Incorporating Next-level Modularity with a Standard Bus CubeSat

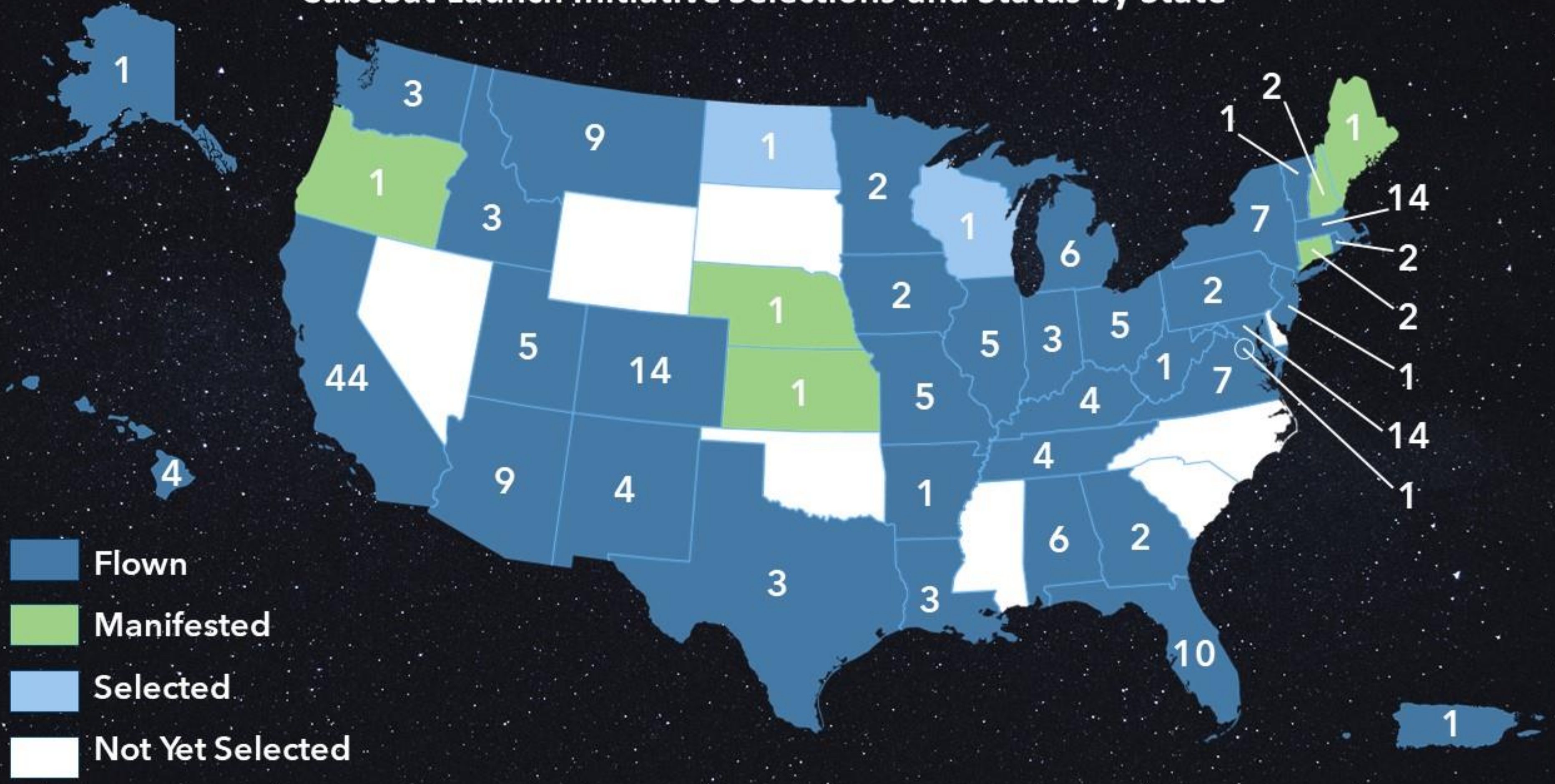
Naval Academy Standard Bus (NASB) Satellite Program

Cal Poly CubeSat Developer's Workshop

25 April 2023

Alexandra Harrison, Oleksiy Lakei, Andrew Javier, Alexander Reitz-Kremp

CubeSat Launch Initiative Selections and Status by State



2023-03-21

Credit: NASA.*csli_manifest_map_3.31.23.jpg (1280×720) (nasa.gov)*

“Modularity” We Are Used to Seeing

Even with “standard” components, integration with payload components turn the satellite into one-off, custom builds → Takes too long

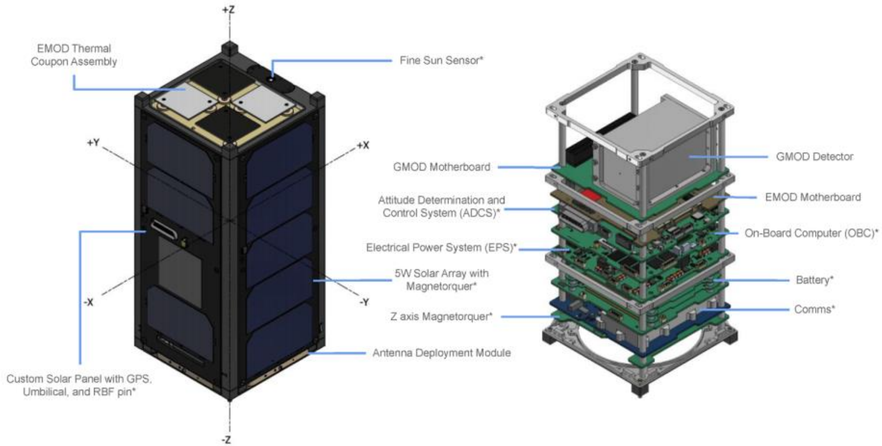
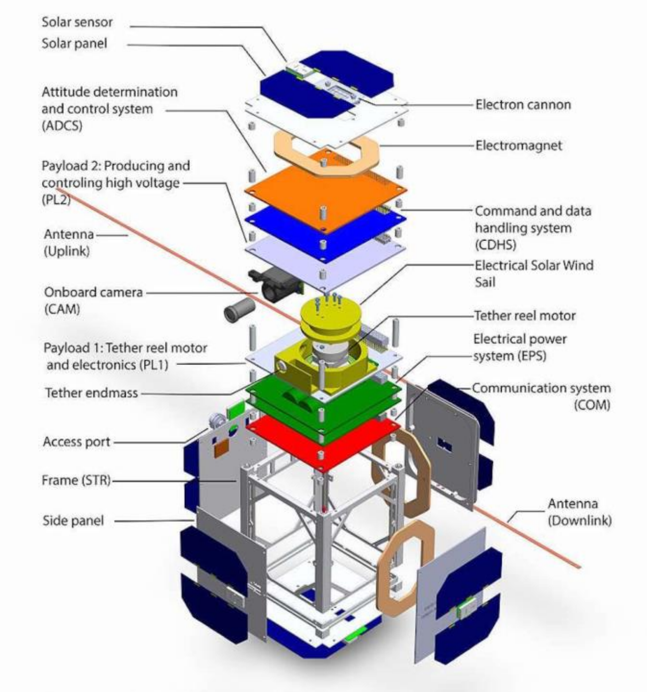


Illustration of EIRSAT-1



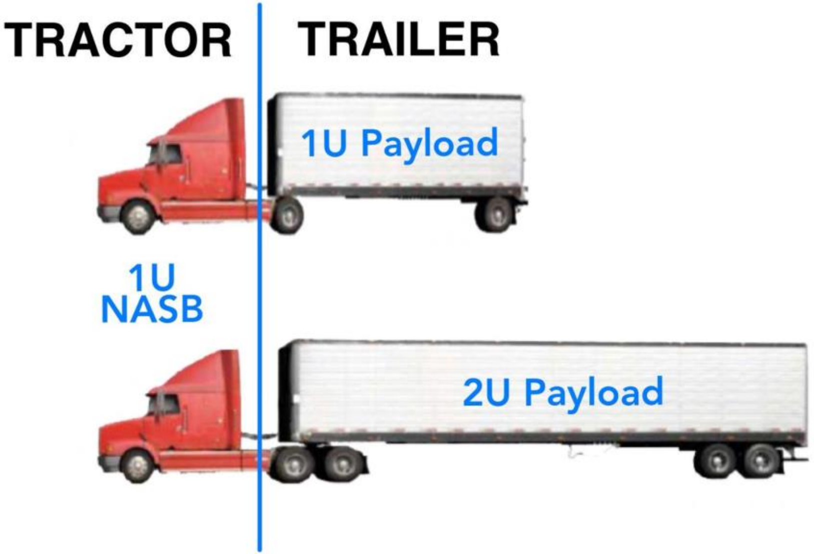
The structure of cubesat ESTCube-1

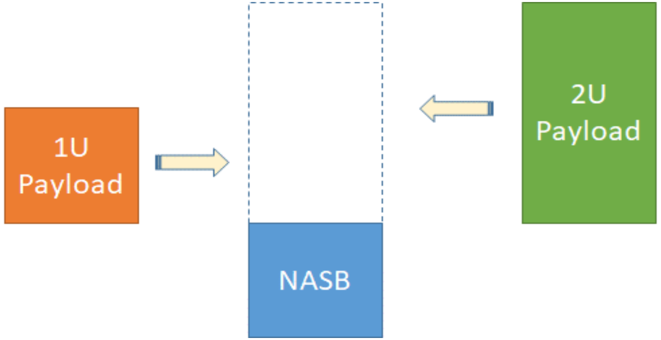
NEXT-LEVEL MODULARITY

United States Naval Academy’s NASB

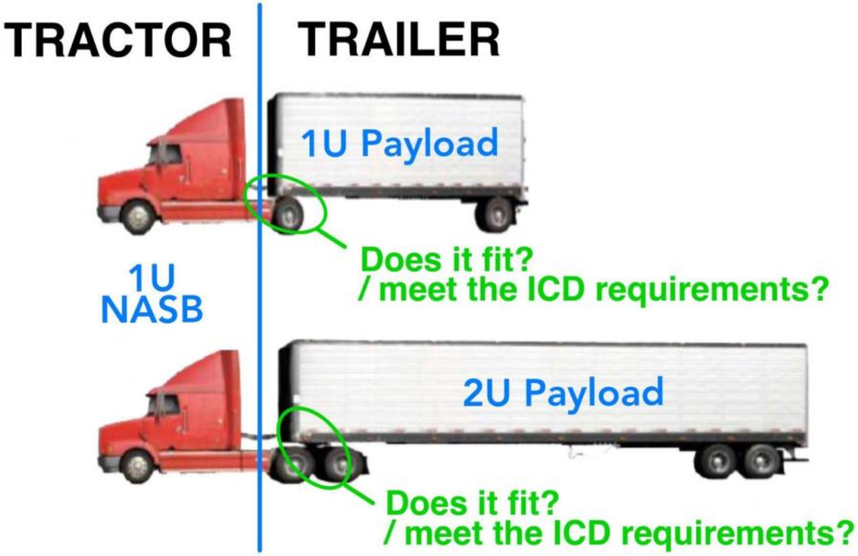
NASB Concept

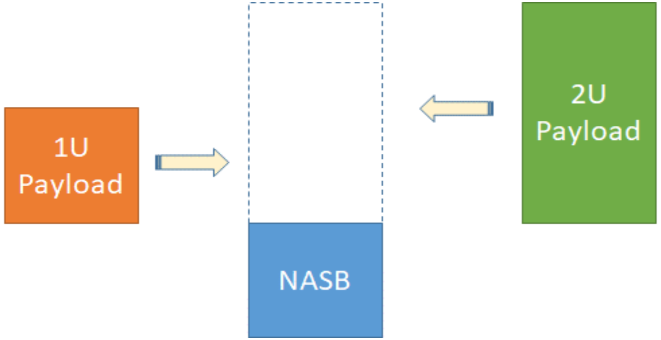
IF IT FITS, IT SHIPS…



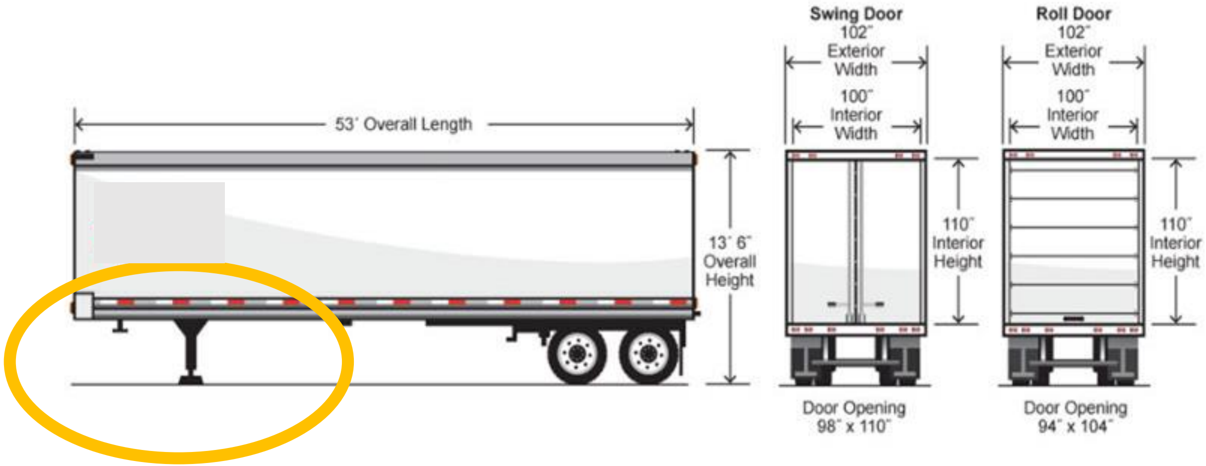


IF IT FITS, IT SHIPS…





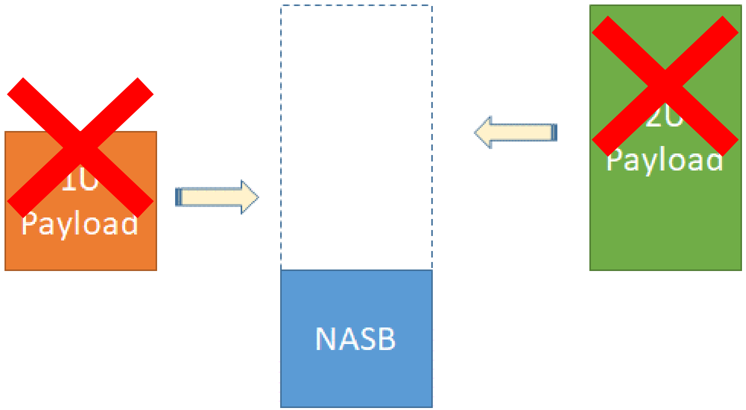
“If it fits” → Meet ICD



- Dimension requirements
- Mass and mass properties requirements
- Integration/adaptor requirements

Bus is standalone satellite

- Can be launch on own, can perform satellite communication mission

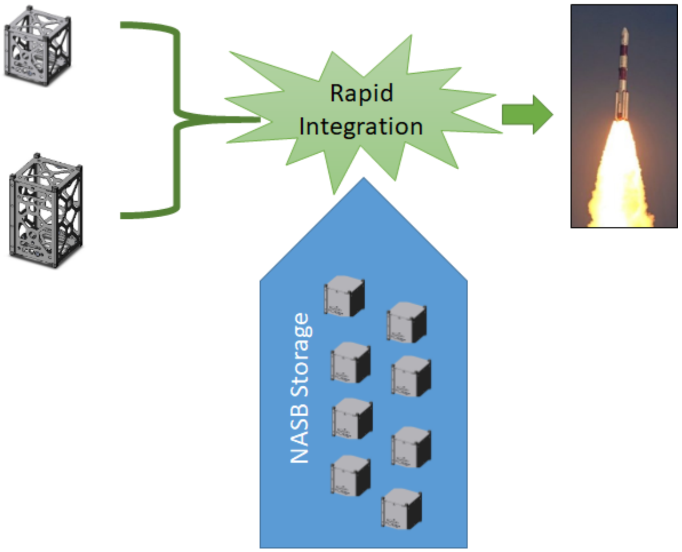


Full Standalone Satellite

Concept of Operation

Capstone Design teams develop payloads

- Student-derived
- Externally sponsored
- Externally provided



Completed satellites launched whenever opportunity given

- Successful payload developed, OR
- NASB on its own

With many NASB comm satellites on orbit, students experience satellite operation as part of curriculum

Every group in the “Spacecraft System Laboratory” Course at USNA assembles one NASB as part of the lab curriculum, while testing/characterizing its performance

→ **stockpile of flight-ready NASBs**

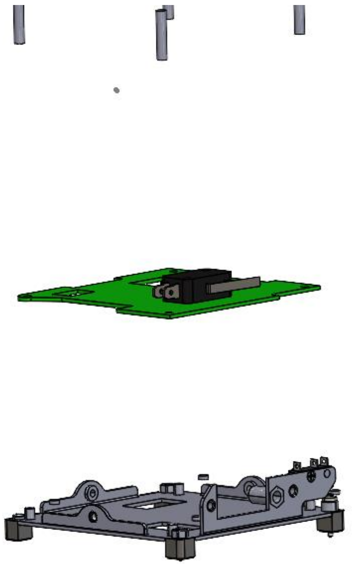
NASB Standard Bus

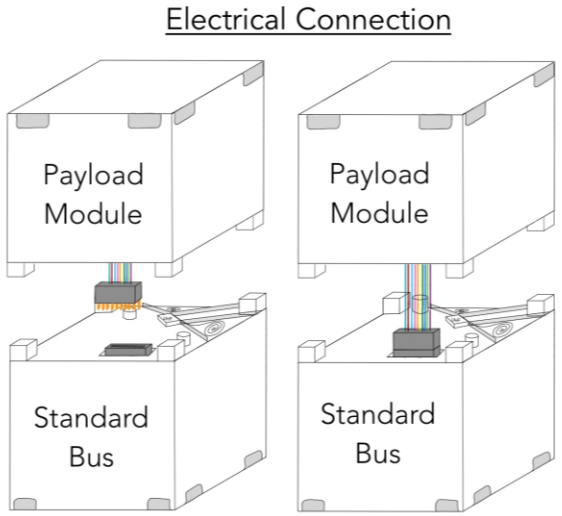
MIDN 1/C Harrison, Javier, Lakei, Ma, Reitz-Kremp

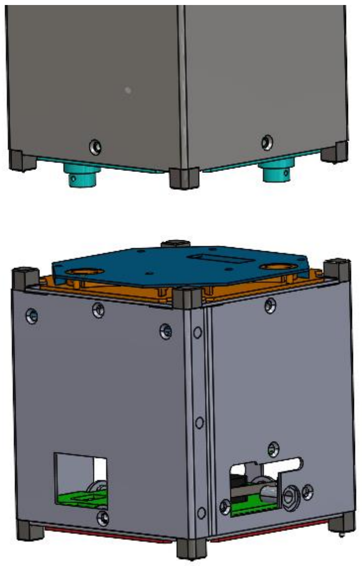
Mission Objectives

Number	Requirement
MO - 1	Provide a modular bus capable of integrating payloads quickly and with minimal connections, to increase flexibility of future CubeSats
MO - 2	Design a self-sufficient standard bus

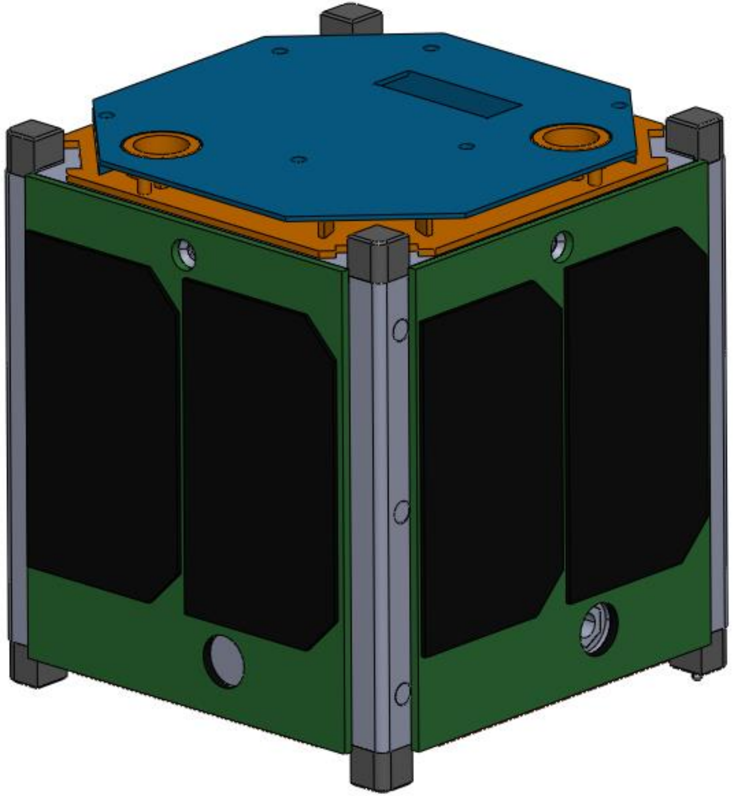
How it all gets put together



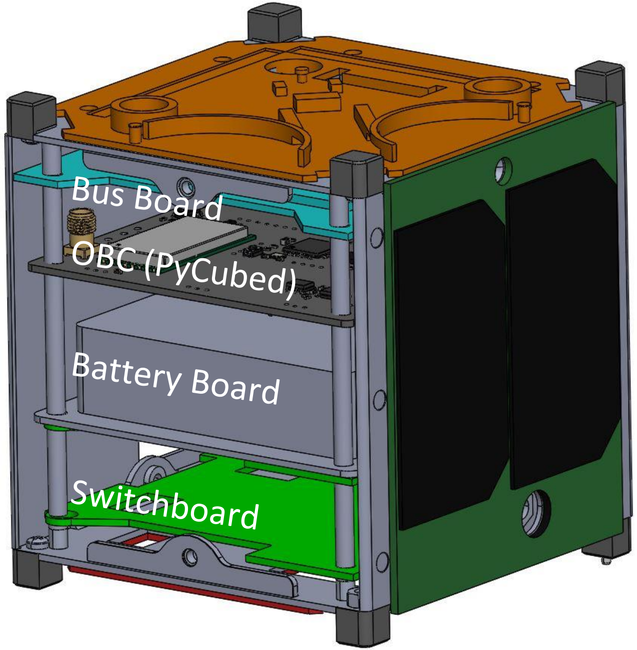




Standard Bus Design

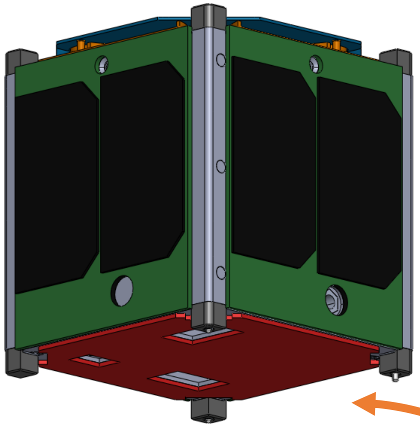


Structures

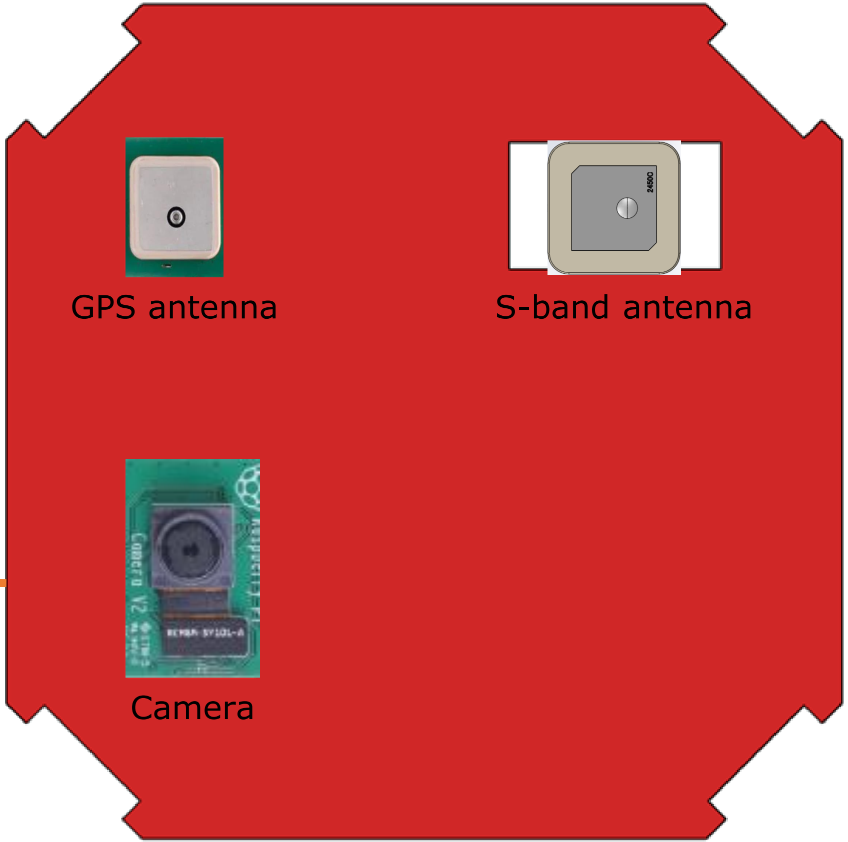


1/C Oleksiy Lakei &
1/C Alexander Reitz-Kremp

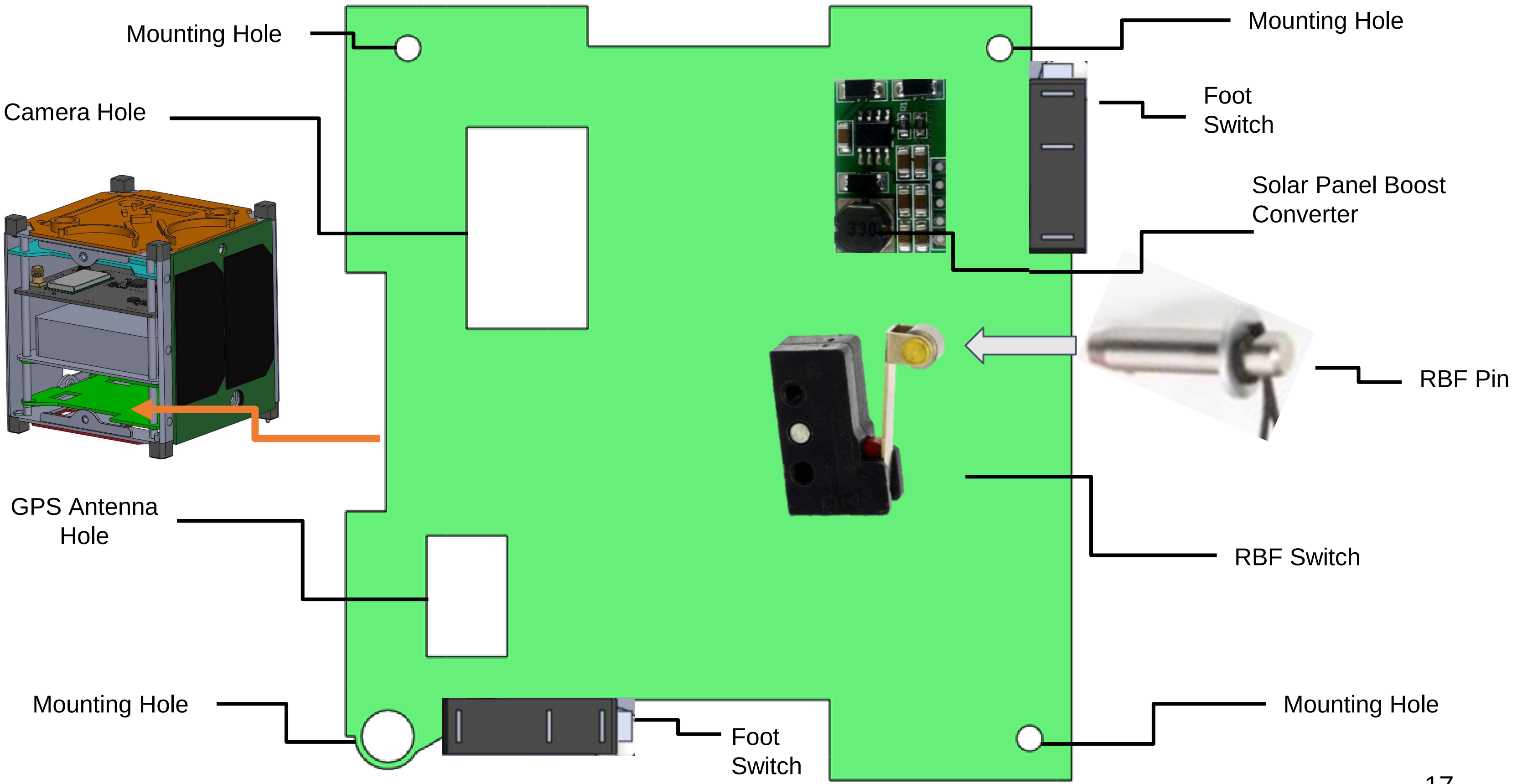
Bottom Board



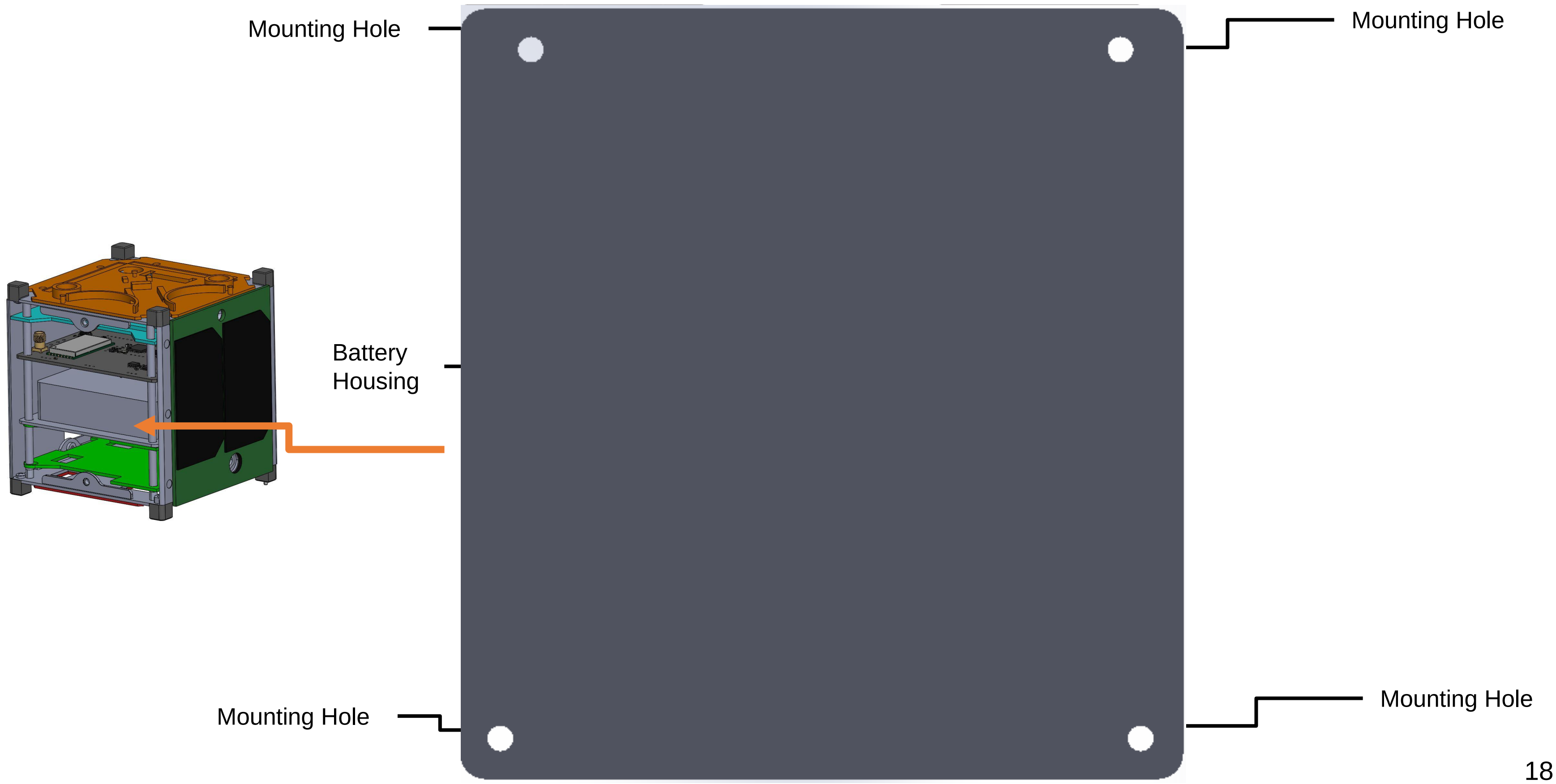
- No solar cells on bottom and top panel
- Bottom panel primarily for nadir-pointing components
- Board houses camera and antennas



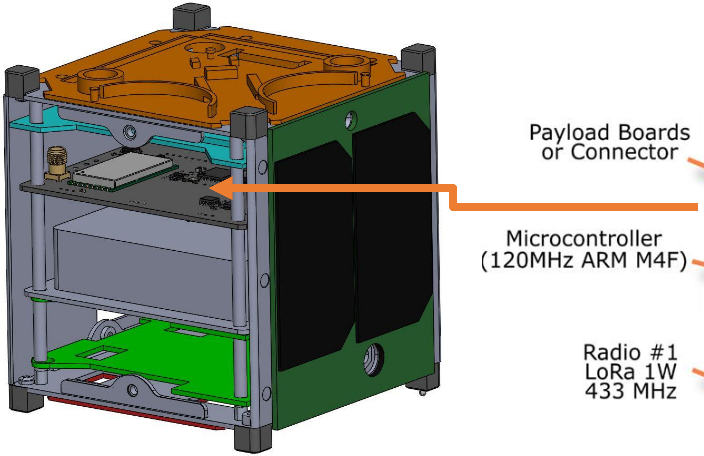
Switch Board

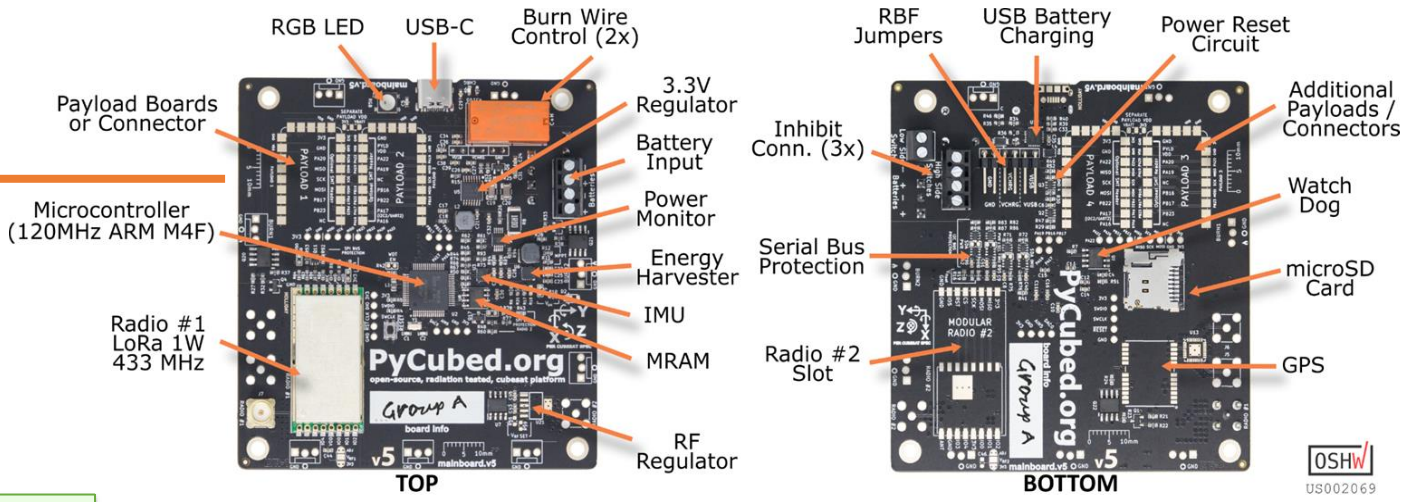


Battery Board



On Board Computer (PyCubed Board)





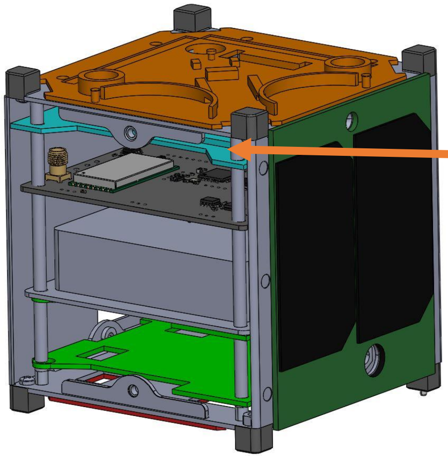
Credit: PyCubed.org

Includes Most Vital Subsystems

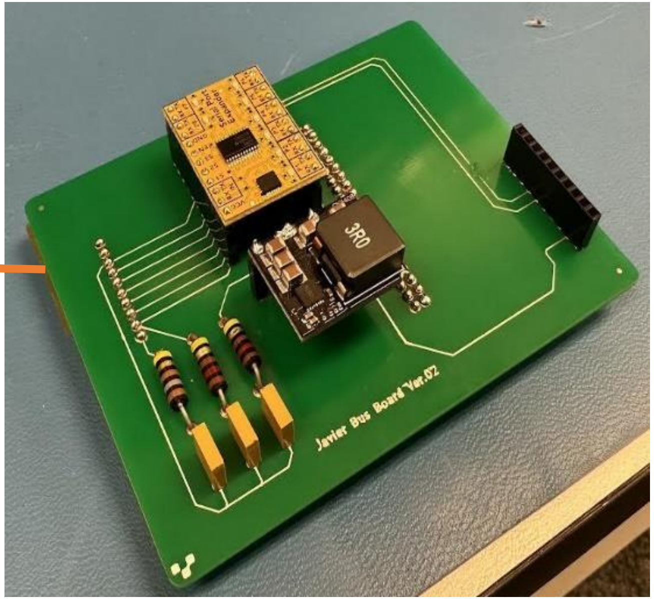
- Radios (UHF & S-band)
- Electrical power
- Burn Wire Control
- Microcontroller
- Inertial Measurement Unit (IMU)
- GPS receiver
- MicroSD Card

Bus/Interface Board

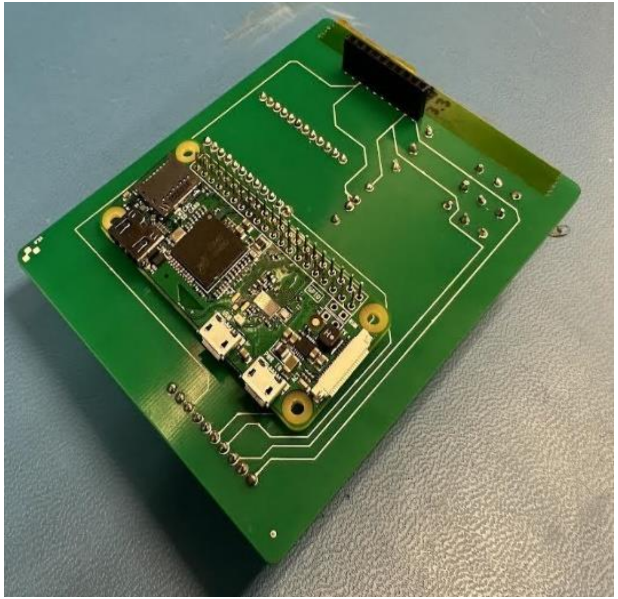
Serves as the interface between Bus and Payload
- Power conditioning and distribution
- Data transfer protocol management



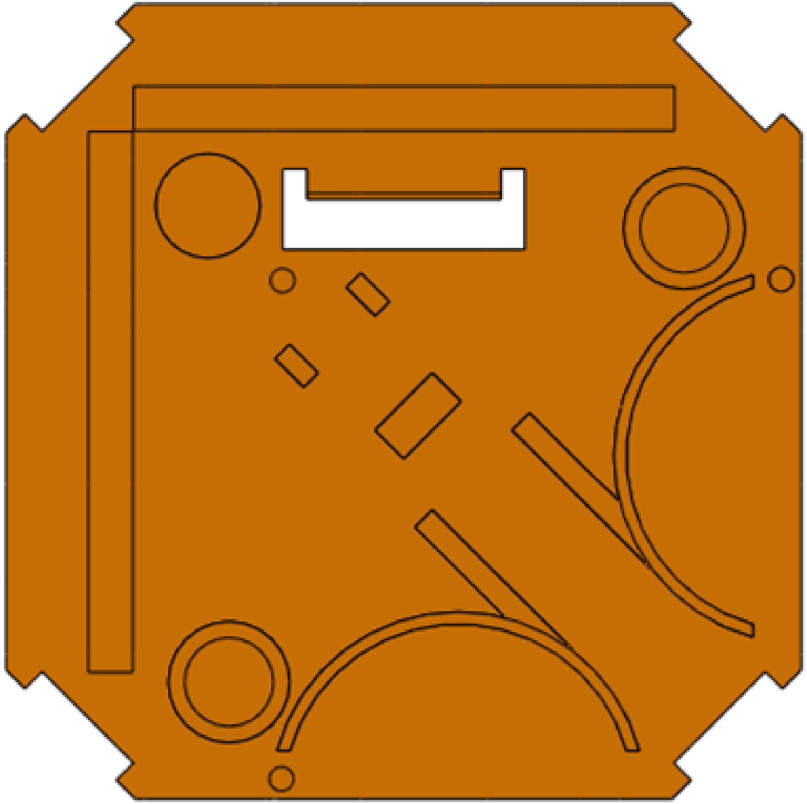
Top



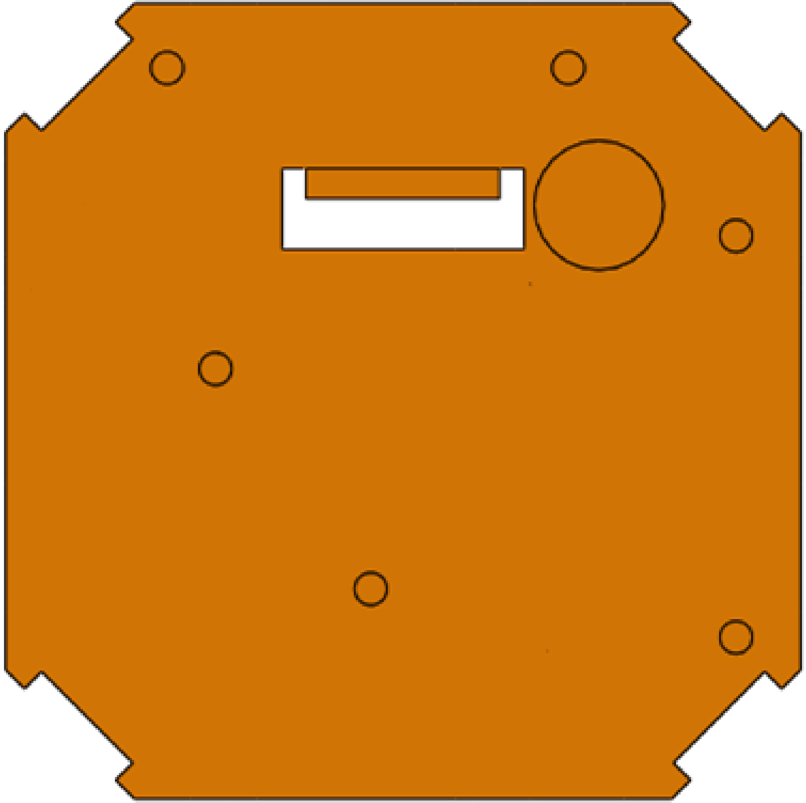
Bottom



Antenna Board

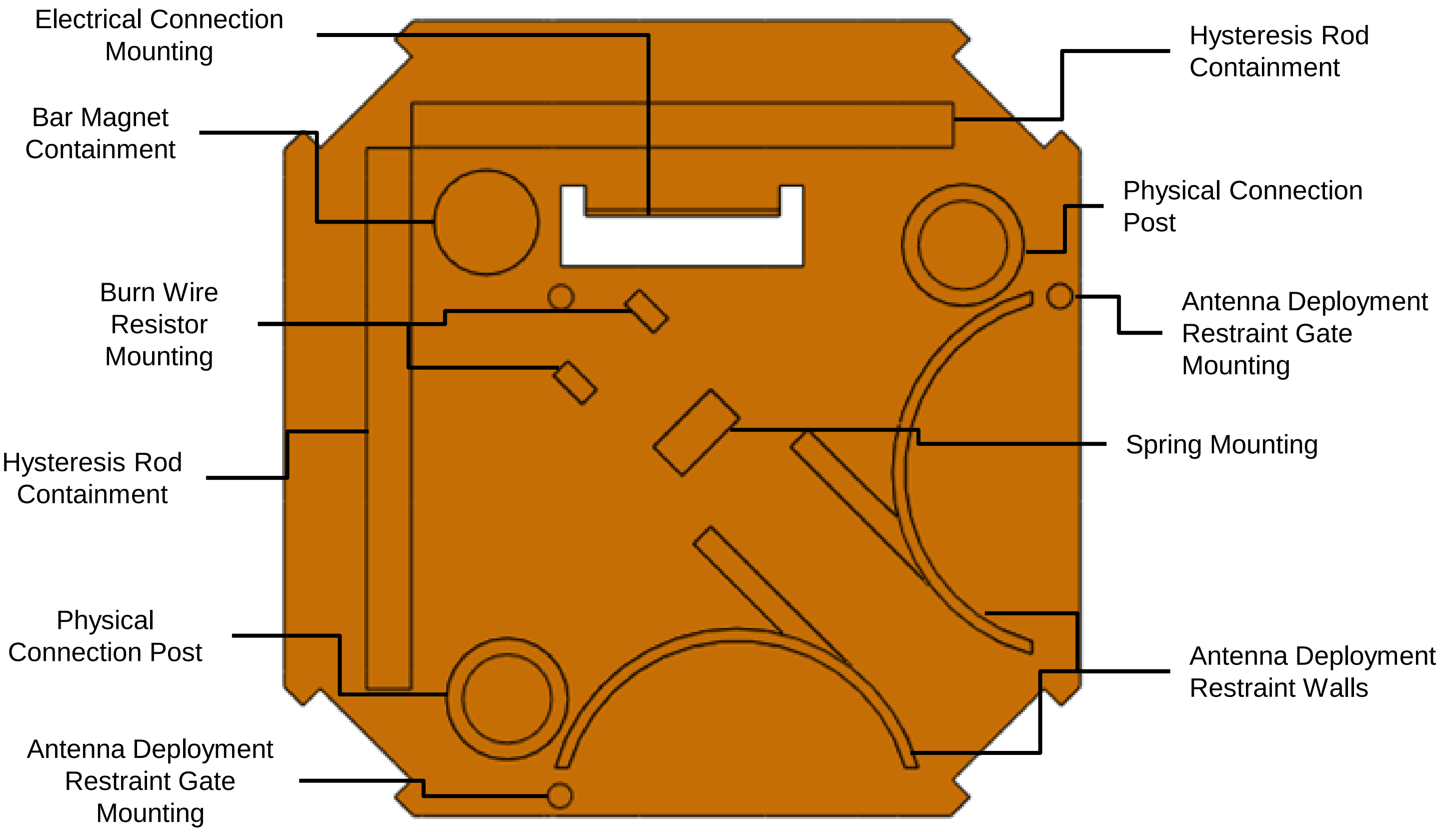


Top View

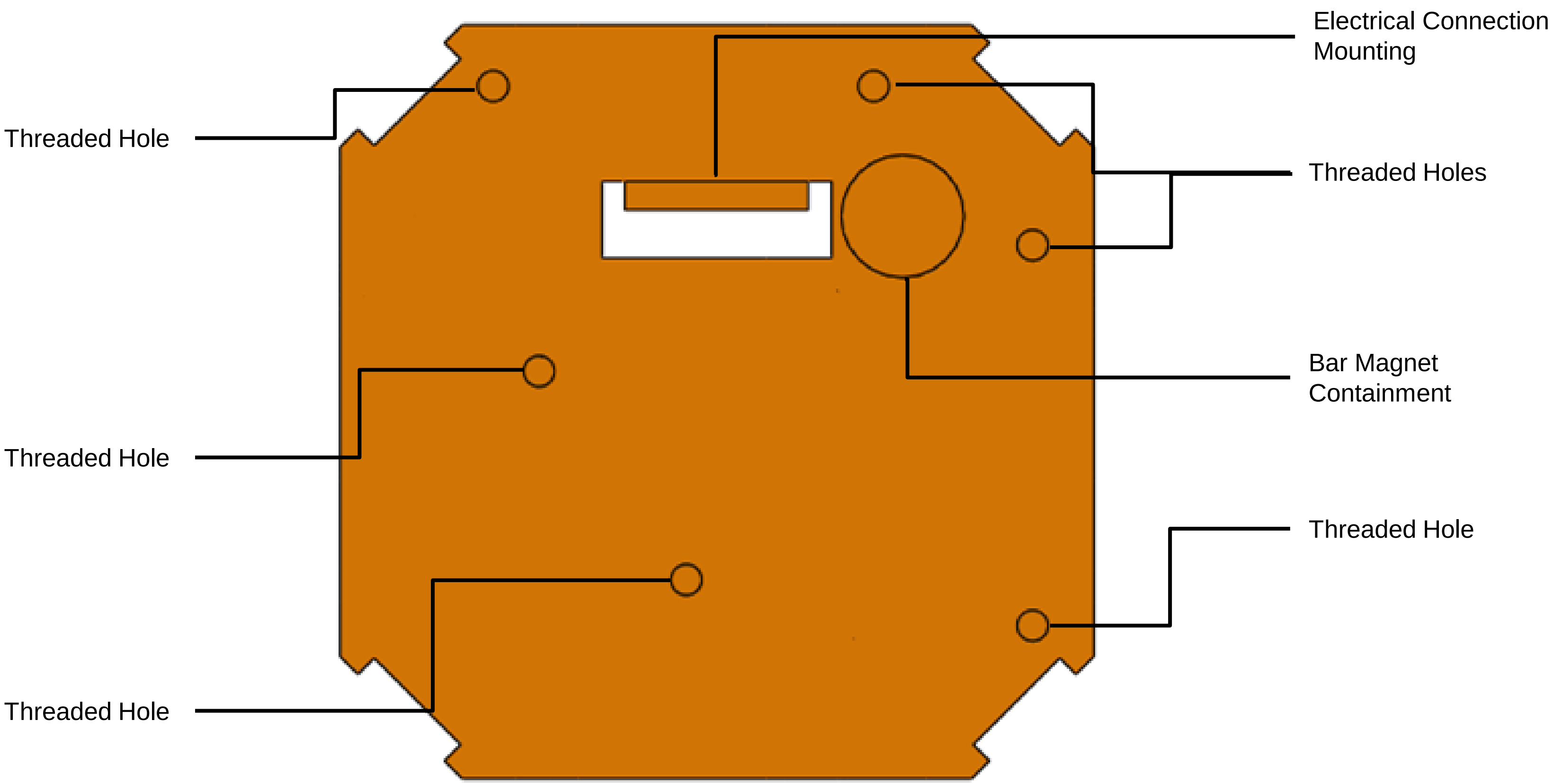


Bottom View

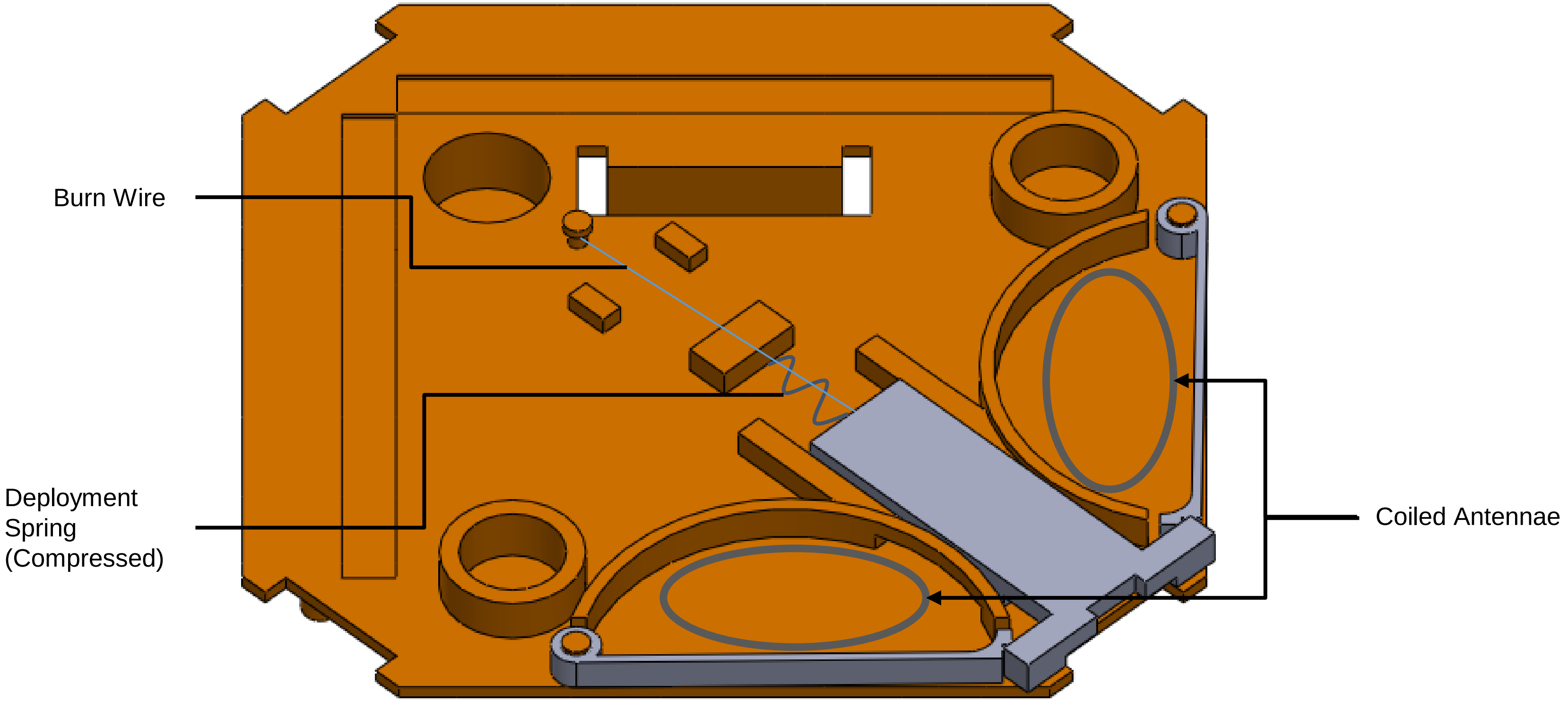
Antenna Board (Top)



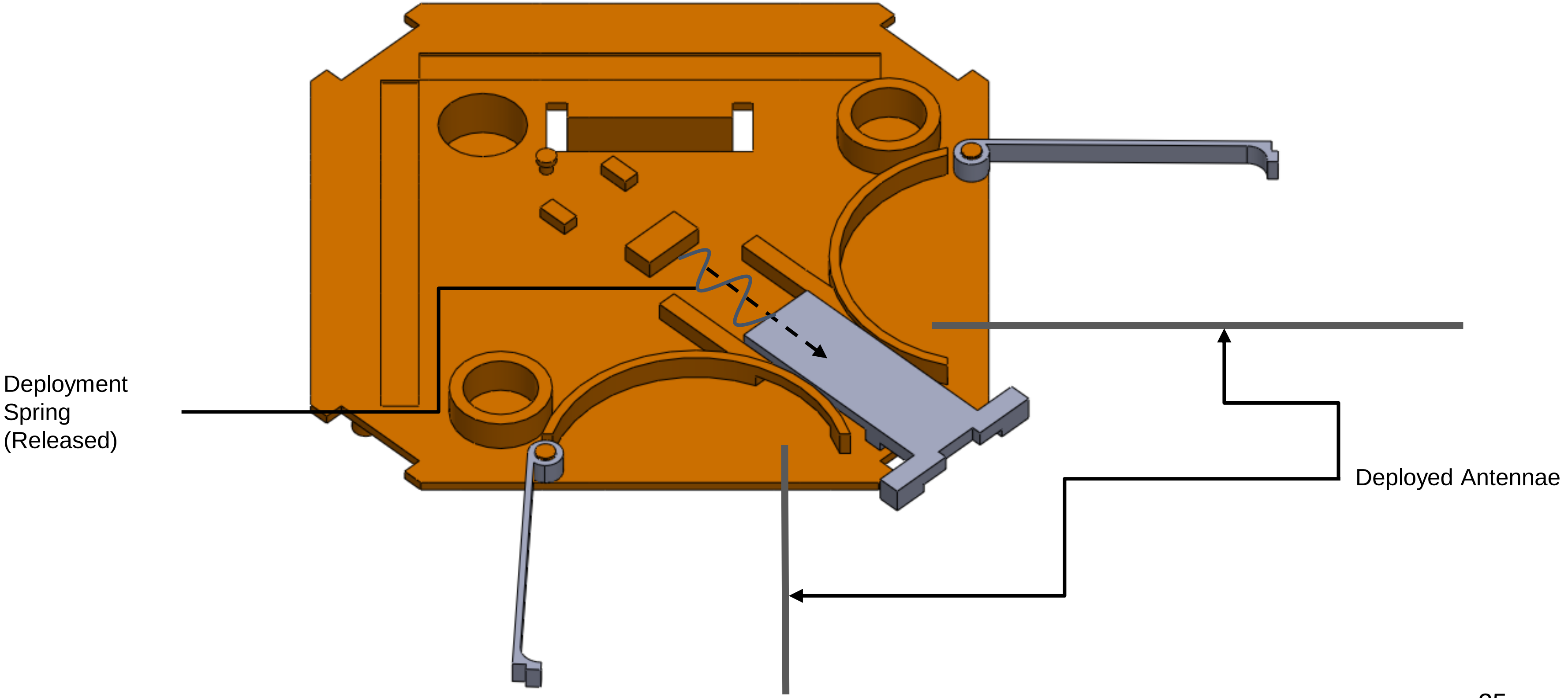
Antenna Board (Bottom)



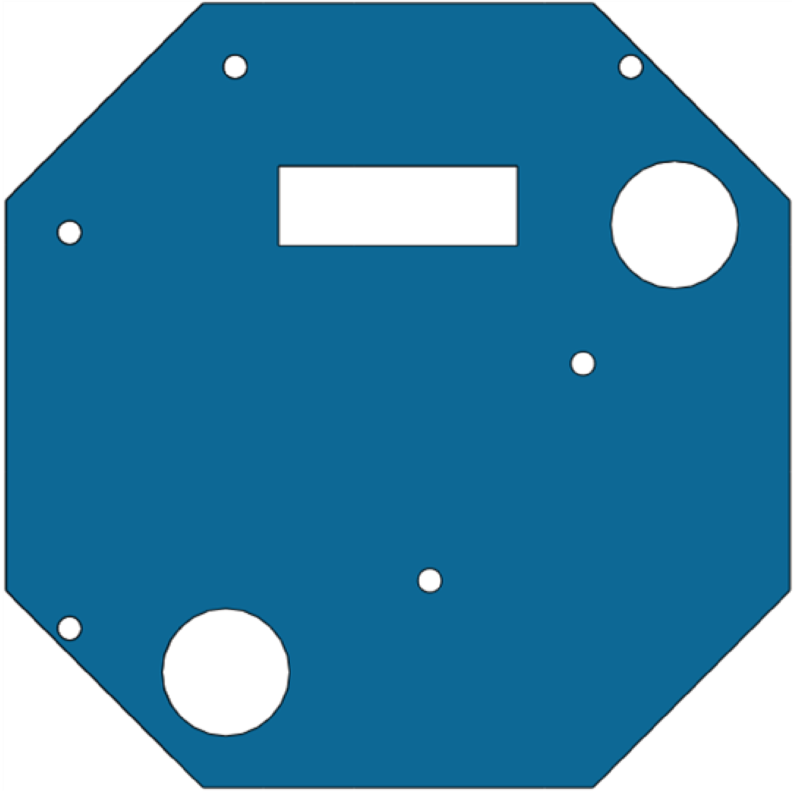
Antenna Stored



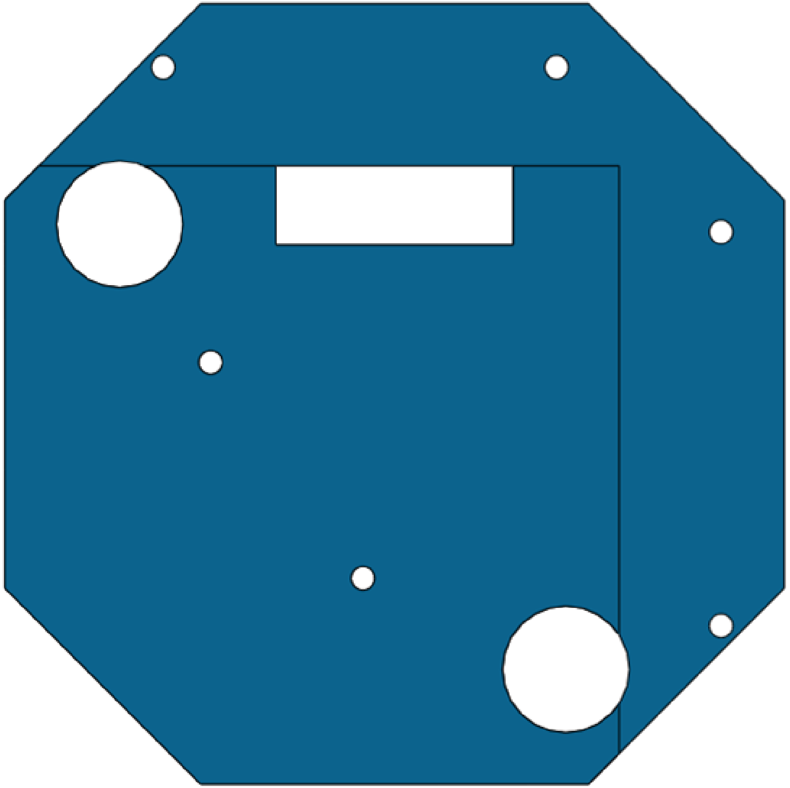
Antenna Deployed



PMAC Housing

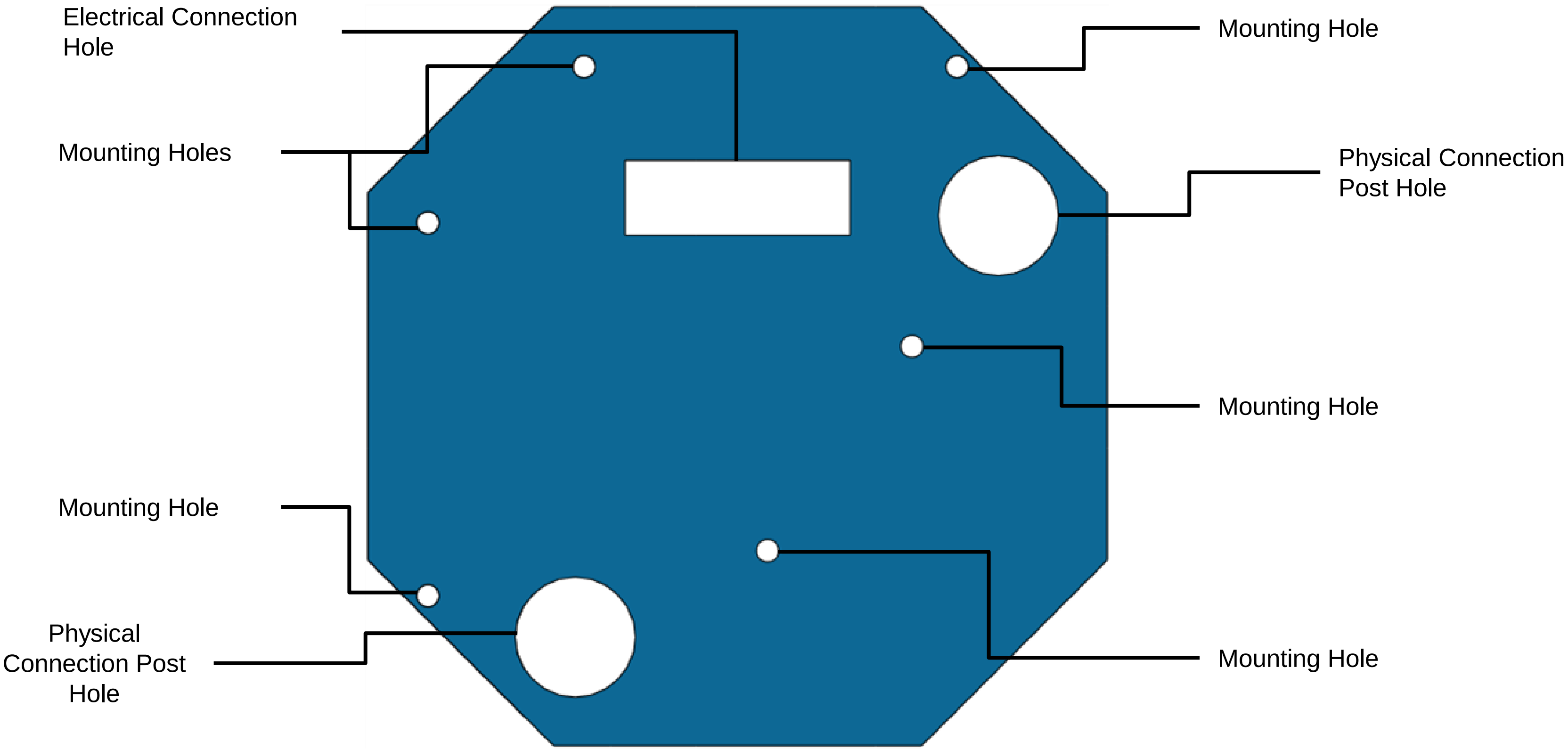


Top View

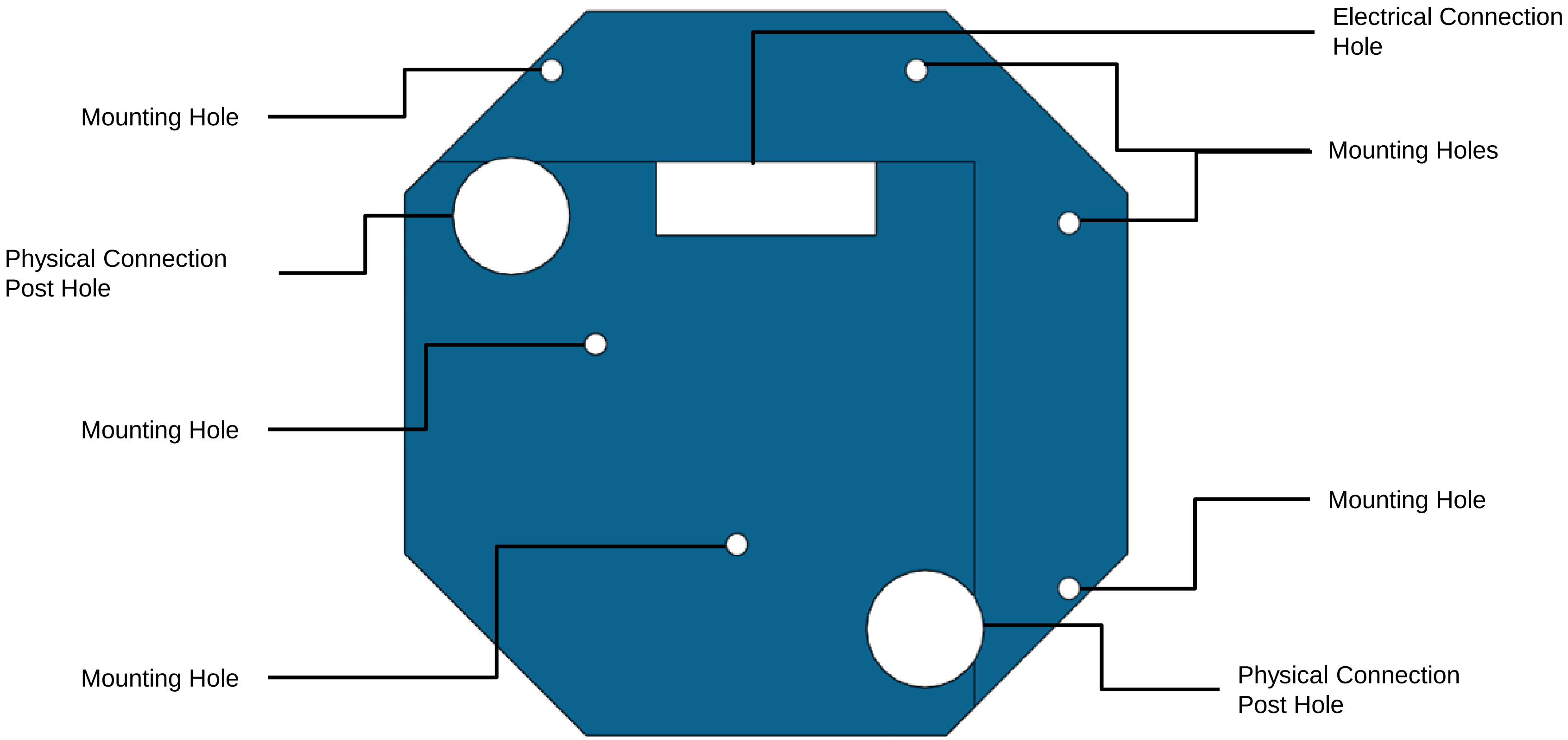


Bottom View

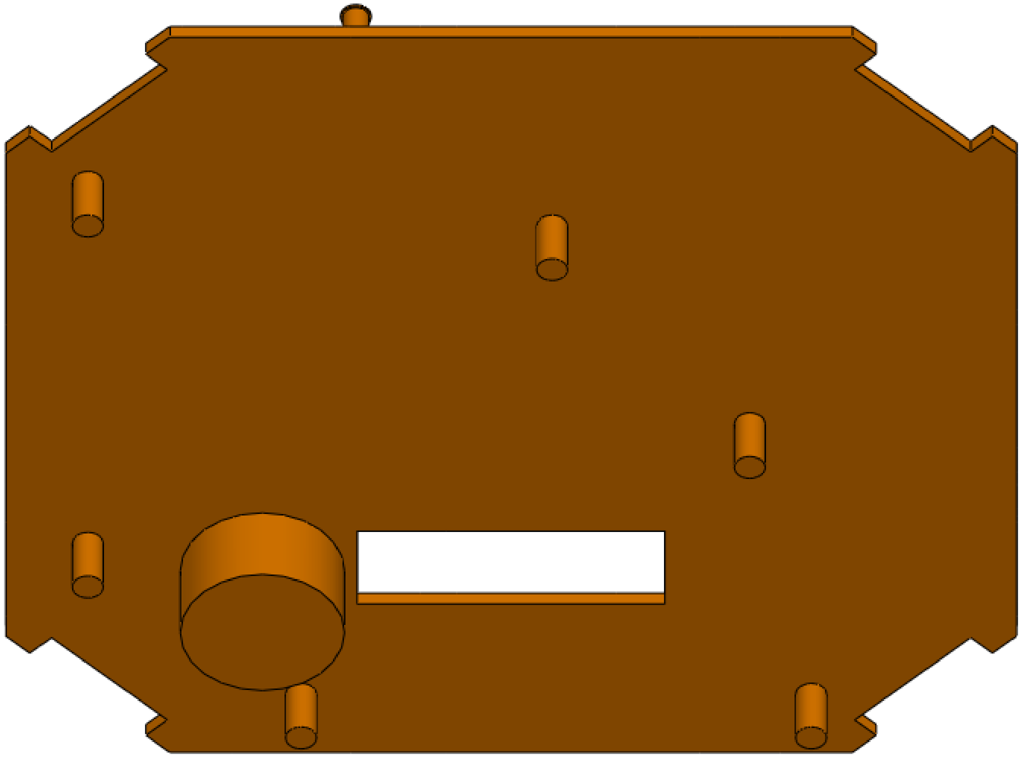
PMAC Housing (Top View)



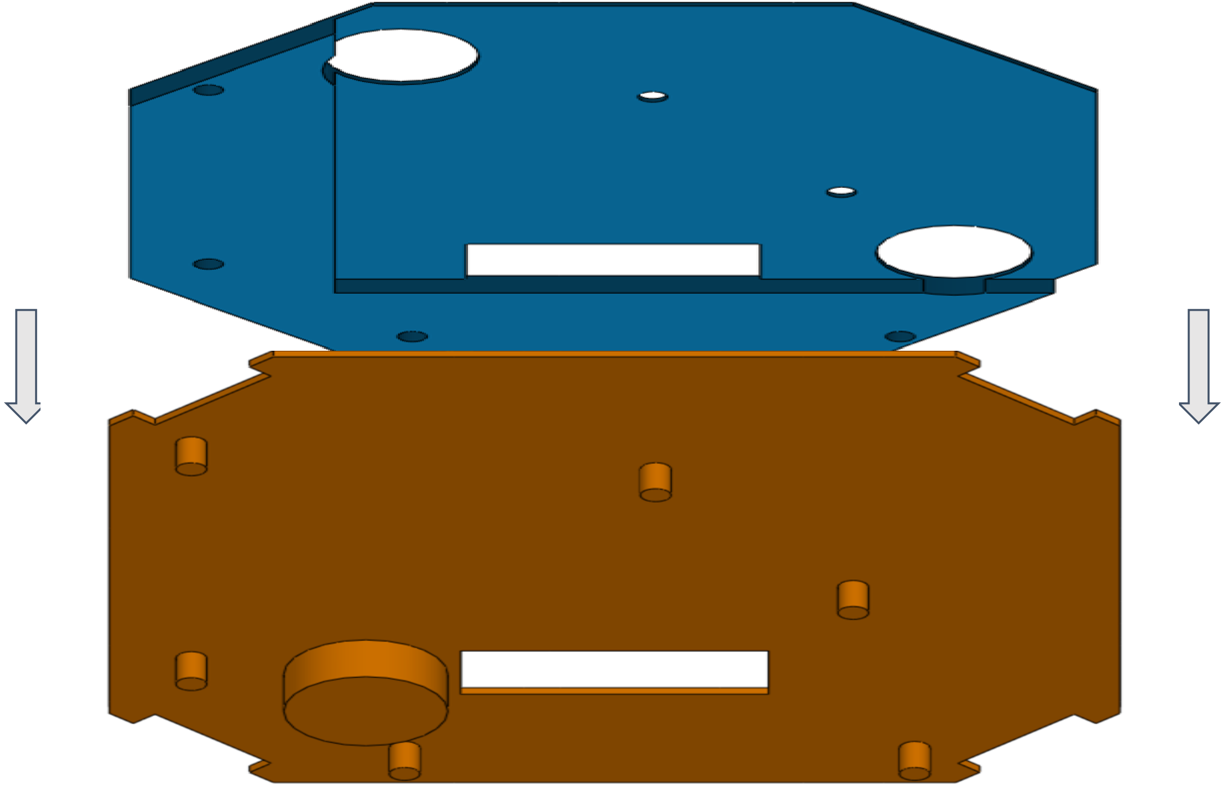
PMAC Housing (Bottom)



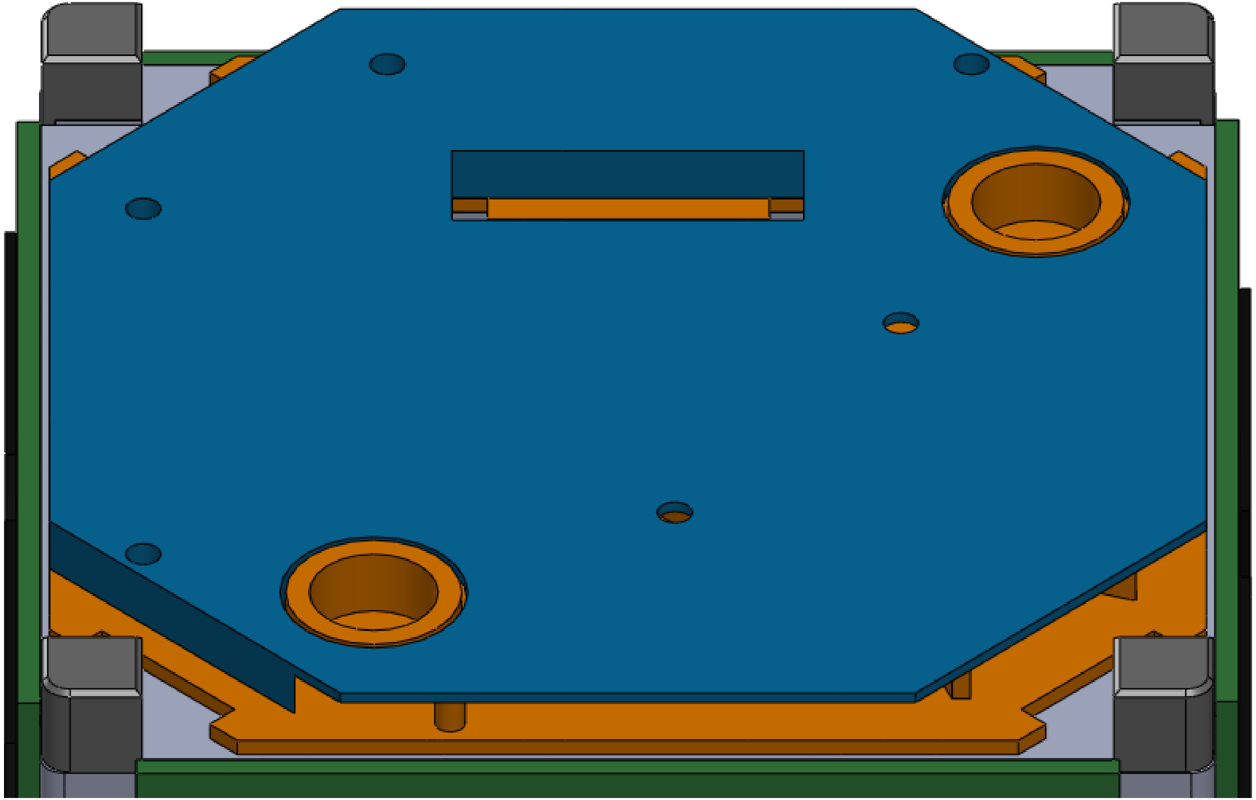
Antenna Board & PMAC Assembly



Antenna Board & PMAC Assembly



Antenna Board & PMAC Assembly



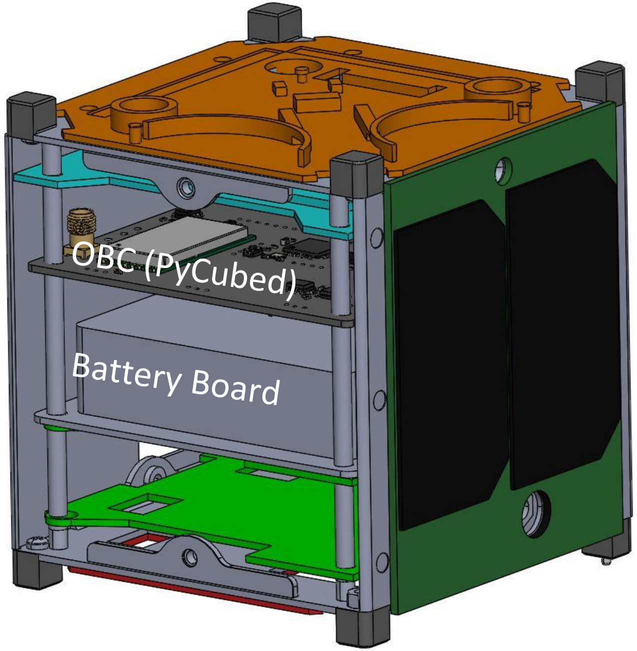
Link Budget Summary

S-Band SX1280 Transmitter
To downlink information from payloads

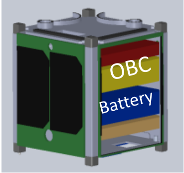
Transmitter Power	0.5W
Transmitter Antenna Gain	0.5 dBi
Downlink Frequency	2.4 GHz
Eb / No Margin	**4.0 - 11.5 dB for elevations over 20°**
Data Rate	**76.1 kbps**
Maximum downlink (accounting for losses and data overhead)	**1.0 MB per day**

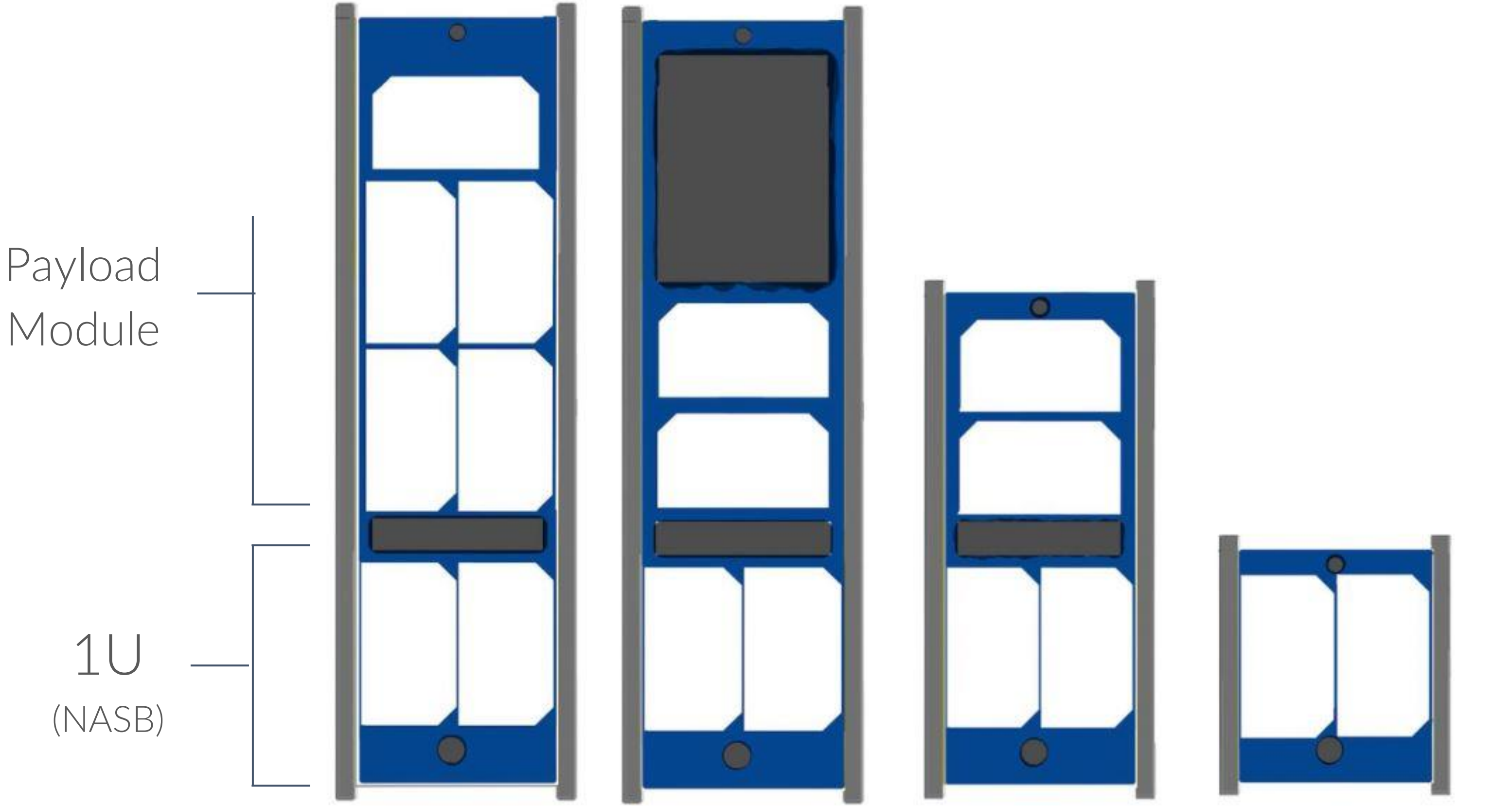
Power

1/C Alexandra Harrison



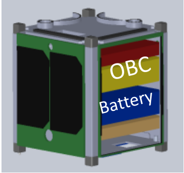
Solar Panel Configurations to Choose From

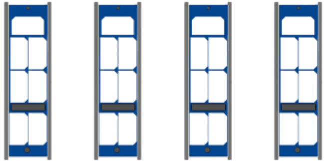
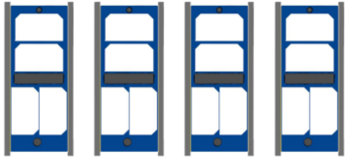
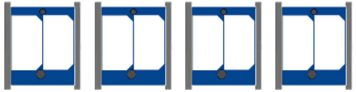




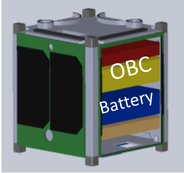
Solar Panel Configuration 1 | Solar Panel Configuration 2 | Solar Panel Configuration 3 | Solar Panel Configuration 4

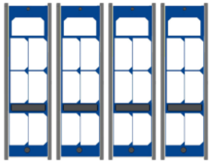
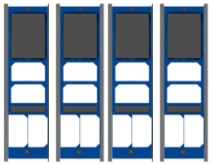
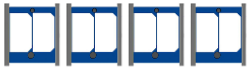
Power Generation



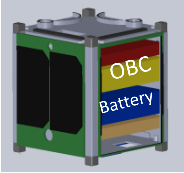
Average Orbital Power Generated for Each Configuration		
Panel Configuration	**Beginning of Life**	**End of Life** *(2 year mission life)*
3U 	5.5 W	5.19 W
2U 	3.1 W	2.97 W
1U 	1.56 W	1.48 W

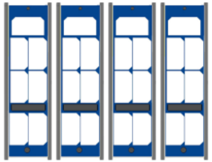
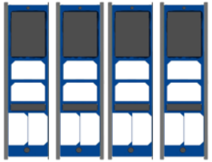
Power Allocations



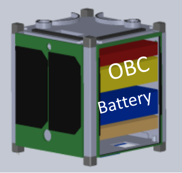
Configuration	Payload Size	Power Available	Power Allocated	Margin
3U 	2U	3.7 W	3.5 W	5 %
2U 	2U	1.5 W	1.3 W	11 %
2U 	1U	1.5 W	1.3 W	11 %
1U 	none	N/A	N/A	N/A

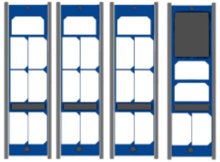
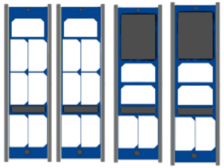
Power Allocations



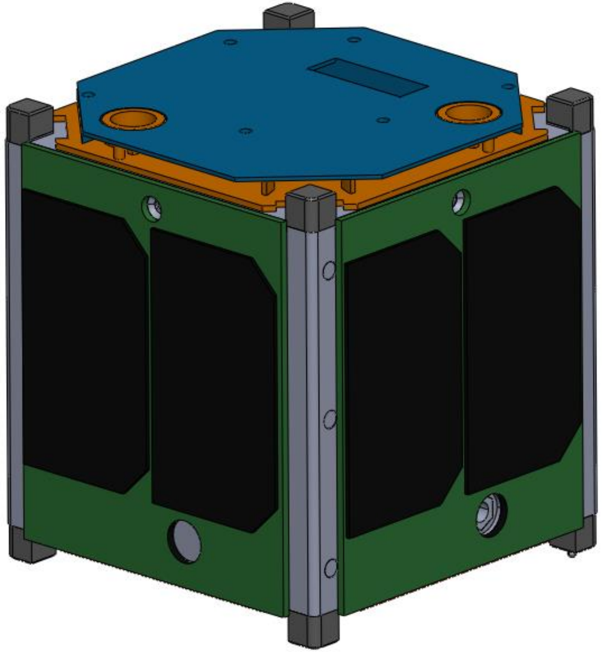
Configuration	Payload Size	Power Available	Power Allocated	Margin
3U 	2U	3.7 W	3.5 W	5 %
2U 	2U	1.5 W	1.3 W	11 %
2U 	1U	1.5 W	1.3 W	11 %
1U 	none	N/A	N/A	N/A

Power Allocations



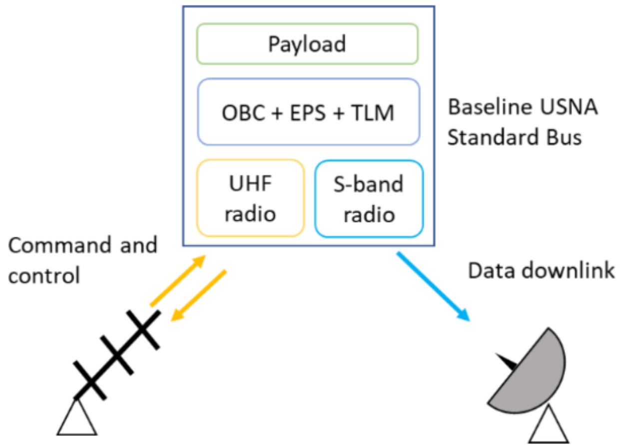
Configuration	Payload Size	Power Available	Power Allocated	Margin
3x **3U** – 1x **2U** 	**2U**	**3.6 W**	**3.4 W**	**5%**
2x **3U** – 2x **2U** 	**2U**	**2.9 W**	**2.6 W**	**9%**
1x **3U** – 3x **2U** 	**2U**	**1.9 W**	**1.7 W**	**12%**

Command and Data Handling/Communications



1/C Andrew Javier

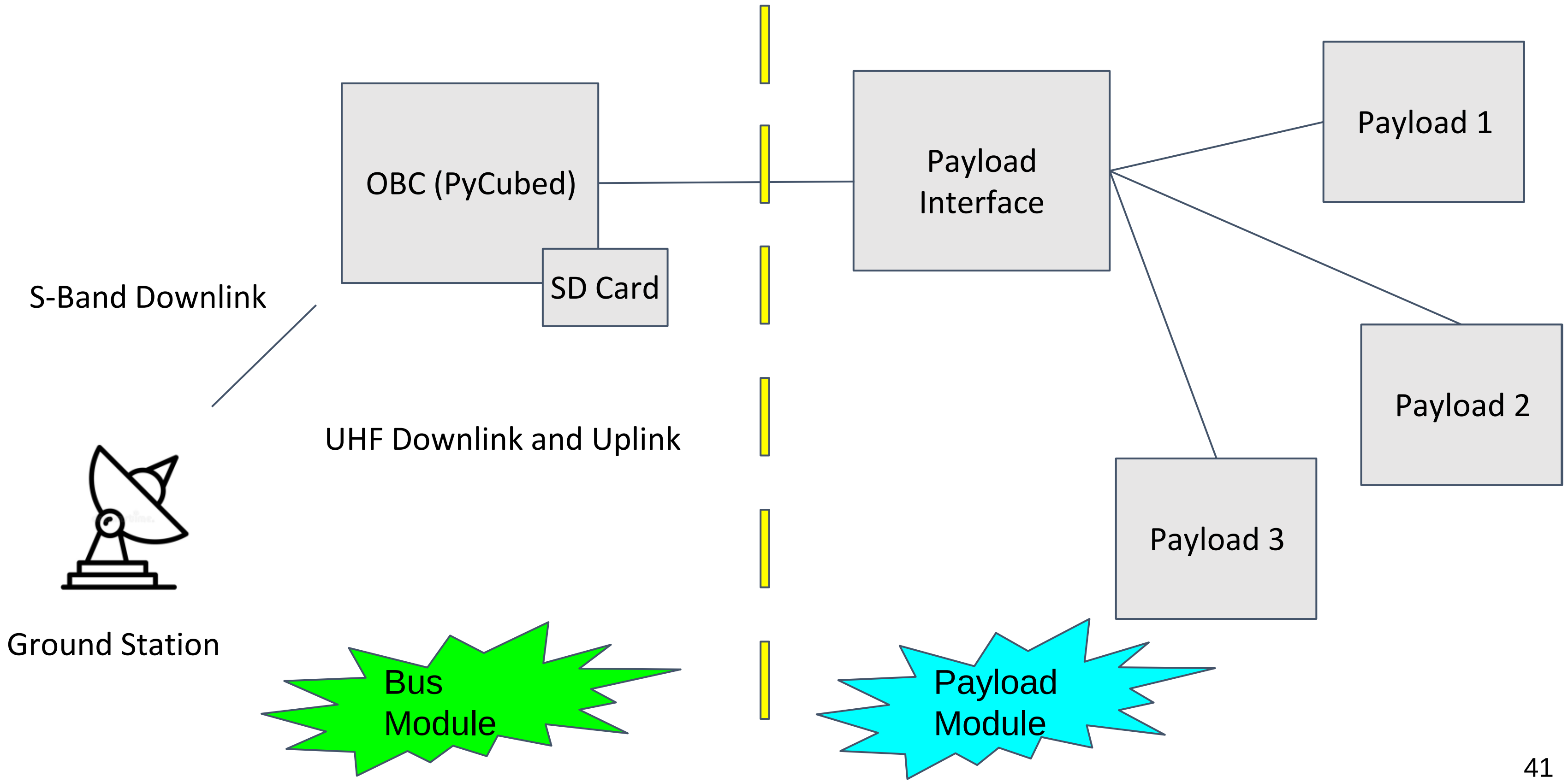
C&DH Summary



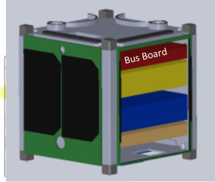
UHF and S-Band capabilities for downlink and uplink using HopeRF and SX1280 Radio:

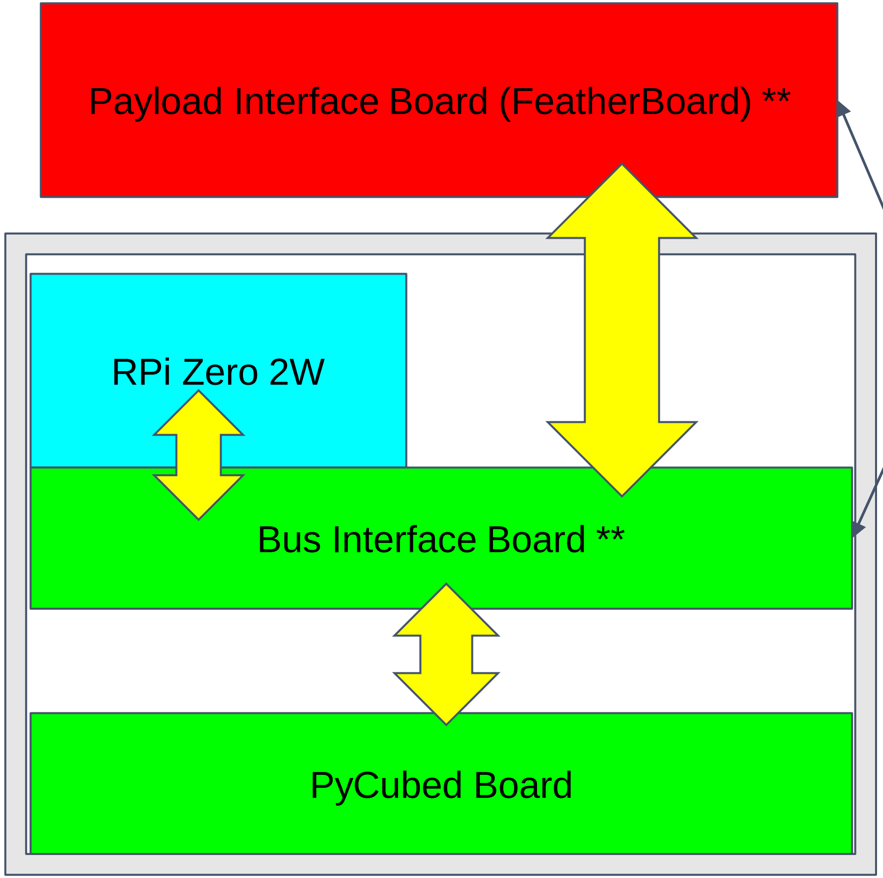
Predicted capability	1 MB/day
Raw data rate	76 kbps at BW 812 kHz
Eb/No margin	>4 dB
Protocol	LoRa
OBC Data Storage	32 GB SD Card

C&DH - Data Flow Overview

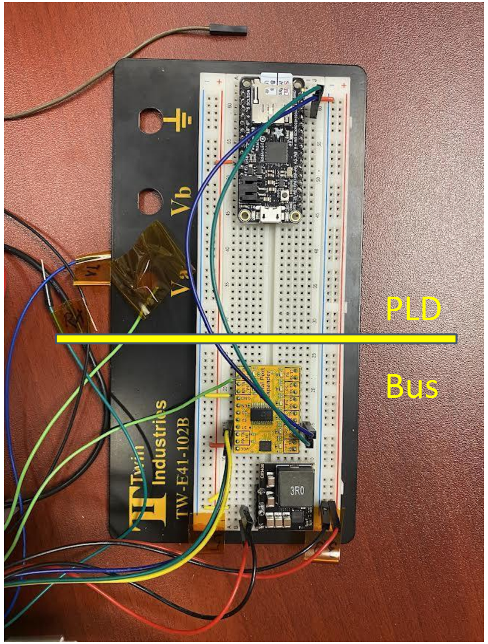


Bus → Payload UART Communication





** Both interfaces have standard board layouts with standard comm software on bus/payload ends. The connection will allow for full intra-satellite in one simple step

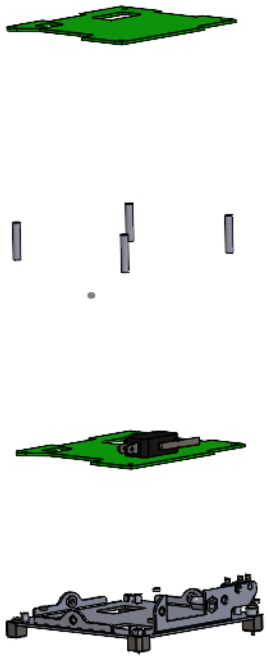


** Communication test setup

Conclusion

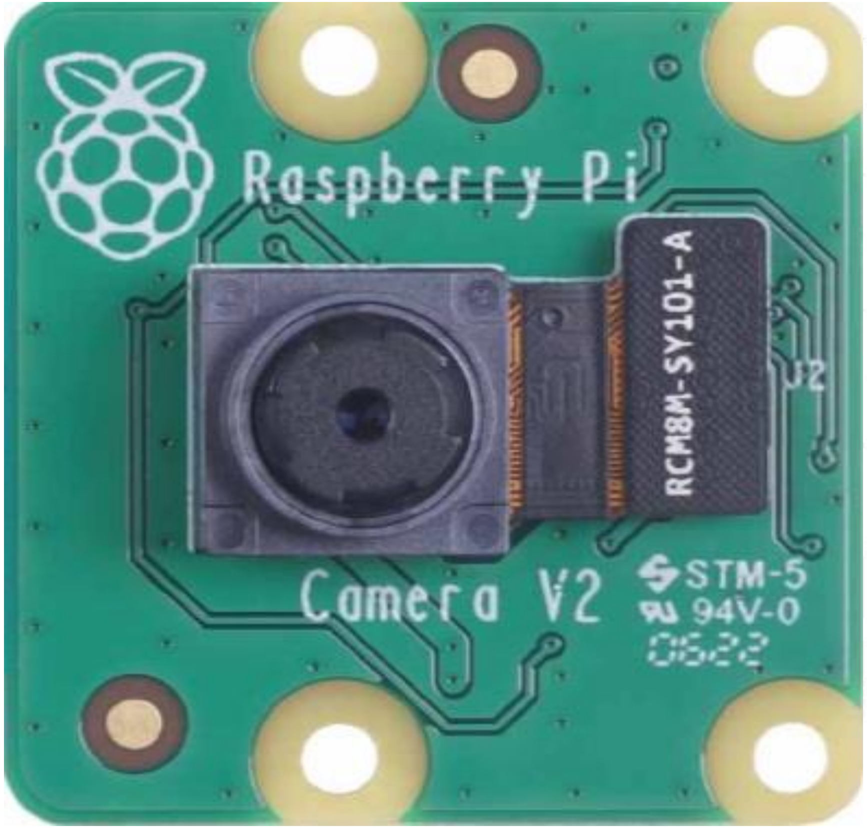
This design accomplishes the desired level of modularity, significantly reducing the time required for spacecraft development.

- All key functionalities made available to the payload with simply a physical and electrical connection
- variety of future projects to be successfully integrated
  - Flexible solar panel options
  - Pre-designed ADCS systems
  - Different payload size options
- Drastically shortened design phase
- Pre-constructed, shelf-stored NASB
- Rapid integration when following ICD



Thank you.
Questions?

Camera



Raspberry Pi Camera Module 2

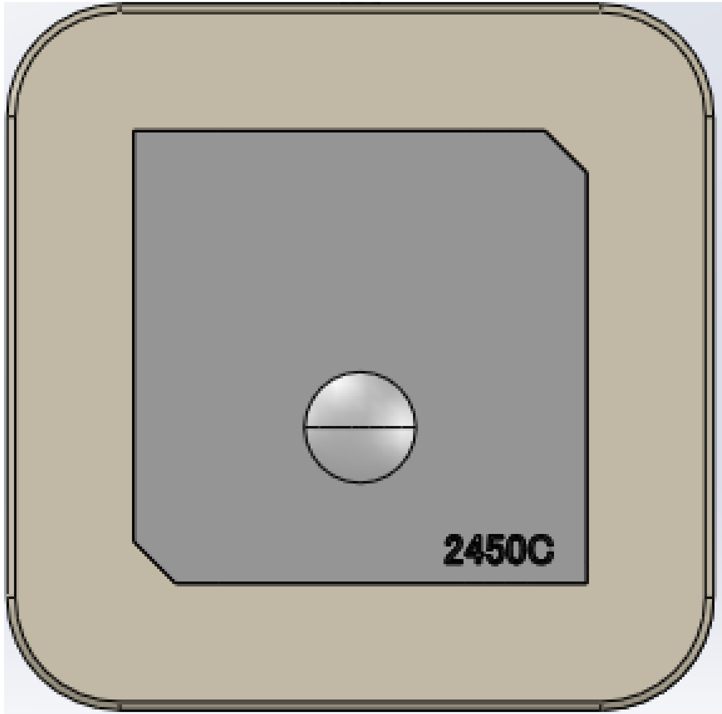
- **Sony IMX219 8-megapixel sensor**
- **Capabilities: high-definition video, as well as stills photographs**
- **Supports: 1080p30, 720p60 and VGA90 video modes, as well as still capture**
- **Carries an 8 megapixel Sony IMX219 image sensor**
- **Dimensions: 120mm x75mm x23mm**
- **Weight: (32g)**
- **Max Operating Temp: 105º C**
- **attaches via a 15cm ribbon cable to the CSI port on the Raspberry Pi**

GPS Patch Antenna

25mm One Stage GPS/GALILEO Active Patch Antenna Module

- **Manufacturer: Taoglas**
- **Dimensions: 25mm Patch on 35mm Ground Plane 35*35*4.5mm, 54mm (chord)**
- **Frequency: 1575.42 ± 1.023MHz**
- **Polarization: RHCP**
- **Weight: 7.00 g**
- **Min Operating Temp: -40º C**
- **Max Operating Temp: 85º C**

S-Band Patch Antenna



WPC.25A 25*25*4mm 2.4GHz Patch Antenna

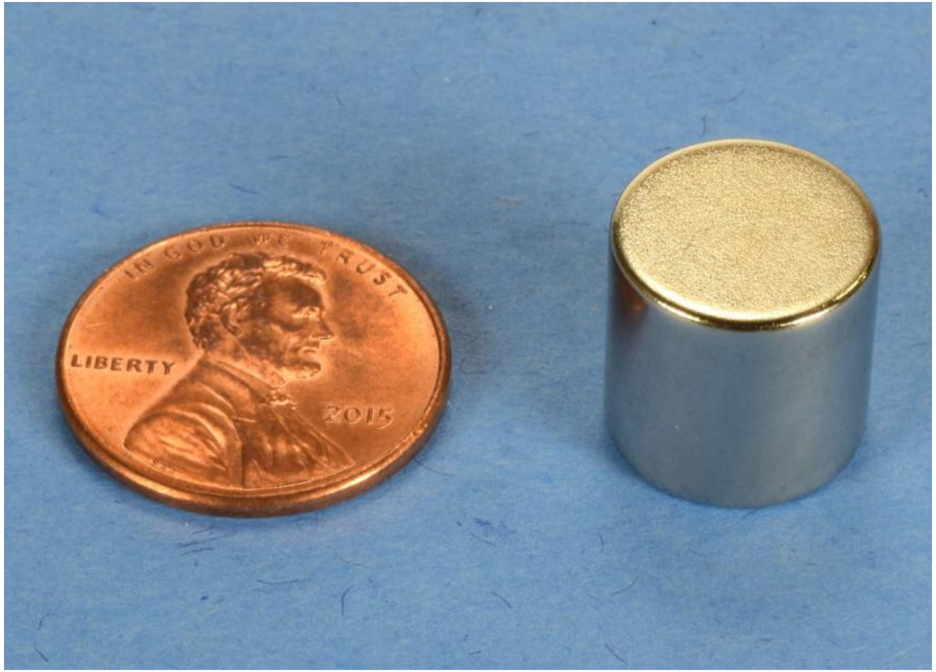
- **Manufacturer: Taoglas**
- **Dimensions: 25mm Patch 25*25*4.5mm**
- **Frequency: 2.4~2.5GHz**
- **Polarization: Broadly Linear**
- **Weight: 15.57 g**
- **Min Operating Temp: -40º C**
- **Max Operating Temp: 85º C**

Batteries

HE2 ICR High-Drain 20A Lithium Ion (Li-ion) Flat Top Batteries

- **Dimensions: 65mm-length, 18.3mm-diameter**
- **Weight: 48.0 g / per cell**
- **Power: 2500 mAh**
- **Nominal Voltage: 3.6 V**
- **Capacity: 300+ charge cycles**
- **Charge time: 0.75 hours**
- **Operating Temp (charge): 0-50º C**
- **Operating Temp (discharge): (-20ºC) - 75º C**

PMAC - Bar Magnet (tracking)



D88-N52

- **Dimensions: 1/2" dia. x 1/2" thick**
- **Material: NdFeB, Grade N52**
- **Plating/Coating: Ni-Cu-Ni (Nickel)**
- **Magnetization Direction: Axial (Poles on Flat Ends)**
- **Weight: 0.426 oz. (12.1 g)**
- **Pull Force, Case 1: 18.08 lbs**
- **Pull Force, Case 2: 20.38 lbs**
- **Surface Field: 6619 Gauss**
- **Max Operating Temp: 80º C**
- **Brmax: 14,800 Gauss**
- **BHmax: 52 MGOe**

PMAC - Hysteresis Strips (damping)

Hy Mu 80 (permalloy)

- **Dimensions: 5.0” (length) x 0.2”(width) x 0.02” (depth)**
- **Material Form: Strip**
- **Material: 80% Nickel-Iron alloy**
- **Plating/Coating: Ni-Cu-Ni (Nickel)**
- **Magnetic feature: highly permeable**
- **Weight: negligible**

Heat Tolerance of other Electronics

- **Buck Converter: 0º - 70º C**
- **RPi Zero 2W: (-20º) - (+70º) C**
- **Serial Port Expander: (-40º) - (+85º) C**
- **Spectrolab UTJ cells: 15º - 80º C**

Thermal Analysis - 250K Average Temperature

1U Thermal Analysis	USNA NASB	EA469 – Capstone Project

Q: A USNA $1000 cm^3$ CubeSat in a circular, LEO @ 400 Km altitude generates power using Spectrolabs UTJ solar cells in daylight & Lithium-ion batteries in eclipse.

On average, the Cubesat generates 1.56 W of power per orbit.

The absorptivity of the solar cells with account for the majority of the CubeSat surface is 0.8 & their emissivity is 0.9.

Use: Solar flux of $1366\ W/m^2$, solar albedo ~30% of solar flux

Earth IR ~$237\ W/m^2$, $\sigma = 5.67 \times 10^{-8}\ W/K^4m^2$

98% of power generated is generated heat.

Short description of factors considered and assumptions made

Thermal Analysis - 250K Average Temperature

Si: $A_{in} = 0.01\,m^2$, $A_{out} = 0.06\,m^2$ 2179.7 sec / 0.60547 hr ~ eclipse

3312.4 sec / 0.92011 hr ~ daylight ~ 0.60312 % of orbit

Daylight: $Q_{gen}, Q_{sun}, Q_{albedo}, Q_{IR}$

Eclipse: Q_{gen}, Q_{IR}

$Q_{gen} = 0.98(1.56\,W) \Rightarrow 1.53\,W$

$Q_{sun} = \alpha S A_{in} = (0.8)(1366\,W/m^2)(0.01\,m^2) \rightarrow 10.928\,W$

$Q_{albedo} = 0.3(Q_{sun}) \Rightarrow 3.2784\,W$

$Q_{IR} = \alpha(IR)A_{in} = (0.8)(237\,W/m^2)(0.01\,m^2) \rightarrow 1.896\,W$

$\sum Q_{in} = \sum Q_{out} = \varepsilon A_{out} \sigma T^4 \Rightarrow T = [\sum Q_{ins} / \varepsilon A_{out} \sigma]^{1/4}$

$T_{day} = [(1.53 + 10.928 + 3.2784 + 1.896\,W)/(0.9)(0.06)(5.67\times10^{-8})]^{1/4}$

$T_{day} = 275.48\,K$

$T_{eclipse} = [(1.53 + 1.896\,W)/(0.9)(0.06)(5.67\times10^{-8})]^{1/4}$

$T_{eclipse} = 183\,K$

$T_{avg} = 250\,K$ ⇒ duty cycle calculation!

Plans for temperature control

Mass/Volume Budget

Components		Mass (grams)	Margin +/- (grams)	Volume (L,W,H) in mm
Primary Structure		241	0.5	100 x 100 x 100
Bottom Board		79	3.5	100 x 100 x 1.5
Switchboard		47	2	96 x 90 x 10
Battery Board + Batteries		252	1	96 x 90 x 20
PyCubed Board		62	1.5	96 x 90 x 20
Bus Board		82	4	96 x 90 x 10
Antenna Board		72.1	3	100 x 100 x 1.5
PMAC Housing		40	1	98 x 98 x 1.5
Mounting hardware (fasteners, standoffs, nuts, wires, epoxy)		100	10	In between components
Total		**975**	26.5	

More than 100% margin

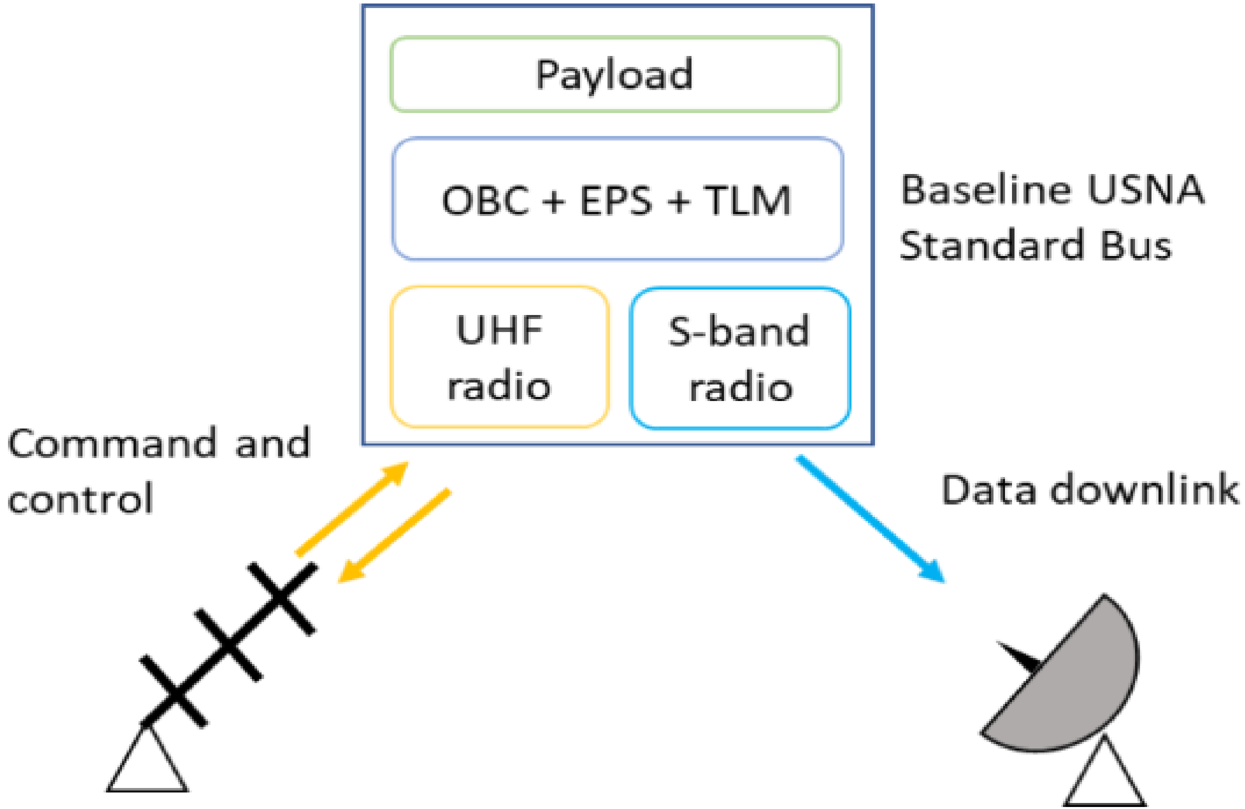
Cost Budget

Component/Item	Item Price ($)
UTJ Solar Cells	2200.00
All Printed Circuit Boards	100.00
Solar Panels	100.00
DC-DC Buck Converter 6~14V to 5V/8A	8.50
Raspberry Pi Zero 2W	15.00
8:1 Serial Port Expander	19.99
CaribouLite SDR	138.00
20 AWG Teflon Coated Wire	13.98
LiPo Batteries	52.72
GPS Antenna	13.62
Bar Magnet	2.32
Solar Panel Step-Up Converter	9.11
1U Fully Solid Pumpkin Structure	1215.00
Cover Plate Assembly	495.00
Base Plate Assembly	690.00

Component/Item	Item Price ($)
Raspberry Pi Camera Module V2	29.95
Diode for Solar Panels	2.80
Solar Panel Boost Converer 3.6-18V to 24V no pin	3.11
C to C extension cable	10.88
USB to C extension cable	13.98
Antenna Splitter	9.30
Patch Antenna	21.19
316 M3 1 meter Through Rods	51.28
Bar Magnet	3.98
Hymu80 (Hysteresis Strips)	600.00
Camera Cable	3.95
Board Connector (Plug)	0.52
Board Connector (Receptacle)	0.44
Solar Panel Connector (Plug)	1.05
Solar Panel Connector (Receptacle)	1.17
MOLEX Crimper for 24-30AWG	410.13

TOTAL	6234.30

Antenna Pointing



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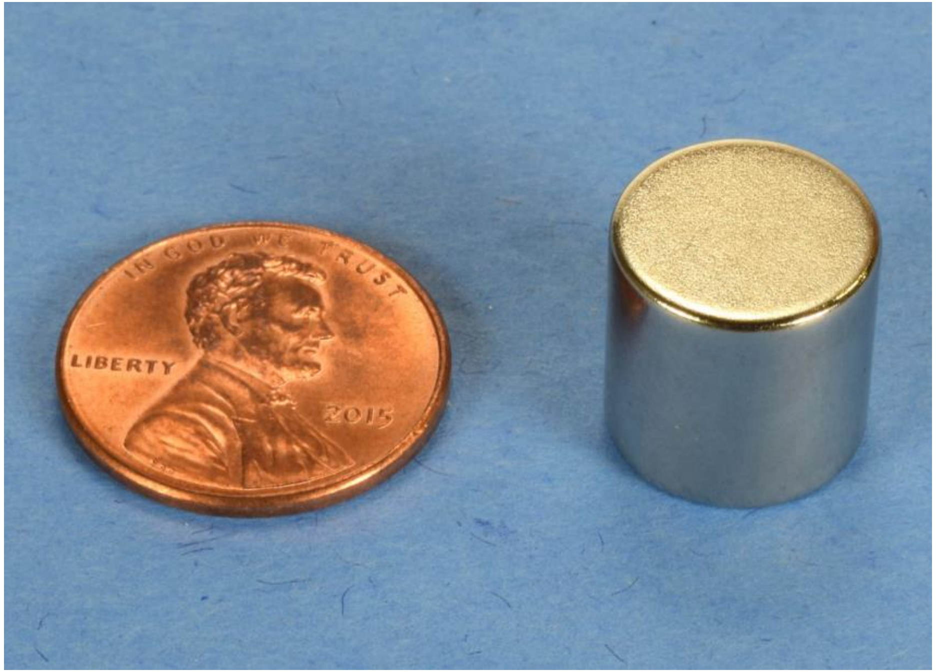

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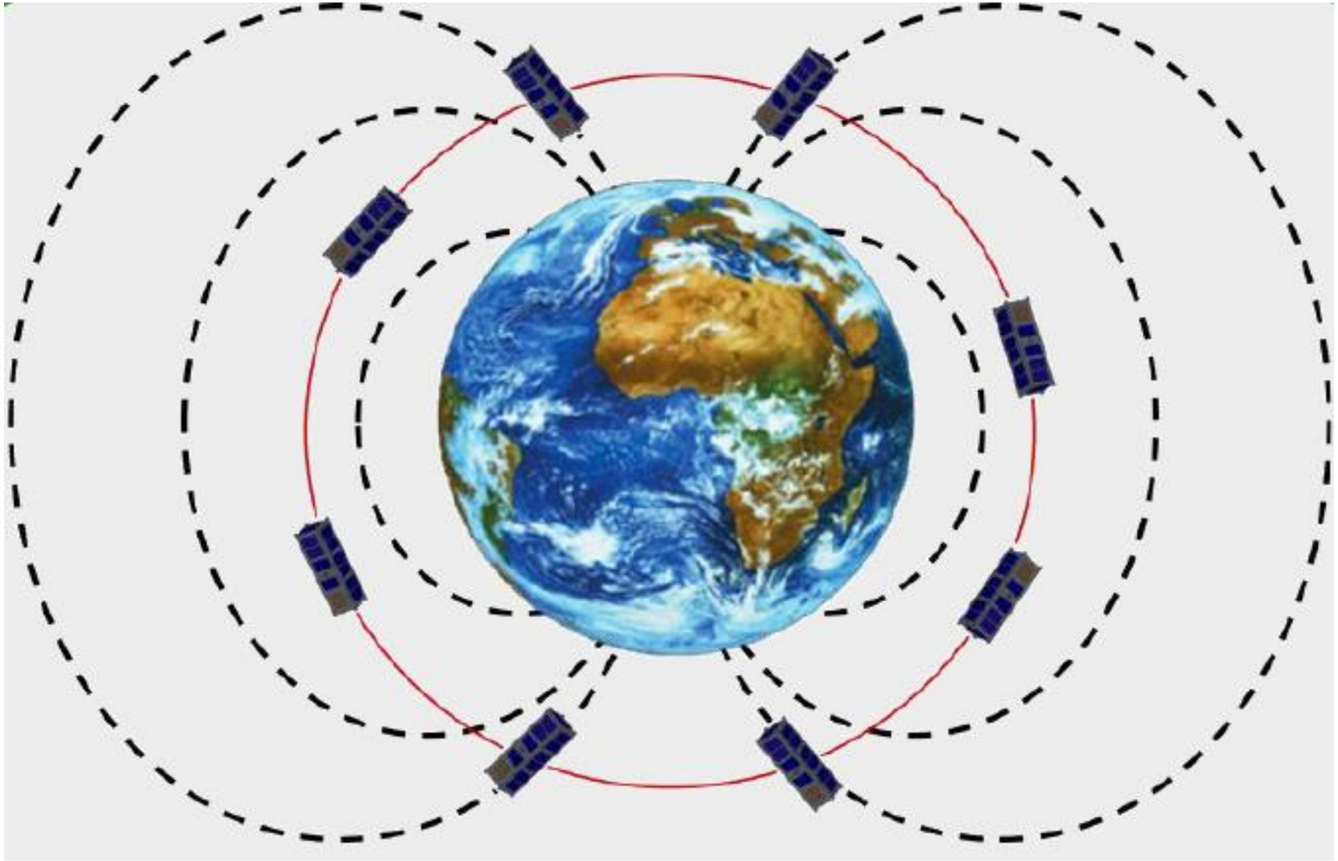
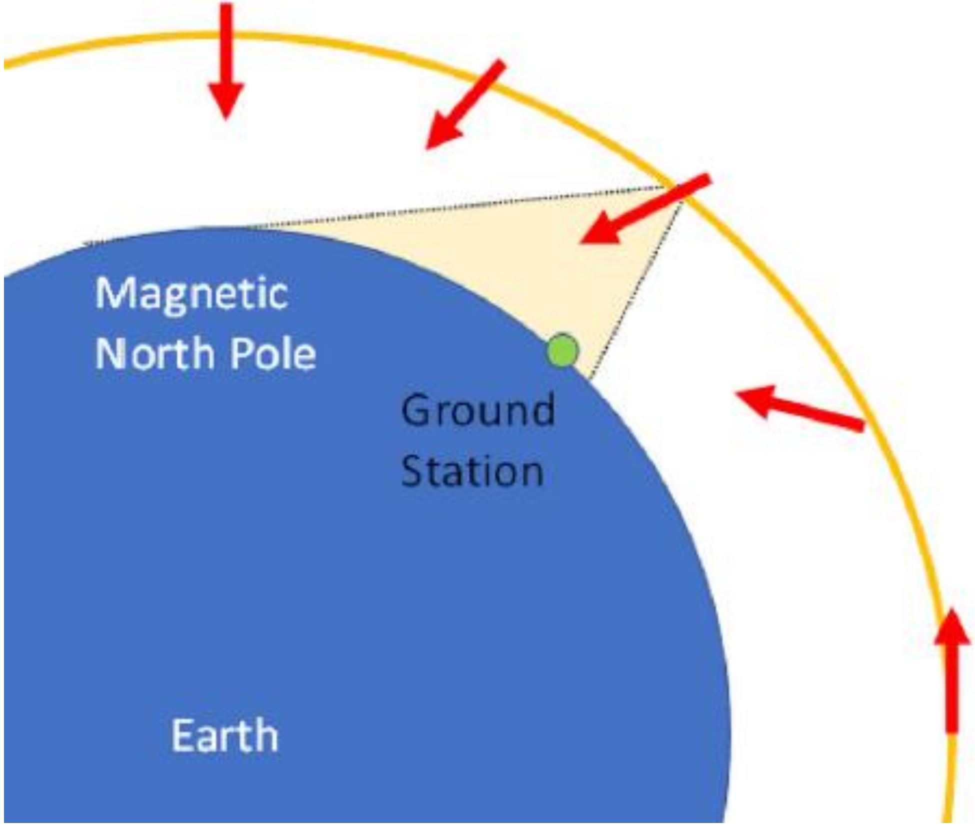
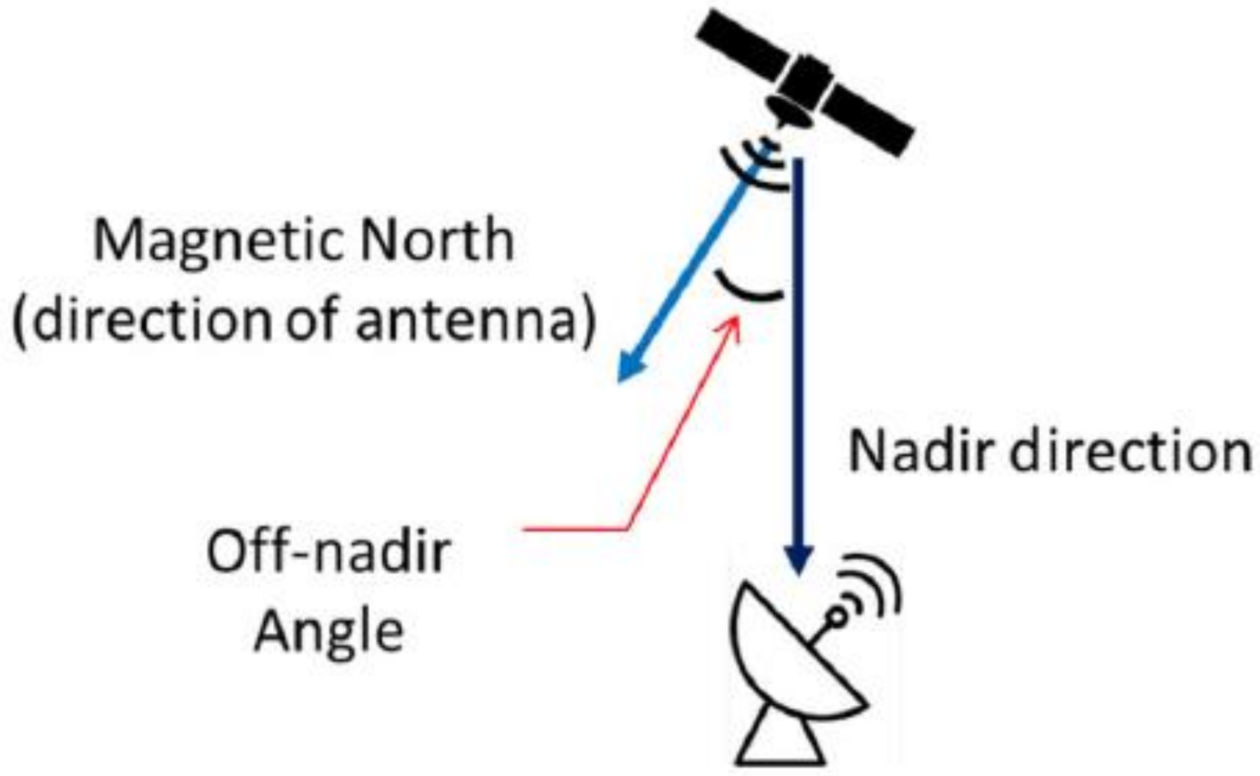
Antenna Pointing



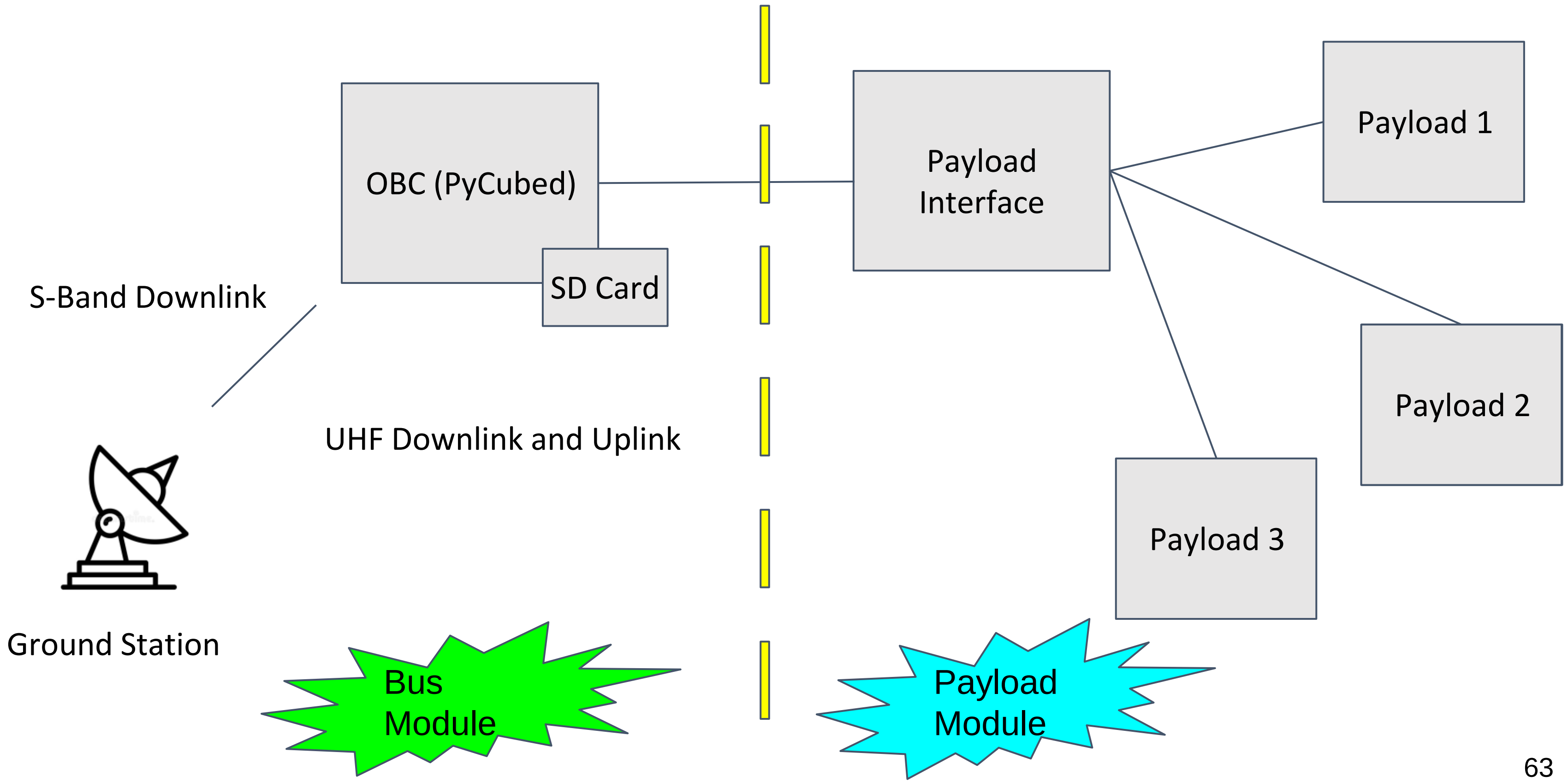
Antenna Pointing



Antenna Pointing



C&DH - Data Flow Overview



Link Budget (⅕)

Item	Units		S Down Link 0.126 Mbps			UHF Down Link 1.563 kbps	
		SX1280			HopeRF		
Orbit Altitude	km	500	500	500	500	500	500
Spacecraft Elevation Angle	deg	20	45	80	0	45	89.99
Frequency	GHz	2.4	2.4	2.4	0.4	0.4	0.4
Wavelength	m	0.125	0.125	0.125	0.750	0.750	0.750
Propagation Path Length	km	1192.99	683.09	507.14	2574.51	683.09	500.00
Space Loss - Ls	dB	-161.58	-156.74	-154.15	-152.70	-141.17	-138.46
System Noise Temperature - Ts	k	500	500	500	500	500	500

Link Budget (⅖)

Bit Error Rate		1.00E-05	1.00E-05	1.00E-05		1.00E-05	1.00E-05	1.00E-05
Required Eb/No for BER 10-5	dB	9.6	9.6	9.6		9.6	9.6	9.6
Calculated Coding Gain	dB							
Achievable Coding Gain	dB							
Data Rate - Rb	kbps	76.13	76.13	76.13		1.563	1.563	1.563
Symbols Per Bit		2	2	2		2	2	2
Symbol Rate - Rs	kbps	38.065	38.065	38.065		0.7815	0.7815	0.7815
ro		1.50	1.50	1.50		1.50	1.50	1.50
Required C/No	dB	58.42	58.42	58.42		41.54	41.54	41.54
Bandwidth - BW	MHz	0.095	0.095	0.095		0.002	0.002	0.002

Link Budget (⅗)

Required C/N	dB	8.63	8.63	8.63	8.63	8.63	8.63
Receiver Bandwidth - B	MHz	2	2	2	2	2	2
GND Antenna Diameter	m	3	3	3	3.04	3.04	3.04
GND Antenna Feed Efficiency	%	60%	60%	60%	60%	60%	60%
GND Antenna Half Power Beamwidth	deg	2.92	2.92	2.92	17.27	17.27	17.27
GND Antenna Pointing Error	deg	2.0	2.0	2.0	2.0	2.0	2.0
GND Antenna Pointing Error Loss - La	dB	-7.50	-7.50	-7.50	-1.81	-1.81	-1.81
GND Antenna Gain - G	dBi	37.55	37.55	37.55	15.00	15.00	15.00
S/C Antenna Diameter	m	0.0419	0.0419	0.0419	[redacted]		
S/C Antenna Feed Efficiency	%	100%	100%	100%			

Link Budget (4/5)

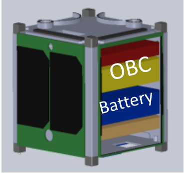
S/C Antenna Half Power Beamwidth	deg	120.00	120.00	120.00	[redacted]		
S/C Antenna Pointing Error	deg	2.0	2.0	2.0			
S/C Antenna Pointing Error Loss - La	dB	-0.28	-0.28	-0.28			
S/C Antenna Gain - G	dBi	0.45	0.45	0.45	0.00	0.00	0.00
Transmitter Power	Watts	0.5	0.5	0.5	1	1	1
Transmitter Power - P	dBW	-3.01	-3.01	-3.01	0.00	0.00	0.00
Transmitter Line Loss - Ll	dB	-1	-1	-1	-1	-1	-1
Transmitter Feed Loss - La	dB	0.00	0.00	0.00	0.00	0.00	0.00
Transmitter EIRP	dBW	-3.56	-3.56	-3.56	-1.00	-1.00	-1.00
Transmission Path Losses - La	dB	-0.50	-0.50	-0.50	-0.50	-0.50	-0.50

Link Budget (5/5)

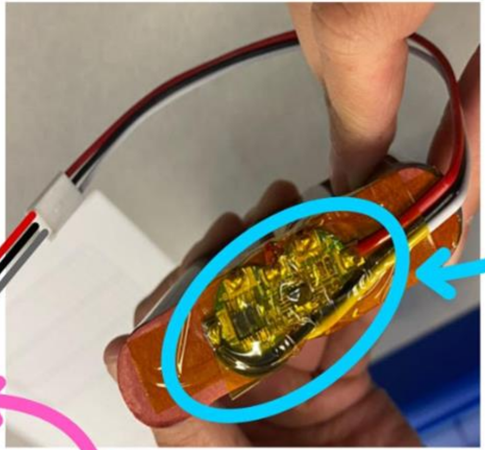
Receiver Polarization Loss - La	dB	-3	-3	-3		-3	-3	-3
Receiver Line Loss - La	dB	-1	-1	-1		-1	-1	-1
Receiver Feed Loss - La	dB	-2.22	-2.22	-2.22		-2.22	-2.22	-2.22
Received Carrier Power - C	dBW	-142.10	-137.25	-134.67		-147.65	-136.12	-133.41
Total Received Noise Power - N	dB	-138.60	-138.60	-138.60		-138.60	-138.60	-138.60
Received Carrier To Noise Ratio - C/N	dB	-3.50	1.35	3.94		-9.05	2.48	5.19
Received Energy Per Bit - Eb	dB	-187.90	-183.06	-180.47		-176.58	-165.05	-162.34
Received Noise Spectral Density - No	dB	-201.61	-201.61	-201.61		-201.61	-201.61	-201.61
Calculated Eb/No	dB	13.71	18.55	21.14		25.03	36.56	39.27
Eb/No Margin	dB	4.11	8.95	11.54		15.43	26.96	29.67

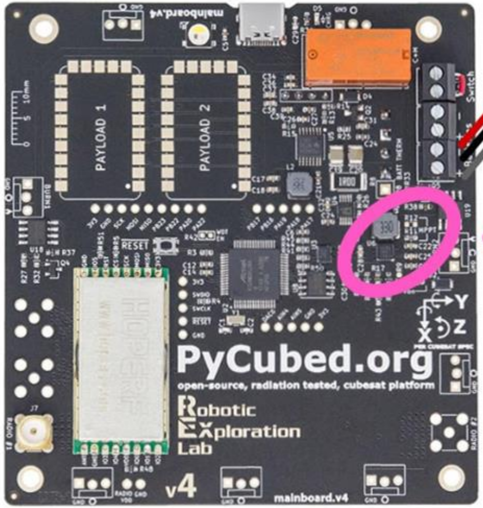
Command List

1st Byte	2nd Byte	Command	Notes / Arguments
0x31	0x71	No-op	
0x31	0x77	Downlink telemetry	
0x31	0x65	Reset satellite	
0x31	0x74	Reset SDR	
0x31	0x79	Downlink telem folder stats	
0x31	0x75	Downlink one telem file	Telem file number
0x31	0x69	Transfer multiple internal bus files in sequence FIFO	File range
0x31	0x6F	FIFO dump + specific payload	Payload # in 3rd byte 1 - 0x78 2 - 0x63 3 - 0x6E range of files
0x31	0x70	I received these files from FIFO dump - you can delete them	File names Note: downlink one at a time, max picture storage ~3
0x31	0x64	Change beacon rate	Beacon rate (seconds)
0x31	0x66	Change telem collection rate	Telem collection rate
0x31	0x6A	Take pic now	Save as picture 1 2 or 3
0x31	0x72	Downlink pic	Most recent Picture number (1 2 or 3)
0x35	0x78	Send to payload interface	Message for payload
0x45	0x4E	Downlink GPS data to ground	Later, include this into Telem and delete this command
0x00	0x01	Override	Override current operation followed by next command



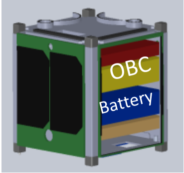
Battery Circuit Protection Board





Energy Harvester with MPPT

Solar Cells



SPECTROLAB

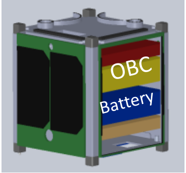
A **BOEING** COMPANY

28.3% Ultra Triple Junction (UTJ) Solar Cells

Features

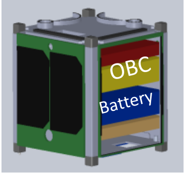
- Small and large cell sizes offered for optimum packing factor and cost competitiveness
- All sizes qualified for LEO and GEO missions

Solar Cell Power Output



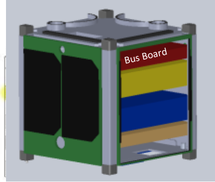
Power Output for Each Configuration			
	3U 	2U 	1U 
Cells per face	7	4	2
Power per face (W)	7	4	2
Voltage per face (V)	16	9	4

Standard Bus Power Consumption

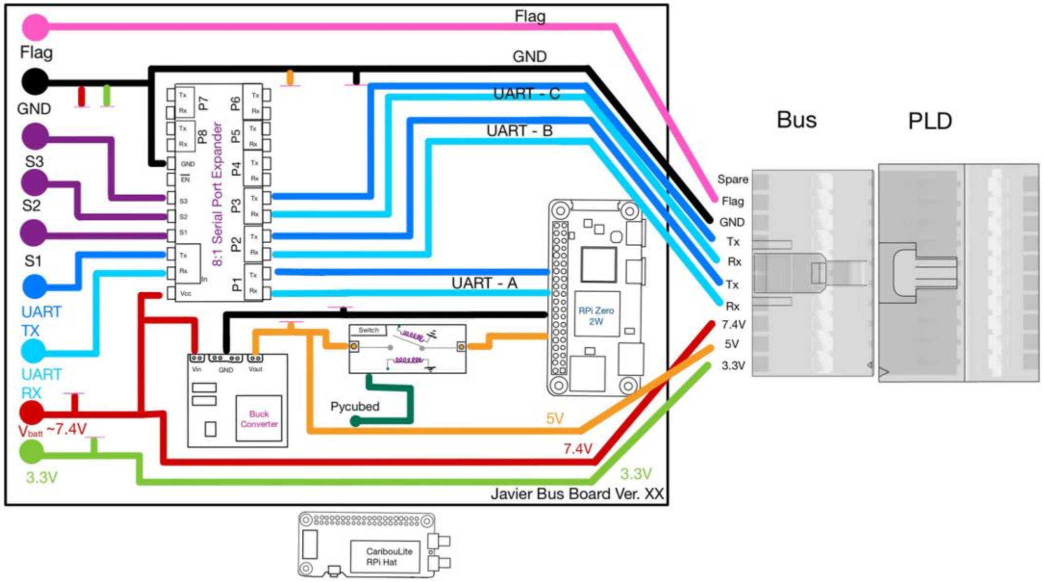


Bus Power Consumption		
	Measured	**Power Consumed in Normal Mode**
PyCubed	0.098 W	0.10 W
RPi	1.23 W	0.12 W
(Worst Case) Radio UHF	3.38 W	0.035 W
Total Bus Power Consumed:		0.25 W
Power Available		1.48 W
Total Margin		83 %

Power Regulation + Contained Components



Inputs From PyCubed



** block diagram not to scale