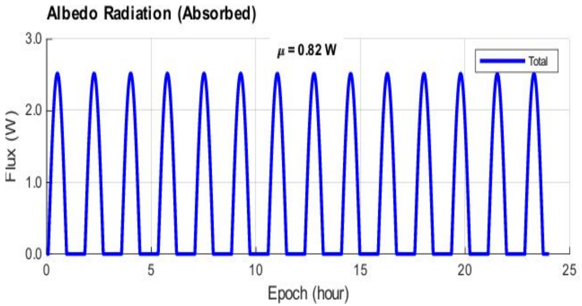


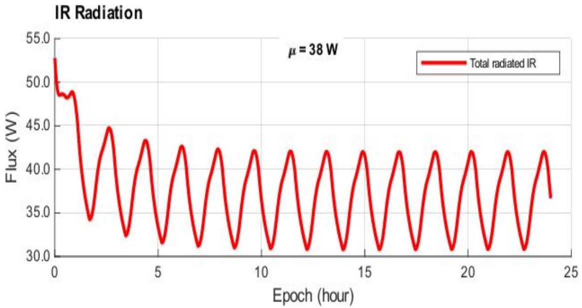
Thermal

Radiation Values: Single Day Orbit



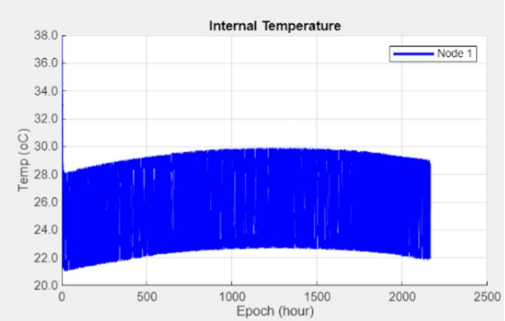


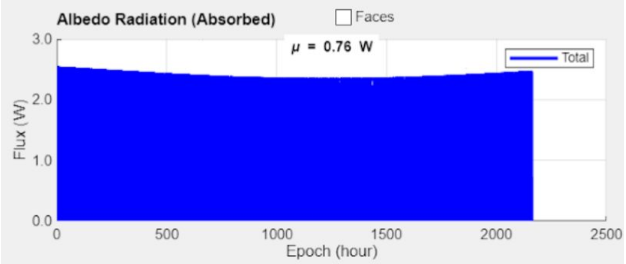


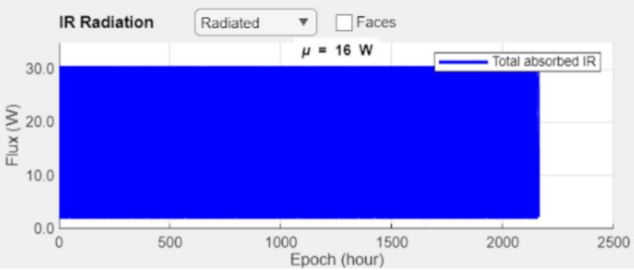


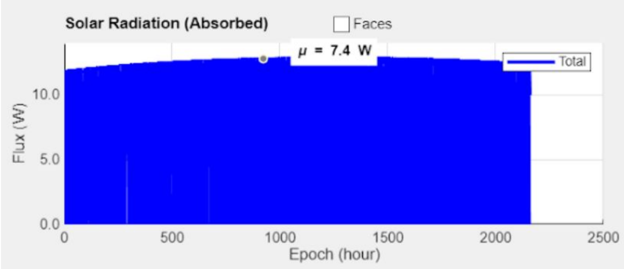
Thermal

90 day orbit: January 1, 2027 - April 1, 2027









Thermal

- Q_{gen}
  - Electric Heater = 2.5W/in^2, about 7.5W total
  - Heat generated by CubeSat components = <10 W
- Q_{stored}
  - 10-20 W, would change based on Z306 usage between systems

Thermal

- Deployable Radiator:
  - $Q_{out,rad} = A_{rad} Q \varepsilon \sigma (T_{rad}^4 - T_{sink}^4)$
  - Deployed Area to Stored Volume [1/m]:
    - A/At = 1/t : Maximum value for panel radiator
    - 32 m^-1
- Heat dissipated per width: $\frac{q}{W} = 2kt\left(\frac{\sigma\varepsilon}{5kt}\right)^{1/2}\left(T_{base}^5 - T_{tip}^5\right)^{1/2}$
  - Maximum 60W dissipated if all surfaces of 3U CubeSat are a radiator
  - A single radiator with area as shown in CAD would dissipate around 5-10 W

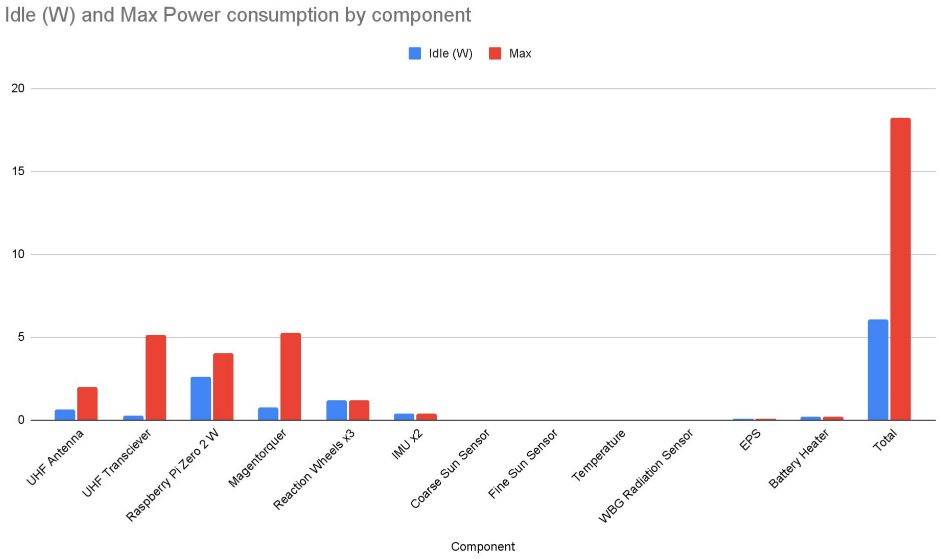
Thermal

- Simulation Data only accounted for A276 Polyurethane and Z306 Polyurethane as sole thermal control
- Electric Heater will still be required for the power system
- Simulation could mean that deployable radiator is not needed to effectively dissipate heat initially
- Coatings will darken with time and lose effectiveness the longer the mission

Thermal

Component	Mass (kg)	Power (W)
Kapton Electric Heater	0.0045 kg	0.2
Temperature Sensor Pt100-500 (x2)	0.00072	0.033
Coatings	0.04	0
Deployable Radiator	0.3	0
Total	0.34594	0.332

Power Budget



Component	Idle (W)	Max
Communications		
UHF Antenna	0.6	2
UHF Transceiver	0.24	5.1
Payload		
Raspberry Pi Zero 2 W	2.6	4
Attitude Control/GnC		
Magnetorquer	0.75	5.25
Reaction Wheels x3	1.2	1.2
Sensors		
IMU x2	0.4	0.4
Coarse Sun Sensor x8	0.00264	0.00264
Fine Sun Sensor x2	0.00495	0.0132
Temperature x2	0.0066	0.0066
WBG Radiation Sensor	0.0015	0.0015
Power Management		
EPS	0.035	0.035
Battery Heater	0.2	0.2
Total	6.04069	18.20894

Power Calculations

Total Power Draw

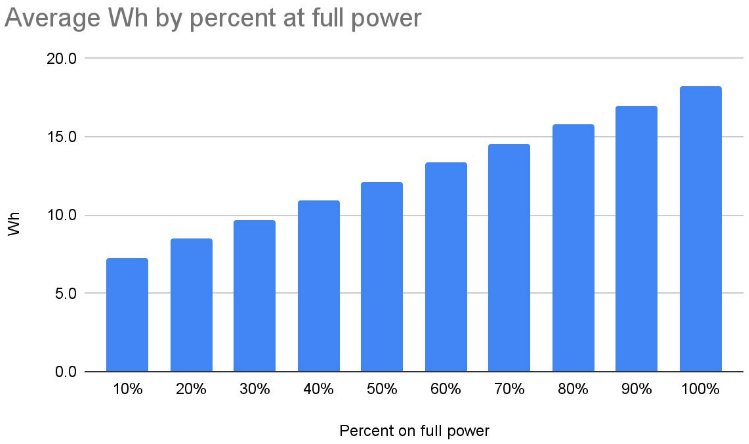
$$P_{\text{total}} = P_{\text{payload}} + P_{\text{bus}} + P_{\text{comms}} + P_{\text{thermal}} + P_{\text{gnc}} + P_{\text{sensors}}$$

Power generated by the solar array

$$P_{\text{SA}} = \eta_{\text{SA}} \cdot A_{\text{SA}} \cdot S \cdot \cos(\theta)$$

Battery Capacity Needed

$$C_{\text{batt}} = \frac{P_{\text{total}} \cdot T_{\text{eclipse}}}{\eta_{\text{batt}} \cdot DOD}$$



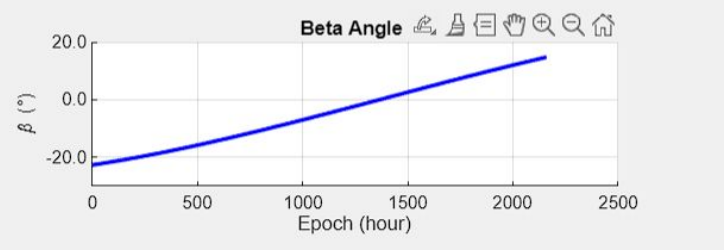
Beta Angle: The angle between the sun and a satellite's orbital plane. 0 Degrees is the least sun the satellite will receive.

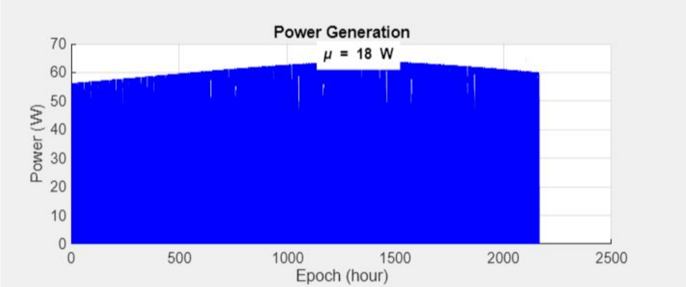
$$\beta = \sin^{-1}[\cos(\Gamma)\sin(\Omega)\sin(i) - \sin(\Gamma)\cos(\epsilon)\cos(\Omega)\sin(i) + \sin(\Gamma)\sin(\epsilon)\cos(i)]$$

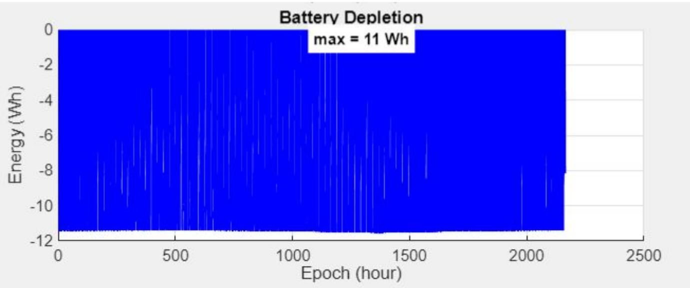
Power Simulation

Used Matlab Cubesat Power/Thermal Toolkit for 90 day increments.
Defined the average Wh usage at 50% operating time at full power.
6U arrays deployed from each Y and Z face

September 30th - December 20th, 2027



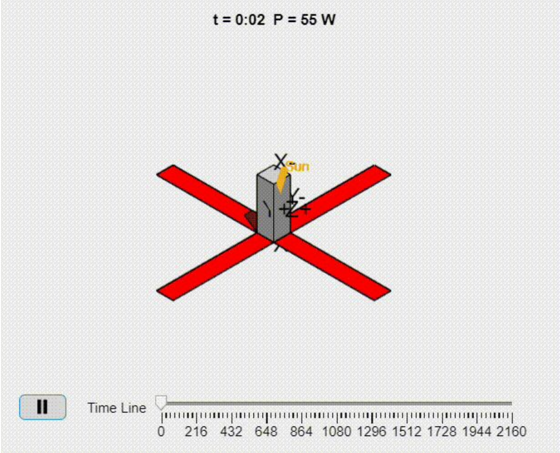




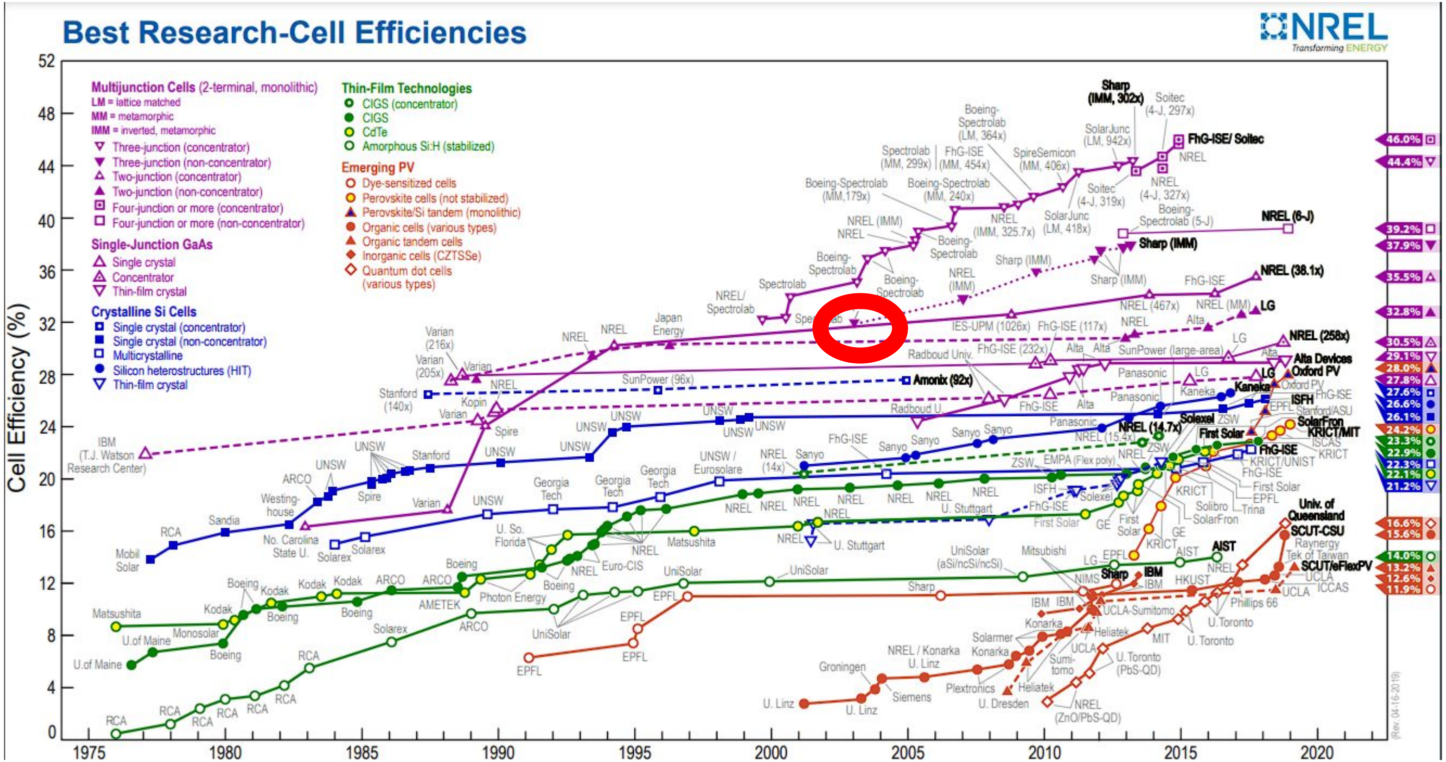
Power Simulation

The 11 Wh max battery discharge requires a battery capacity of 14 Wh to ensure that 80% DoD is never reached

Time Period	Average Power Draw (W)	Mean Power Generated (W)	Max Discharge (Wh)
1/1 - 3/31/27	12.1	18	11
4/1 - 6/30/27	12.1	19	11
7/1-9/29/27	12.1	18	11
9/30-12/26/27	12.1	18	11



Solar Cell Timeline



Flight Heritage and Certifications

Recent mission of IM-1, used Spectrolab's cells. Flight heritage goes back to Apollo missions [10]

NASA SOA: 90%+ of Satellites use solar power as the means to generate power.[1]

Spectrolab has produced over 1,500 triple junction arrays for space use [9] as of 2010, and millions of multi-junction cells [8].

XTJ cell line is AIAA-S111 & AIAA-S112 Space Qualified [6]

Flight Heritage and Certifications

NASA's Pace mission flew the LG MJ1 battery cell [1]

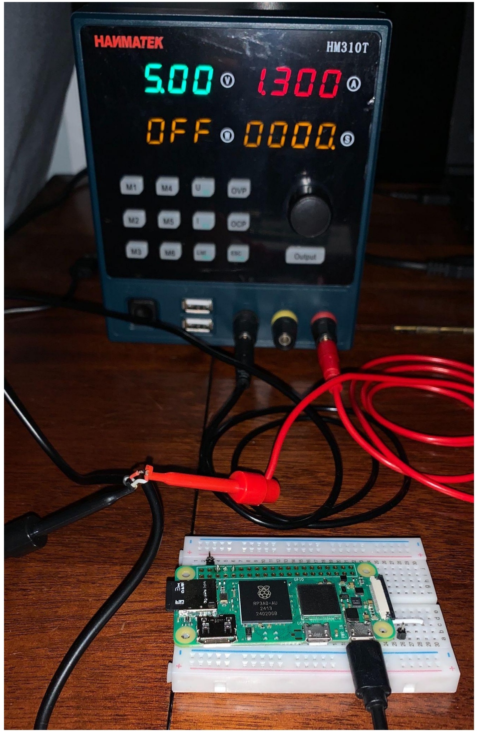
Lithium Ion batteries are used to power the ISS space suits [7]

Payload Processor Comparison

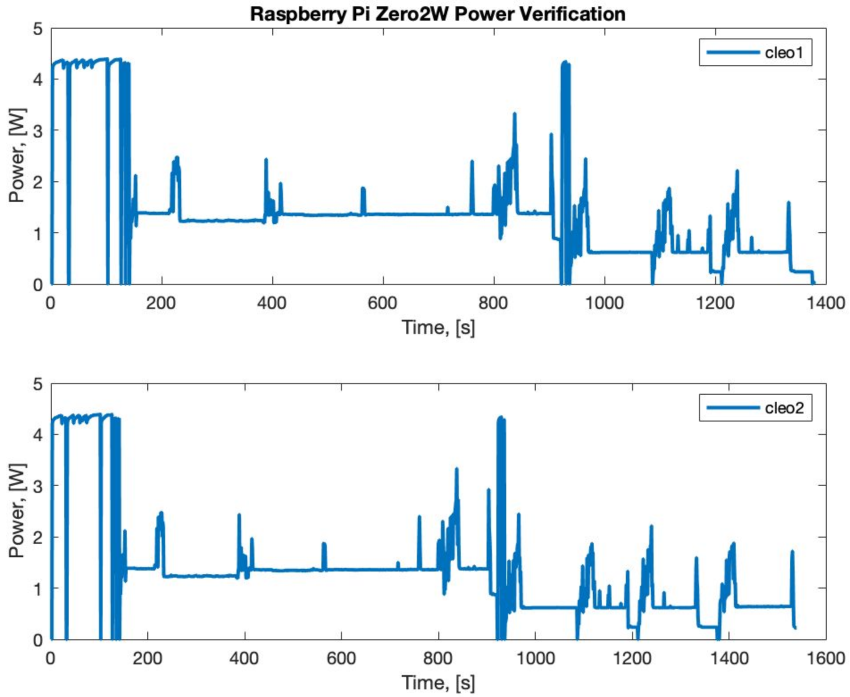
Raspberry Pi Zero 2W's power consumption was verified during the boot sequence

- Experiments run at 5 volts nominal
- Over-current protection set to 1.3, but allows up to 2.6

- $V = I*R \Rightarrow P = V*I$



Pi Power Results



- Correctly verified Zero 2W core-throttling
- Will be undervolting to 3.5-4 volts
- Tests run with Wifi, SSH, & LEDs running

Error Logging

radiation_errors.log

Reveal Now Clear Reload Share Search

```
2024-11-13 23:56:43,981 - INFO - Starting radiation error monitoring...
2024-11-13 23:56:43,981 - INFO - Initial checksum of critical file: e1088f9990693a84bf64a136096a61d5
2024-11-14 00:02:57,276 - INFO - Starting radiation error monitoring...
2024-11-14 00:02:57,279 - INFO - Initial checksum of critical file: e1088f9990693a84bf64a136096a61d5
2024-11-14 00:02:58,320 - WARNING - Detected 1789 error(s) in system logs.
2024-11-14 00:02:58,424 - CRITICAL - Potential radiation-induced error detected!

2024-11-14 00:03:09,459 - WARNING - Detected 1789 error(s) in system logs.
2024-11-14 00:03:09,556 - CRITICAL - Potential radiation-induced error detected!

2024-11-14 00:03:20,592 - WARNING - Detected 1789 error(s) in system logs.
2024-11-14 00:03:20,692 - CRITICAL - Potential radiation-induced error detected!

2024-11-14 00:03:31,728 - WARNING - Detected 1789 error(s) in system logs.
2024-11-14 00:03:31,829 - CRITICAL - Potential radiation-induced error detected!

2024-11-14 00:03:42,864 - WARNING - Detected 1789 error(s) in system logs.
2024-11-14 00:03:42,953 - CRITICAL - Potential radiation-induced error detected!

2024-11-14 00:03:53,988 - WARNING - Detected 1789 error(s) in system logs.
2024-11-14 00:03:54,083 - CRITICAL - Potential radiation-induced error detected!

2024-11-14 00:04:05,118 - WARNING - Detected 1789 error(s) in system logs.
2024-11-14 00:04:05,208 - CRITICAL - Potential radiation-induced error detected!

2024-11-14 00:04:16,243 - WARNING - Detected 1789 error(s) in system logs.
2024-11-14 00:04:16,337 - CRITICAL - Potential radiation-induced error detected!

2024-11-14 00:04:27,372 - WARNING - Detected 1789 error(s) in system logs.
2024-11-14 00:04:27,469 - CRITICAL - Potential radiation-induced error detected!

2024-11-14 00:04:38,503 - WARNING - Detected 1789 error(s) in system logs.
2024-11-14 00:04:38,598 - CRITICAL - Potential radiation-induced error detected!

2024-11-14 00:04:49,633 - WARNING - Detected 1789 error(s) in system logs.
2024-11-14 00:04:49,731 - CRITICAL - Potential radiation-induced error detected!

2024-11-14 00:05:00,766 - WARNING - Detected 1789 error(s) in system logs.
2024-11-14 00:05:00,874 - CRITICAL - Potential radiation-induced error detected!

2024-11-14 00:05:11,927 - WARNING - Detected 2760 error(s) in system logs.
2024-11-14 00:05:12,011 - CRITICAL - Potential radiation-induced error detected!

2024-11-14 00:05:23,064 - WARNING - Detected 2760 error(s) in system logs.
2024-11-14 00:05:23,152 - CRITICAL - Potential radiation-induced error detected!

2024-11-14 00:05:34,205 - WARNING - Detected 2760 error(s) in system logs.
2024-11-14 00:05:34,297 - CRITICAL - Potential radiation-induced error detected!

2024-11-14 00:05:45,350 - WARNING - Detected 2760 error(s) in system logs.
2024-11-14 00:05:45,436 - CRITICAL - Potential radiation-induced error detected!
```

- Successfully checked memory with initial checksums
- Detects potential radiation-induced processor error
- Determines if the error exceeds critical threshold
- Logs date, time, radiation level # of errors
- Adding Pi-Pi communication next

Manufacturing

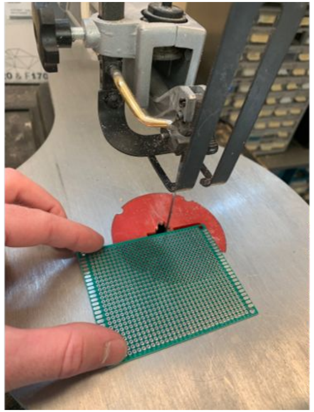
Subsystem Manufacturing

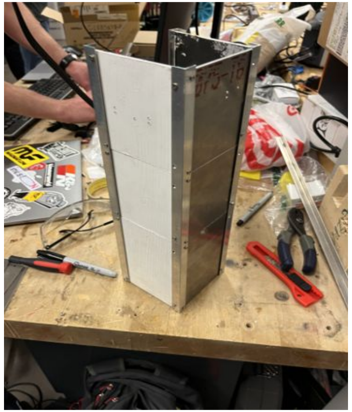
Structures

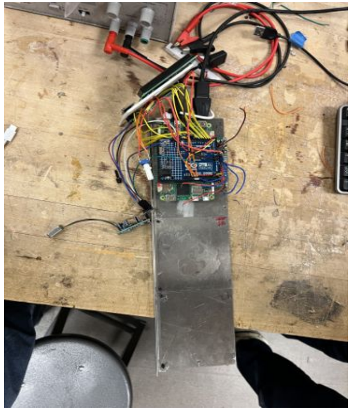
- Cutting of panels and corner bars
- Drilling of holes for system components

Payload

- Raspberry Pi wiring and configuration
- Watchdog script integration into Arduino Beetle
- Conformal coating procurement







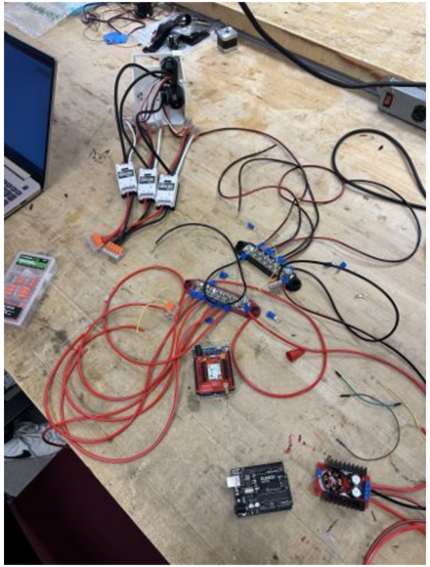
Subsystem Manufacturing

Thermal

- Painting of +Y, -Y, +X face
- Integration of temperature sensor and heater

Power

- Battery and solar panel setup
- Configuration for power connection to each system

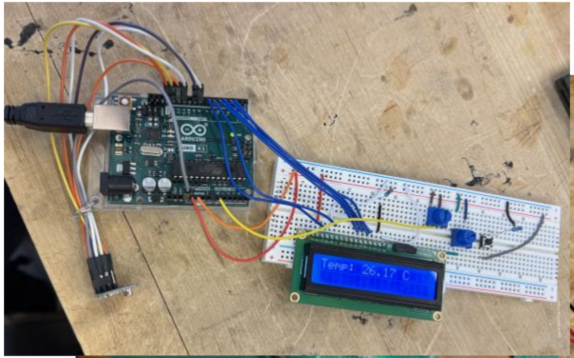


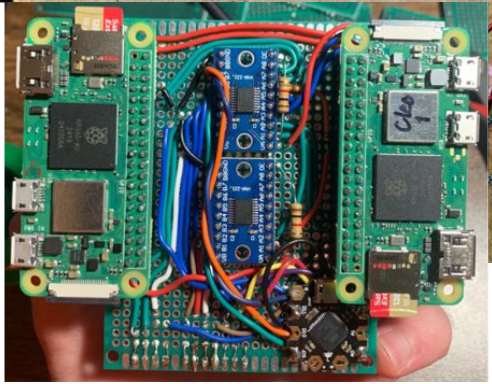
Subsystem Manufacturing

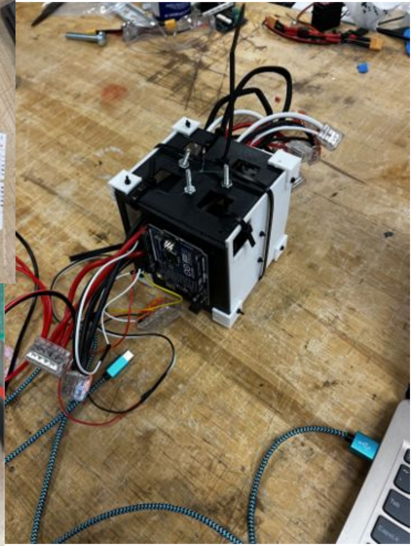
<u>Mobility Control</u>
- Motor and controller wiring and setup
- IMU and telemetry data creation

<u>Communications</u>
- Arduino R4 data handling and setup
- Integration for transmitting with Ground Station

<u>Ground Station</u>
- NRF Module and LCD screen setup
- Integration with Communications



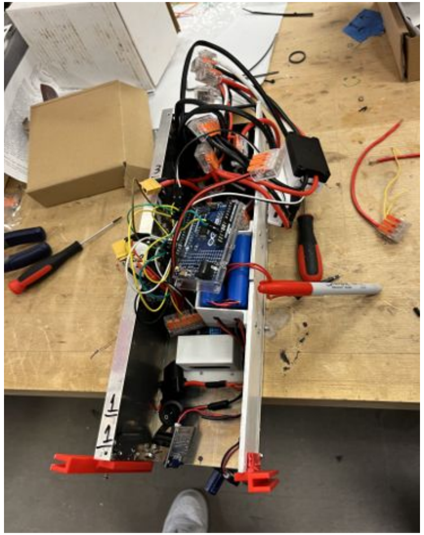


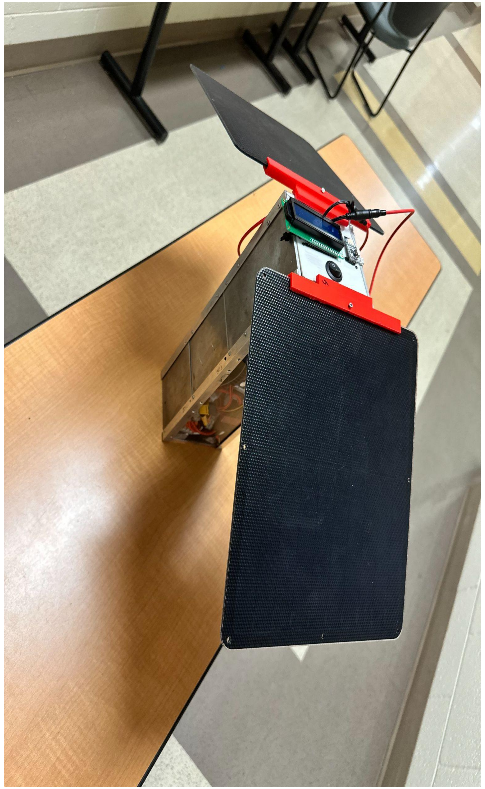


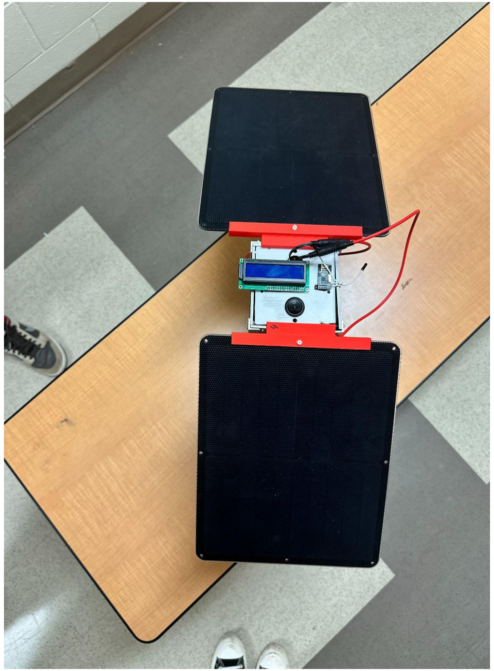
Results: Final Prototype

Final Integration

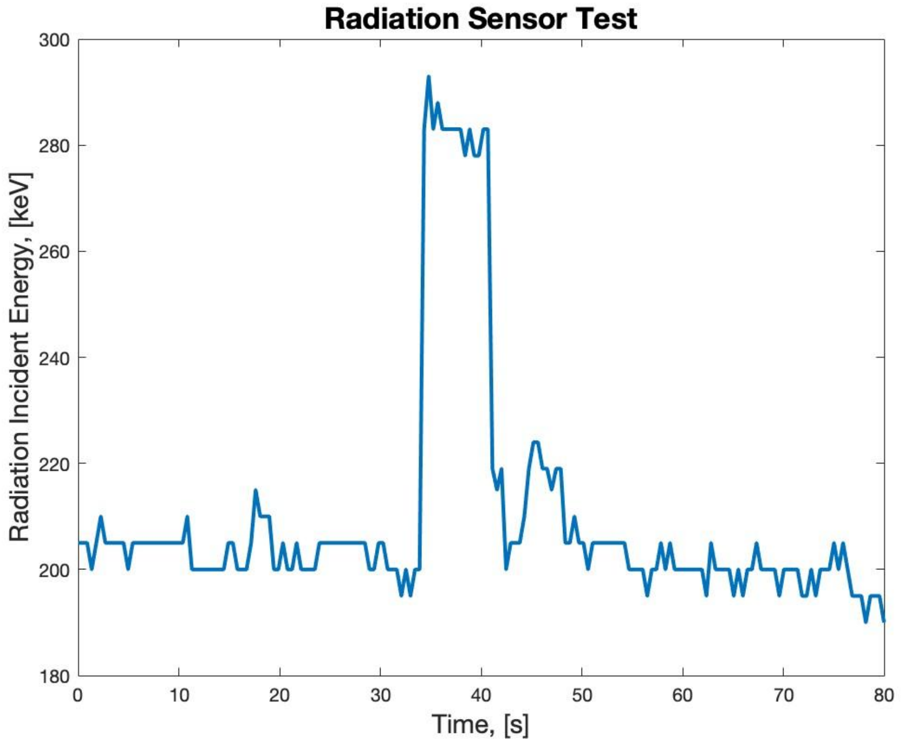
Components from each of the subsystems were integrated as required and input into the final prototype according to CAD placement.







Radiation Testing Results



- Background radiation in the lab ~200 keV
- Spiked when approached with radiation sample
  - Jumped to ~280 keV
- Radiation sensor was located between the processors

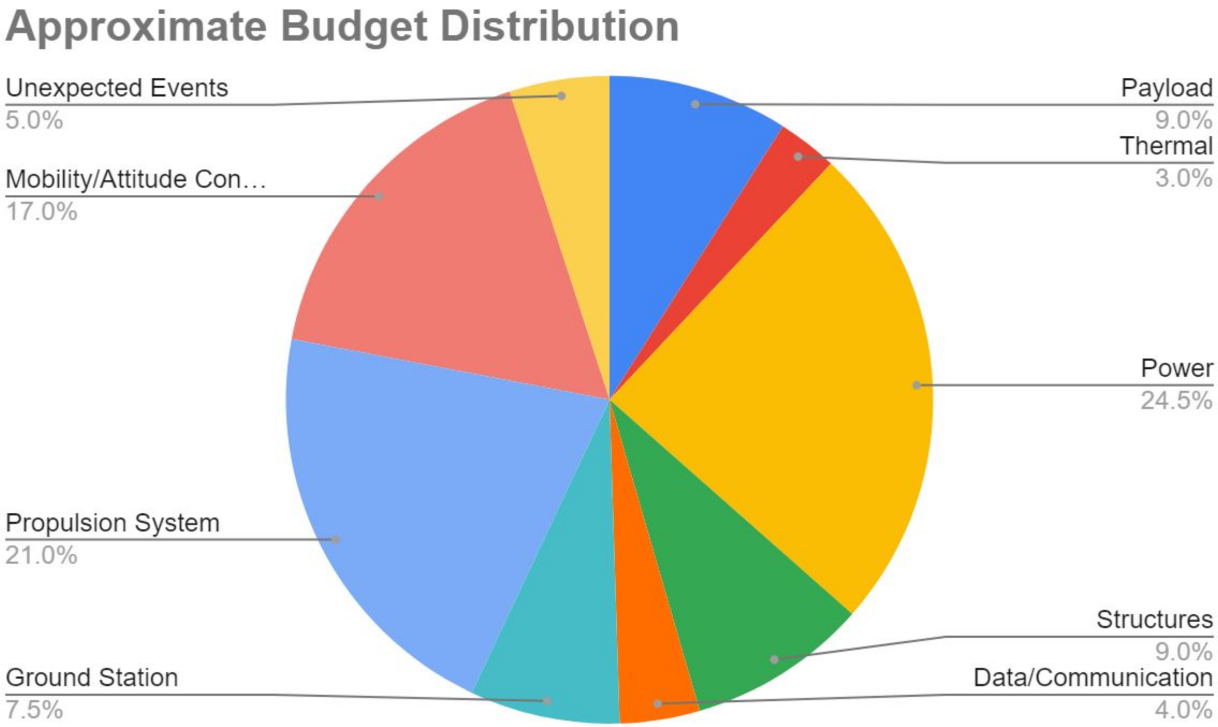
Budget

Budget Overview

Total Budget: $240,000	**Approximate Budget for Subsystem:**		
Subsystem	**Low End**	**Middle Ground**	**High End**
Payload	$19000	$25000	$30000
Thermal	$5000	$11000	$25000
Power	$45000	$70000	$130000
Structures	$15000	$30000	$50000
Data/Communication	$5000	$15000	$40000
Ground Station	$12500	$24000	$40000
Propulsion System	$40000	$60000	$100000
Mobility/Attitude Control	$30000	$50000	$65000
Unexpected Events	$6000	$8400	$12000
Total Approximate Budgets:	**$177500**	**$293400**	**$492000**

Budget Overview Cont.

Total Budget: $240,000

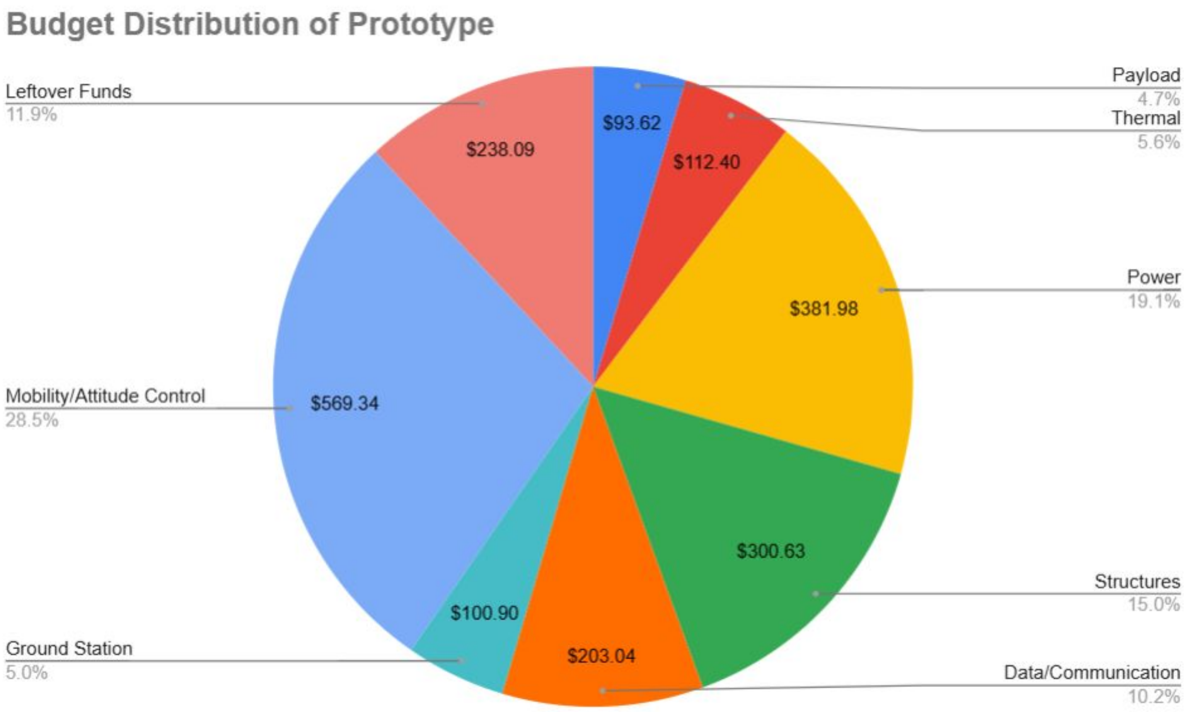


Prototype Budget Overview

Subsystem	Component	Cost
Payload	Raspberry Pi Zero 2 W	$42.78
	M2.5x4.5mm Hex Male Stand-off	$5.40
	Black-Oxide Alloy Steel, M2.5 x 0.45 mm Thread, 5 mm Long	$8.46
	127 gb SD Card	$25.98
	Beetle, arduino	$11.00
Thermal	Cool Cat Thermal Barrier, White Matte	$58.99
	Paint Primer, White Matte	$7.49
	Flexible Electric Kapton Heater	$14.59
	AHT21 Temp Sensor	$6.69
	Heat Lamp Guard/housing	$12.86
	Heat Lamp Bulb	$11.78
Power	Solar charger	$29.90
	Solar Panels	$129.90
	Batteries	$49.00
	3.3v Step down converter	$24.75
	5v converter	$7.99
	12v Step up converter	$14.75
	DC connector converter cable	$3.00
	DC Bus Bar	$39.98
	High Power 12V step up converter (2 pack)	$9.99
	12v Inline Fuses (66 pack)	$7.29
	Ring connectors 16-14 AWG	$9.18
	14 Gauge Wire	$16.99
	Parallel JST Connector	$6.99
	1s Parallel Charger	$8.57
	Barrel Connector to Alligator clips	$3.21
	1/4" ring connector	$7.50
	High Power 5V step up	$12.99
Data/Communication	nRF24L01 Transceiver	$25.00
	Arduino Uno R4	$18.00
	2.4 GHz Dipole Antenna	$6.99
	Radiation Sensor	$144.27
	SMA to IPX MHF	$8.78
Ground Station	nRF24L01 Transceiver	$25.00
	Arduino Uno R4	$18.00
	2.4 GHz Antenna	$9.99
	SMA Connectors kit	$12.96
	Nooelec Lana LNA	$34.95
Mobility/Attitude Control	Brass Rod for 3 reaction wheels	$172.39
	Adafruit 9-DOF Absolute Orientation IMU Fusion Breakout	$24.95
	NEO Brushless 12V DC Motor V1.1	$84.00
	Arduino Uno R4	$18.00
	SPARK MAX motor controller	$270.00
Total Approximate Budget		$1,761.91

Budget Overview Cont.

Total Budget: $2,000



Conclusion

CLEOSATRA aims to redefine how electronics are shielded from radiation in space, while establishing a reliable commercial 3U-cubesat architecture.

- CLEOSATRA was selected to participate in the UNP Mission Concepts Program for the summer of 2025.

References

1. NASA State of the Art Small Spacecraft Technology, 2023
2. Candini, Piergentili, Santoni. "Miniaturized attitude control system for nanosatellites", *Acta Astronautica*, *Volume 81, Issue 1, 2012*. https://doi.org/10.1016/j.actaastro.2012.07.027.
3. Soo-Jin Kang and Hyun-Ung Oh, "On-orbit thermal design and validation of 1 U standardized CubeSat of STEP cube lab", *International Journal of Aerospace Engineering 2016*, 2016.
4. D.W. Hengeveld, M.R. Wilson, J.A. Moulton, et al, "Thermal design considerations for future high-power small satellites", *48th International Conference on Environmental Systems*, Albuquerque, New Mexico, 2018.
5. Casper Versteeg and David L. Cotten. "Preliminary thermal analysis of small satellites". *AIAA Student Conference Proceedings*, 2018.
6. Space Solar Cells/CICs," Rocket Lab. Retrieved 13 November 2024. https://www.rocketlabusa.com/space-systems/solar/space-solar-cellscics/
7. "Nobel-Winning Lithium-Ion Batteries Powering Space." Retrieved 13 November 2024. https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Nobel-winning_lithium-ion_batteries_powering_space
8. https://www.spectrolab.com/DataSheets/cells/2015%20UTJ%20CIC%20Datsheet.pdf
9. "Boeing's Spectrolab to Power NASA's Roman Space Telescope," MediaRoom. Retrieved 13 November 2024. https://boeing.mediaroom.com/2022-04-05-Boeings-Spectrolab-to-Power-NASAs-Roman-Space-Telescope
10. Sol, G. A. and S. R. N., San Fernando Valley Sun/el, "From the Backyard of the Northeast Valley, Spectrolab Has Taken Us to the Moon," The San Fernando Valley Sun, Nov 30 2023. Retrieved 13 November 2024. http://sanfernandosun.com/2023/11/29/from-the-backyard-of-the-northeast-valley-spectrolab-has-taken-us-to-the-moon/
11. Denby, B., and Lucia, B., "Orbital Edge Computing: Nanosatellite Constellations as a New Class of Computer System," New York, NY, USA, 2020. https://doi.org/10.1145/3373376.3378473
12. Fernholz, T., "Aethero Wants to Bring Edge Compute Into Orbit," Payload, Mar 15 2024. Retrieved 13 November 2024. https://payloadspace.com/aethero-wants-to-bring-edge-compute-into-orbit/
13. "Multi-Orbit SATCOM to Boost Army Network Resiliency, Capability in Large Scale Combat Operations," www.army.mil, Mar 13 2024. Retrieved 13 November 2024. https://www.army.mil/article/274494/multi_orbit_satcom_to_boost_army_network_resiliency_capability_in_large_scale_combat_operations
14. Shendar, R., "Beyond the Stratosphere: Computing in Orbit," Western Digital Corporate Blog, Feb 08 2023. Retrieved 2 September 2024. https://blog.westerndigital.com/data-center-computing-in-orbit/
15. Systems, G., "Gran Systems," Gran Systems Available: https://gransystems.com/

NC STATE UNIVERSITY

Mechanical and Aerospace Engineering

Thank You

Questions?

Appendix

Risk Management

Mechanical and Aerospace Engineering

Risk	Risk Type	Callsign	Likelihood	Consequences
Power system doesn't have enough capacity for eclipse conditions	Technical	Tech-1	3	5
Solar Panels fail to deploy	Technical	Tech-2	3	5
Thermal Coating degrades drastically before mission finish	Technical	Tech-3	3	5
Deployable Radiator fails to deploy properly	Technical	Tech-4	3	2
Electric Heater overheats or fails to heat	Technical	Tech-5	2	3
Ordered part incorrect	Cost	Cost-1	1	2
Ordered part breaks	Cost	Cost-2	2	3
Ordered part fails to arrive	Schedule	Sched-1	2	3

Mechanical and Aerospace Engineering

Callsign	Risk Mitigation	New Likelihood	New Consequences
Tech-1	Analysis of orbit and solar conditions and buffering the analysis with 40% more capacity than needed	2	4
Tech-2	SMA are tested thoroughly before launch, backup deployment mechanism are used.	2	1
Tech-3	Test coating qualities and test degradation over time, apply excess amount of coating	2	4
Tech-4	Test deploying mechanism, test code for deployment	2	2
Tech-5	Test failure rate, apply failsafe that heater turns off if any malfunction detected	1	3
Cost-1	Contact manufacturer, rummage look in local area	1	1
Cost-2	Plan for safe handling, keep fragile or expensive items separate with extra protection	1	3
Sched-1	Contact manufacturer, prepare alternative	2	2

Payload Risk Management

Risk	Risk Type	Callsign	Likelihood	Consequences
Reference Pi dies	Technical	Pi-1	3	4
Shielded Pi dies	Technical	Pi-2	2	5
Communication cannot be established between Pi’s	Technical	Coms-1	2	5
Radiation sensor unable to communicate with main Pi	Technical	Coms-2	3	4
Sensors unable to send signals to one Pi (redundant signal sent to both)	Technical	Coms-3	1	2
Ordered part breaks	Cost	Cost-3	1	2
Ordered part fails to arrive	Schedule	Sched-1	2	3

Verification Test Plan

Thermal

Design Requirement	Verification	Method Type	Success Criteria
DR2.1, DR3.1	Simulation of heat dissipation from deployable radiator	Simulation/Analysis	Determine radiators optimal heat dissipation
DR2.1, DR3.1	Simulation of orbit radiation and temperature	Simulation/Analysis	Determine orbit theoretical values
DR2.1, DR3.1	Internal temperatures will be measured and compared to external temperature	Experimental	Determine overall system thermal performance, maintain preferred temperature range
DR2.1, DR3.1	Electric Heater will be tested to turn on and off as needed based on temperature measured	Experimental	Confirm deployable heater will turn on and off for the correct temperature range

Power

Design Requirement	Verification	Method/Type	Success Criteria
DR.11.1, DR.11.2	Solar panels will be tested outside once fabricated	Experimental	Solar power gained at 60% of the estimated power from on-orbit operations
DR.12.2, DR.12.2.1, DR.13.2	Simulation of orbit and power generation/use using MATLAB	Simulation	Max discharge is less than 80% of the total Wh of storage
DR.11.4	Voltage Output will be measured from MPPT module when connected to controlled power source	Experimental	Voltage matches the manufacturer minimum specs
DR.12.1	Batteries will be tested prior to integration	Experimental	Batteries show full charge

Payload

Design Requirement	Verification	Method/Type	Success Criteria
DR.5.1	Processors separated by shield	Experimental	Shielded Pi covered to wire sheaths
DR.5.1.1	Transmitter node on shielded Pi tested before launch	Experimental	Read high signal on TX pin found upon final power-up
DR.7.1	Radiation meter signals are functioning	Simulation	Detection.py produces functional error log
DR.7.1.1	Rad meter signal is sent to main processor	Simulation	Rad meter signal reaches main Pi in 50 ms
DR.7.1.2	Communication to reference Pi is received through buffer of shielded Pi's signal	Simulation	Singal is received through UART within 5 seconds

Data and Communication

Design Requirement	Verification	Method/Type	Success Criteria
DR.8.1, DR.8.2	Processor metrics will be logged and evaluated by the software	Experiment	All processor metrics (Performance, error rates, etc) are correctly logged
DR.8.1.2	Reduce processor performance to generate error message	Simulation	System generates error message when given values to show drop in processor performance
DR.9.1	Data rate will be measured with different loads	Experiment	Data rate remains around 9.6 kbps under different data loads
DR.10.1.1	Transmit processor data to ground station every 10 seconds	Experiment	Processor data is transmitted to ground station every 10 seconds
DR.10.2	Test that processor status is prioritized during mission	Simulation	Processor status will override other telemetry information when simulated failures occur

Mobility and Attitude Control

Design Requirement	Verification	Method/Type	Success Criteria
DR 1.16.2	STK will be used to determine pitch, roll and yaw data	Simulation	Data outputs are used to calculate the necessary torque for orientation.
DR 1.16.2, DR 1.16.2.1	Reaction wheel system will be tested while stationary and moving with 4 kg mockup satellite	Experiment	Can precisely rotate the satellite in all 3 directions (x,y,z).The system achieves required angles with minimal overshoot and within specified time limits.
DR 1.16.1, DR 1.16.2.1	Given initial conditions, simulation can be created to determine IMU data	Simulation	Data aligns with experimental data, within the known error margins.
DR 1.16.1, DR 1.16.2.1	Collect data from tests while stationary and moving	Experiment	Data aligns with modeled simulation data and reaction wheel movement

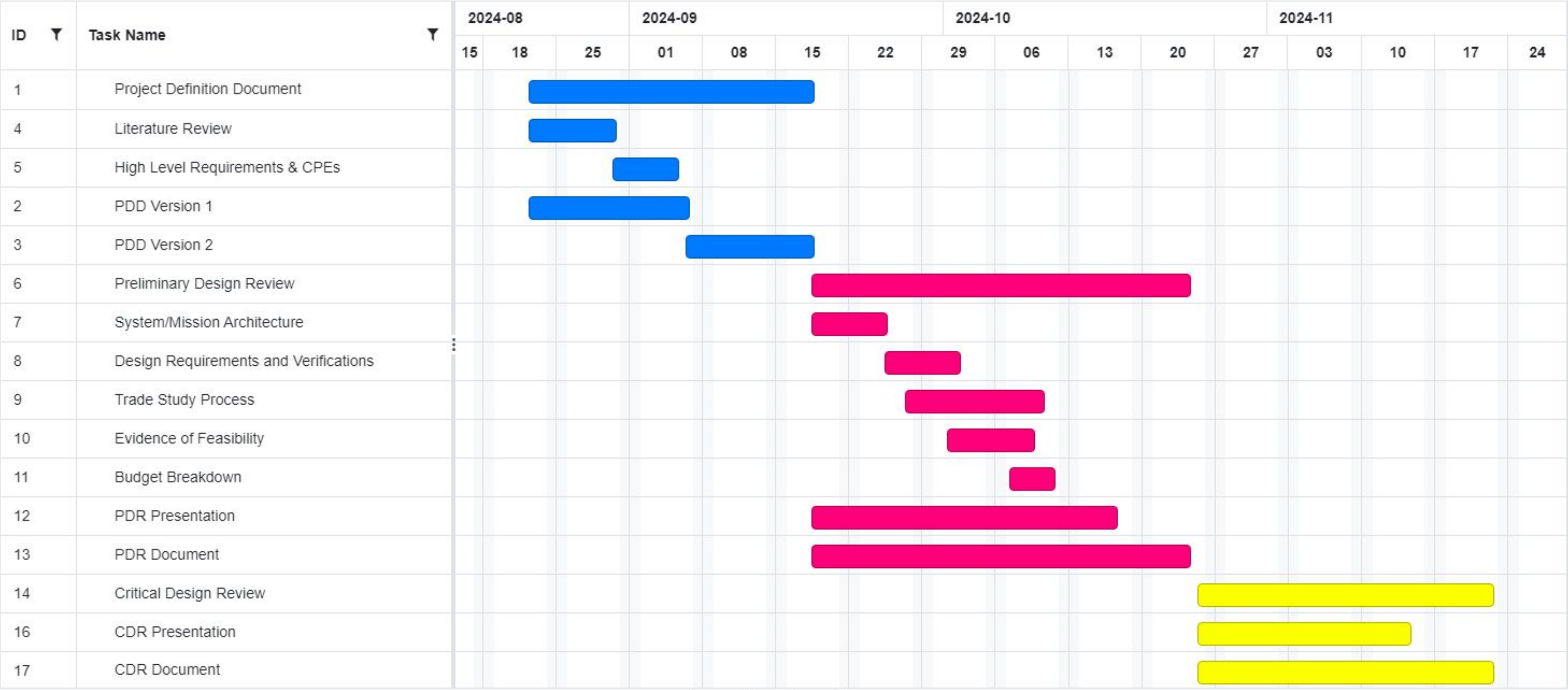
Ground Station

Design Requirement	Verification	Method/Type	Success Criteria
DR.18.1	Simulate the transmission of data from the ground station to the CubeSat using a link budget analysis tool such as MATLAB/Simulink	Simulation	Signal strength at the CubeSat receiver is above the minimum threshold for reliable data reception.
DR.18.1	Conduct a live test with a radio transmission from the ground station and monitor signal reception at the CubeSat.	Experimental	Transmission is successful, with data correctly received by the CubeSat receiver at the expected signal strength.
DR.19.1	Set up a test to receive data from the CubeSat and verify that the received data matches the expected data payload.	Experimental	The data received from the CubeSat matches the transmitted data within error tolerance limits.

Structures

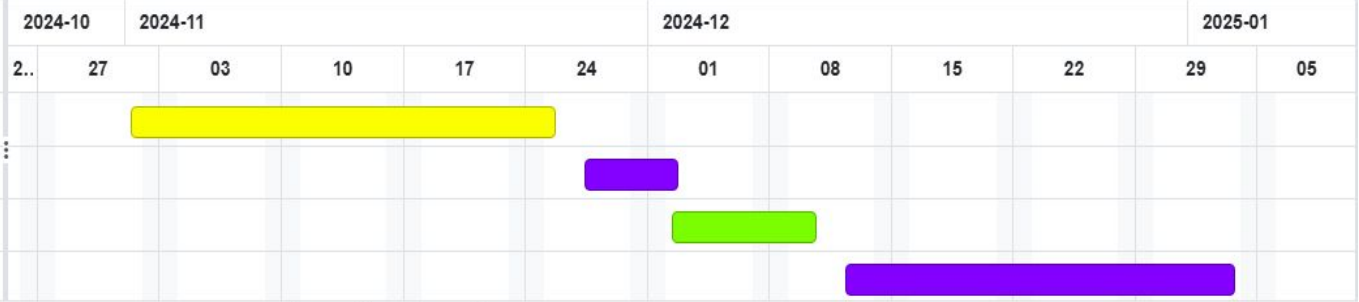
Design Requirement	Verification	Method/Type	Success Criteria
DR4.1	Simulate the forces experienced in orbit using STK and calculate the induced stress	Simulation	Stress induced does not exceed the yield strength of aluminum
DR4.1.1	Perform stress tests to generate a stress-strain curve for the material	Experiment	Yield strengths and Young's/Shear Modulus matches that provided by manufacturers

Schedule Phase 1



Schedule Phase 2

ID	Task Name
15	VV&T Proposal
18	Holiday Break (Thanksgiving)
19	Order Parts for Manufacturing
20	Winter Break



Schedule Phase 3