Canadian Satellite Design Challenge

CSDC-5

Critical Design Review

Queen’s Space Engineering Team (QSET)

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Oct 9, 2019

Agenda

- Mission Overview
- Trade Selection
- Payload
- Spacecraft Structure
- Thermal Analysis
- Power Subsystem
- Attitude Determination & Control System (ADCS)
- Communications Systems
- On Board Computer (OBC)
- Assembly, Integration & Testing (AI&T)
- Risk Management
- Anomaly Mitigation
- Concept of Operations (CONOPS)
- Program Management
- Educational Outreach
- Summary

Mission Overview

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Problem

- Allow for an Amateur Radio Operator to send command to take a "Space Selfie“
- Have the image downlinked to them immediately

Solution

- Use active attitude control to point telescope at Earth
- Take image and compress it for downlink
- Downlink the image to the Amateur Radio Operator

Result

- Successful delivery of a distinguishable image of the Earth
- Return to standby mode while awaiting next "selfie" request

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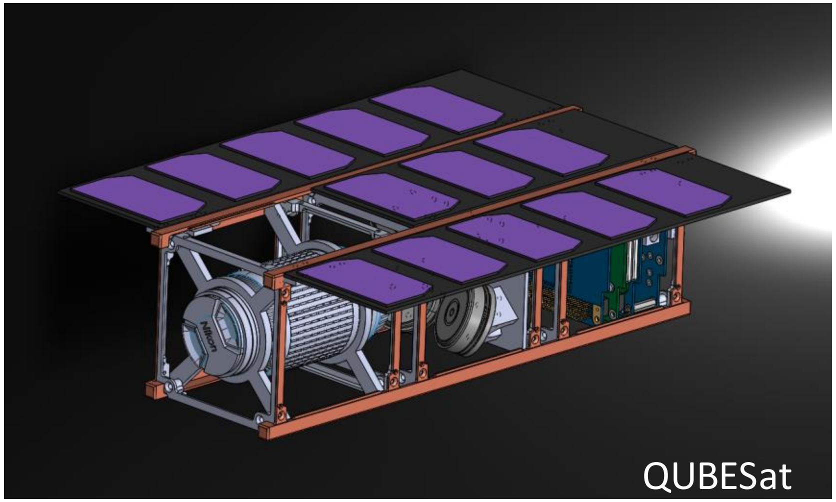
Mission Overview: Spacecraft

- 3U CubeSat design
  1. Optical payload
  2. Attitude control system
  3. Electrical stack
- Deployable solar arrays
- Gold anodized structure
- Combination of in-house made components and COTS components

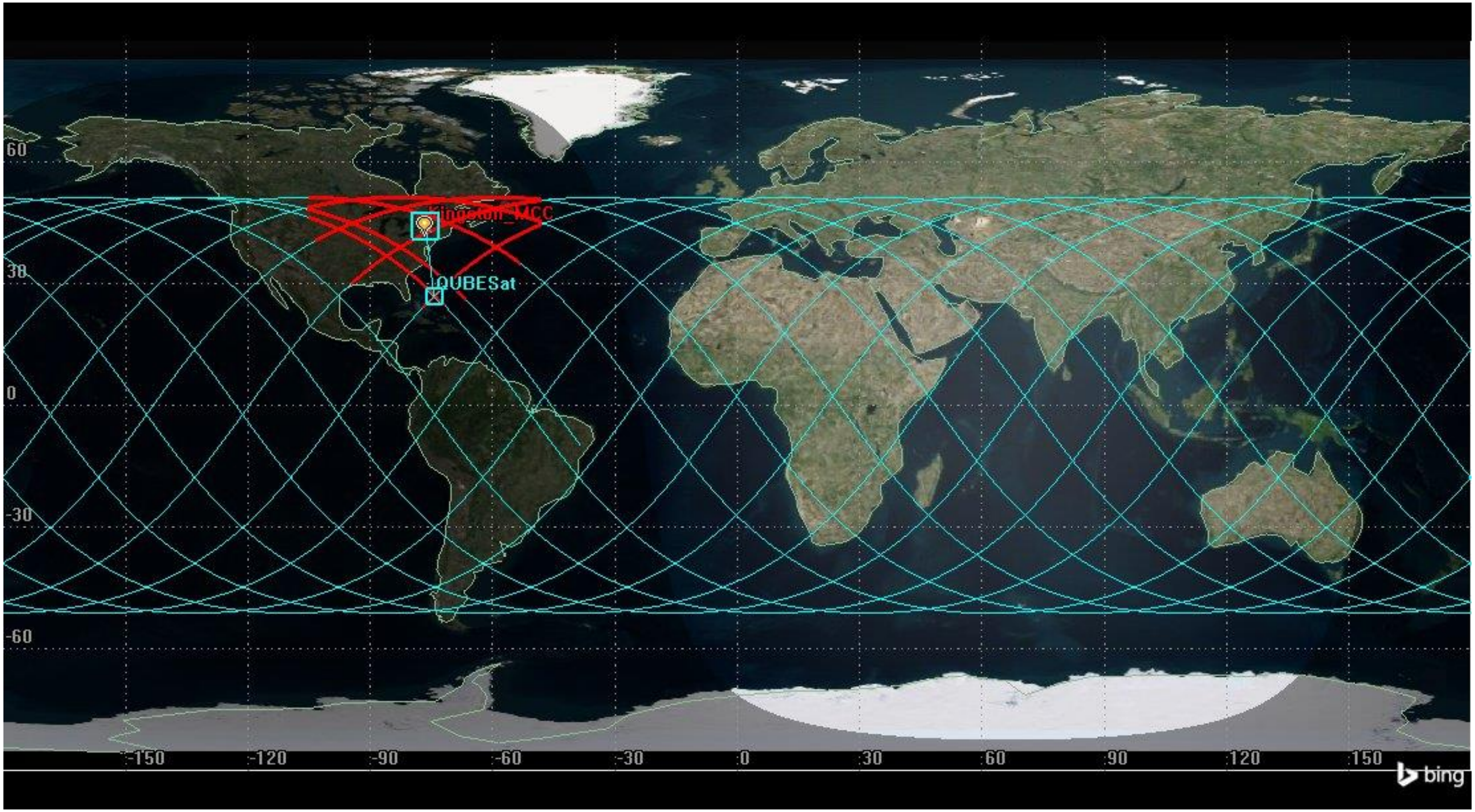


Mission Overview: Spacecraft Subsystems

- Optics Payload
- Spacecraft Structure
- Power System
- Attitude Determination and Control System (ADCS)
- Communications Systems
- On Board Computer (OBC)

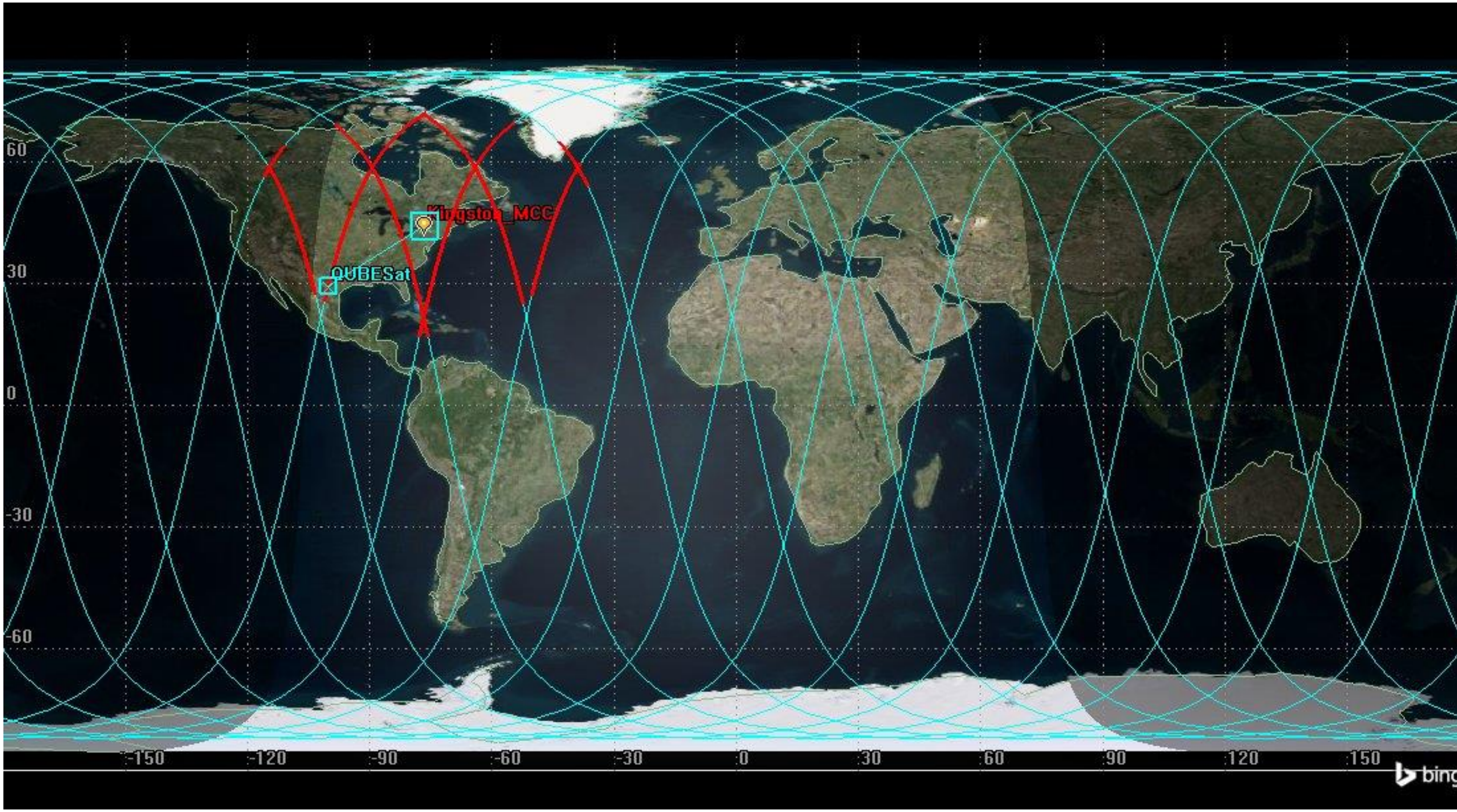
Mission Overview: Ground Track and Ground Station Access (1/3)

- 400 km ISS orbit



Mission Overview: Ground Track and Ground Station Access (2/3)

- 800 km Sun-synchronous orbit



Mission Overview: Ground Track and Ground Station Access (3/3)

- Mission Control Centre:
  - Royal Military College of Canada SSRL
  - 44°14’1.97” N, 76°28’3.02” W

	400 km ISS orbit		800 km sun-synchronous orbit	
	Minimum	Average	Minimum	Average
Passes per day	6	6.8	6	7.2
Single pass contact time (minutes)	7.5	9.7	2.3	10.2

Trade Selection

Trade Selection: Overview

- Build
  - Chosen to design subsystems in areas where members possess expertise
  - Team involves graduate students with specialized skill sets
  - Some designs were chosen specifically to challenge members, such as deployables
  - Parts manufactured in-house will undergo rigorous qualification
- Buy
  - Subsystems requiring extensive background knowledge to build from the ground up
  - Preference given to flight heritage components

Trade Selection: Comparison

Build	Buy
Structure	Power System
ADCS	Payload
OBC	Thermal
Communications System	
Antenna	

Trade Selection: Build (1/5)

Build	Buy
Structure	Power System
ADCS	Payload
OBC	Thermal
Communications System	
Antenna	

- Structure
  - Team has strong background in mechanical design and have structure that performed strongly at CSDC-4 as per judges

Trade Selection: Build (2/5)

Build	Buy
Structure	Power System
ADCS	Payload
OBC	Thermal
Communications System	
Antenna	

- ADCS
  - Background in applied mathematics and control theory
  - In-house design of reaction wheel control system using COTS motors

Trade Selection: Build (3/5)

Build	Buy
Structure	Power System
ADCS	Payload
OBC	Thermal
Communications System	
Antenna	

- OBC
  - OBC is being built due to sufficient member interest in imbedded system design and radiation tolerant computer design
  - Previously purchased OBCs also did not pass radiation testing

Trade Selection: Build (4/5)

Build	Buy
Structure	Power System
ADCS	Payload
OBC	Thermal
Communications System	
Antenna	

- Communications System
  - Saves on cost
  - Available hardware and personnel to test
  - Allows for custom interfacing with other subsystems which makes downlinking images easier

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Trade Selection: Build (5/5)

Build	Buy
Structure	Power System
ADCS	Payload
OBC	Thermal
Communications System	
Antenna	

- Antenna
  - Antennas will be designed in-house
  - Manufactured using tape measures
  - Matching network will be designed to match antenna impedance with transceiver impedance (50 Ω).

Trade Selection: Buy (1/3)

Build	Buy
Structure	Power System
ADCS	Payload
OBC	Thermal
Communications System	
Antenna	

- Power System
  - Team does not possess knowledge to create in house system; opted for reliable flight heritage COTS electrical power system (EPS) from ClydeSpace

Trade Selection: Buy (2/3)

Build	Buy
Structure	Power System
ADCS	Payload
OBC	Thermal
Communications System	
Antenna	

- Payload
  - Buying a lens allows for higher image quality and reliability
  - Buying a sensor allows the team to learn how to interface with the lens and achieve the desired field of view

Trade Selection: Buy (3/3)

Build	Buy
Structure	Power System
ADCS	Payload
OBC	Thermal
Communications System	
Antenna	

- Thermal
  - Active cooling/heating is limited by power budget
  - Passive cooling/heating copper heat pipes are an affordable and simple solution

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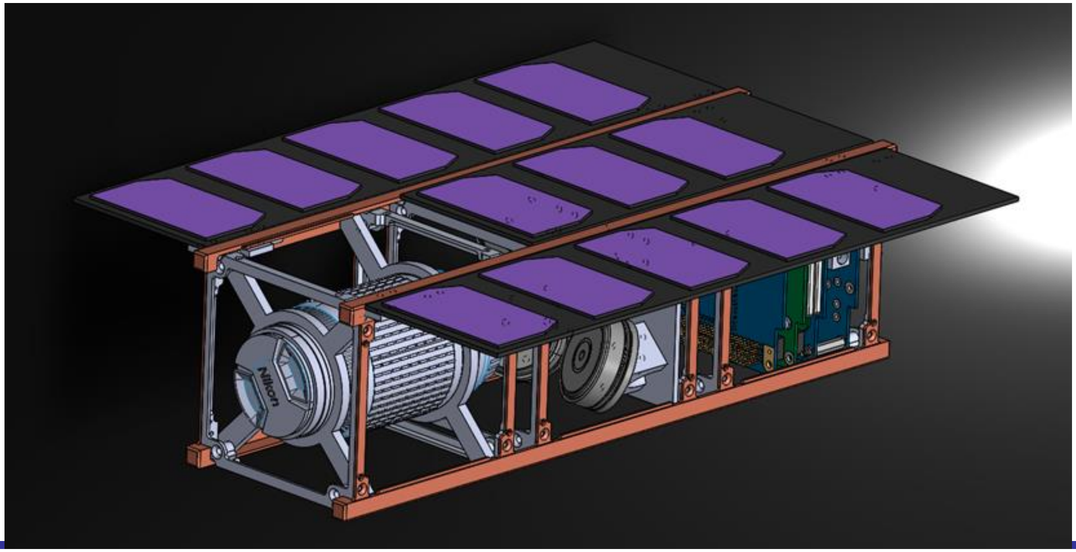
Payload

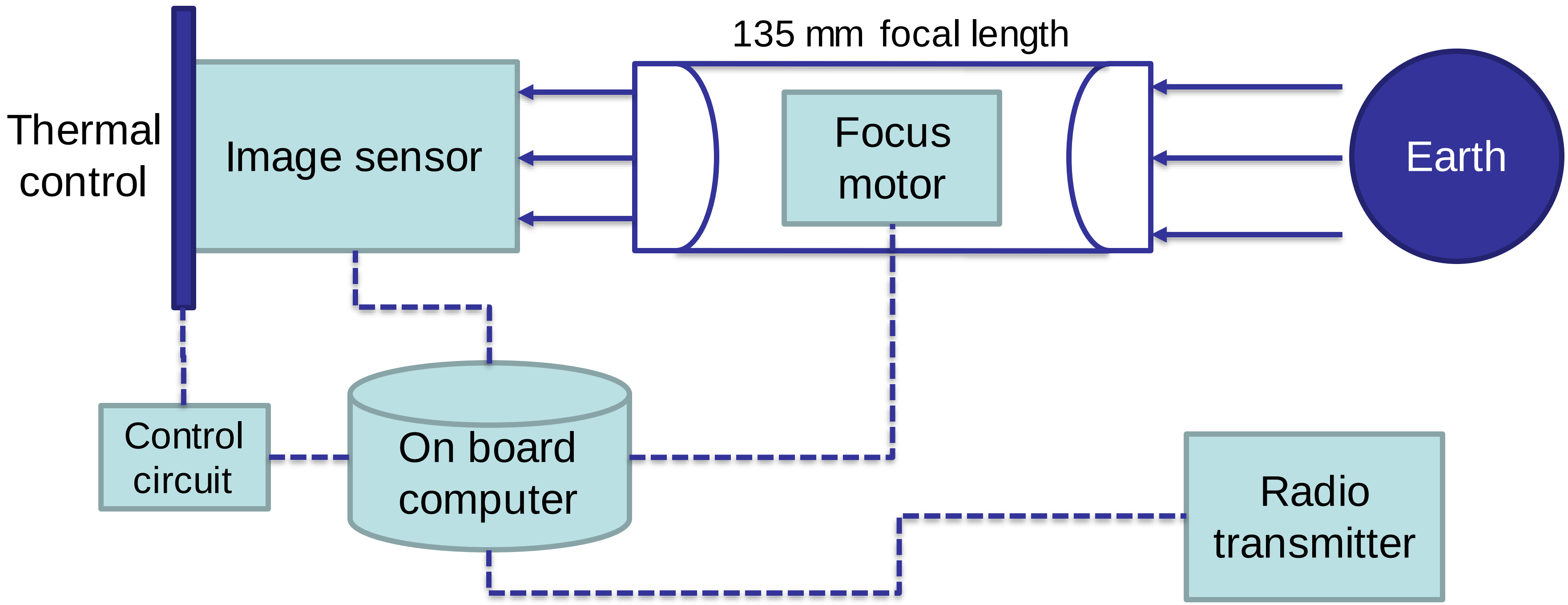
Payload: Overview

“Selfie-Sat” key constraints:

- Field of View (FoV) 40x40 km to 100x100 km at nadir
- Durable to space conditions
- Image must be within downlink budget (90 sec downlink at 9600 bps)
- Relative speed to earth, $V_{relative}$ = 7000 - 7200 m/s (depending on orbit)



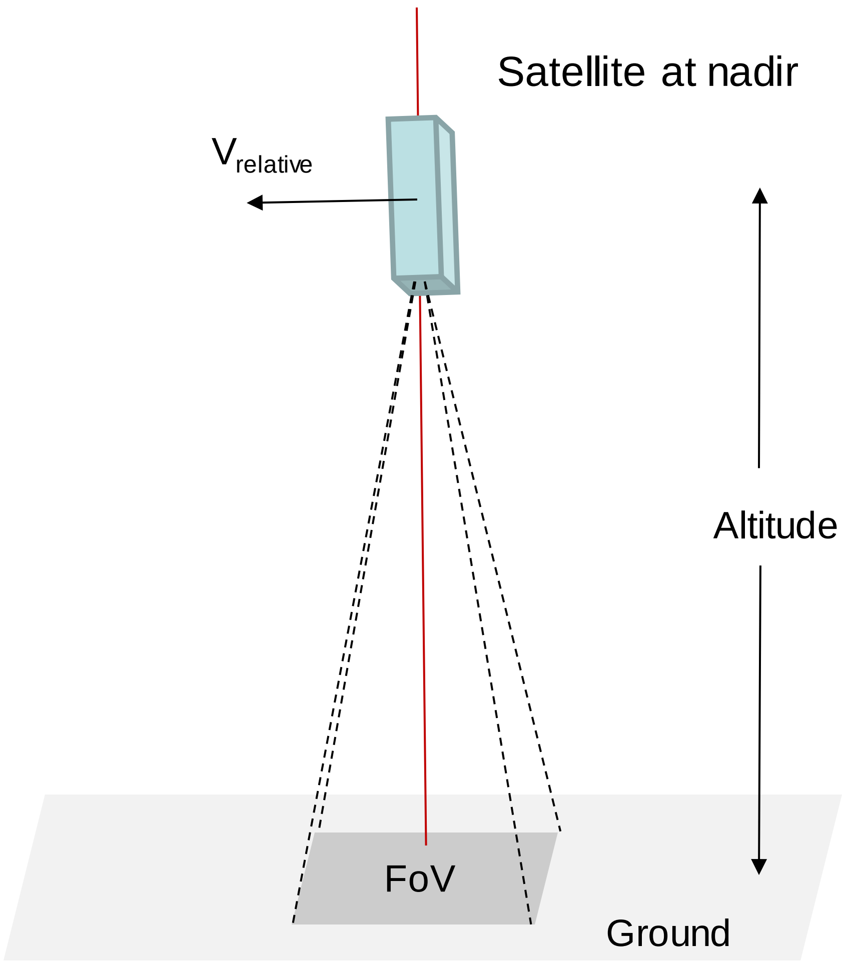
Payload: System Overview



- Standard CMOS image sensor coupled with telescopic lens
- Image compression performed by OBC
- Thermal control of image sensor achieved using heat pipes

Payload: Image Parameters

- Field of View
  - ~ 66.8 km x 44.5 km
- Pixel dimensions on ground
  - ~ 14 x 12 m
- To reduce motion blur
  - Minimize exposure time
  - Control look angle (ADCS)
- At minimum exposure time (32µs) ground blur = 0.23 m
- Exceptionally low-cost solution composed of easily accessed parts



Payload: Physical Characteristics

ZWO ASI1600mm (Mono)

- CMOS sensor not susceptible to degradation of CTE
- Well documented SDK
- Monochrome for higher image detail

Canon EF 135mm f/2L USM

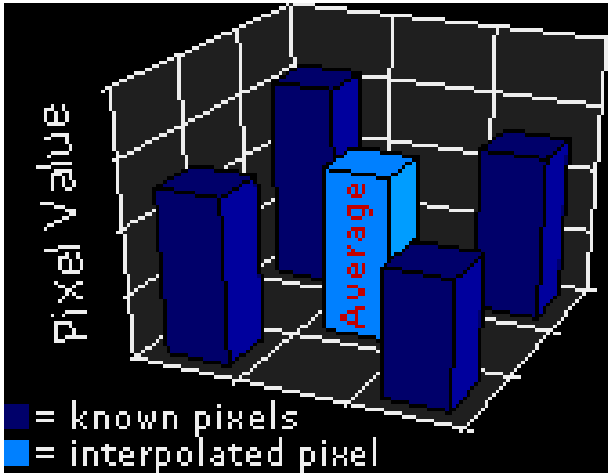
- Fixed focal length
- Ultrasonic motor controls focus
- Relatively low weight
- Large aperture allows in more light

Physical Size	Total Mass	Field of View
82.5 x 153 mm	890 g	66.8 x 44.5 km

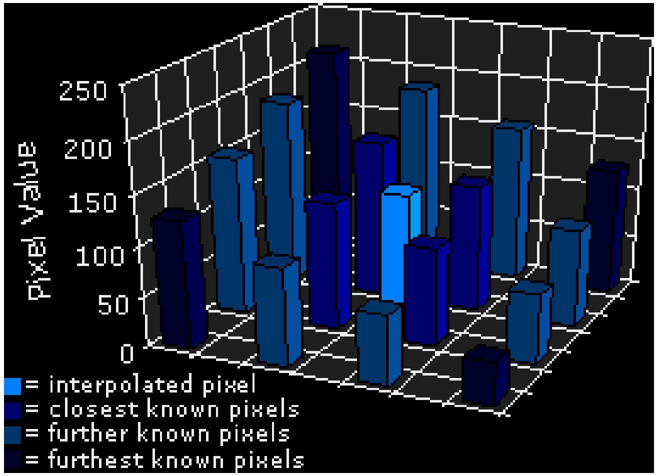
Payload: Image Compression

- Image compression will be optimized to maximize available downlink budget
- Onboard **DST-II** and **bi-linear** or **bi-cubic** downsampling algorithms used depending on performance

Bi-Linear Interpolation

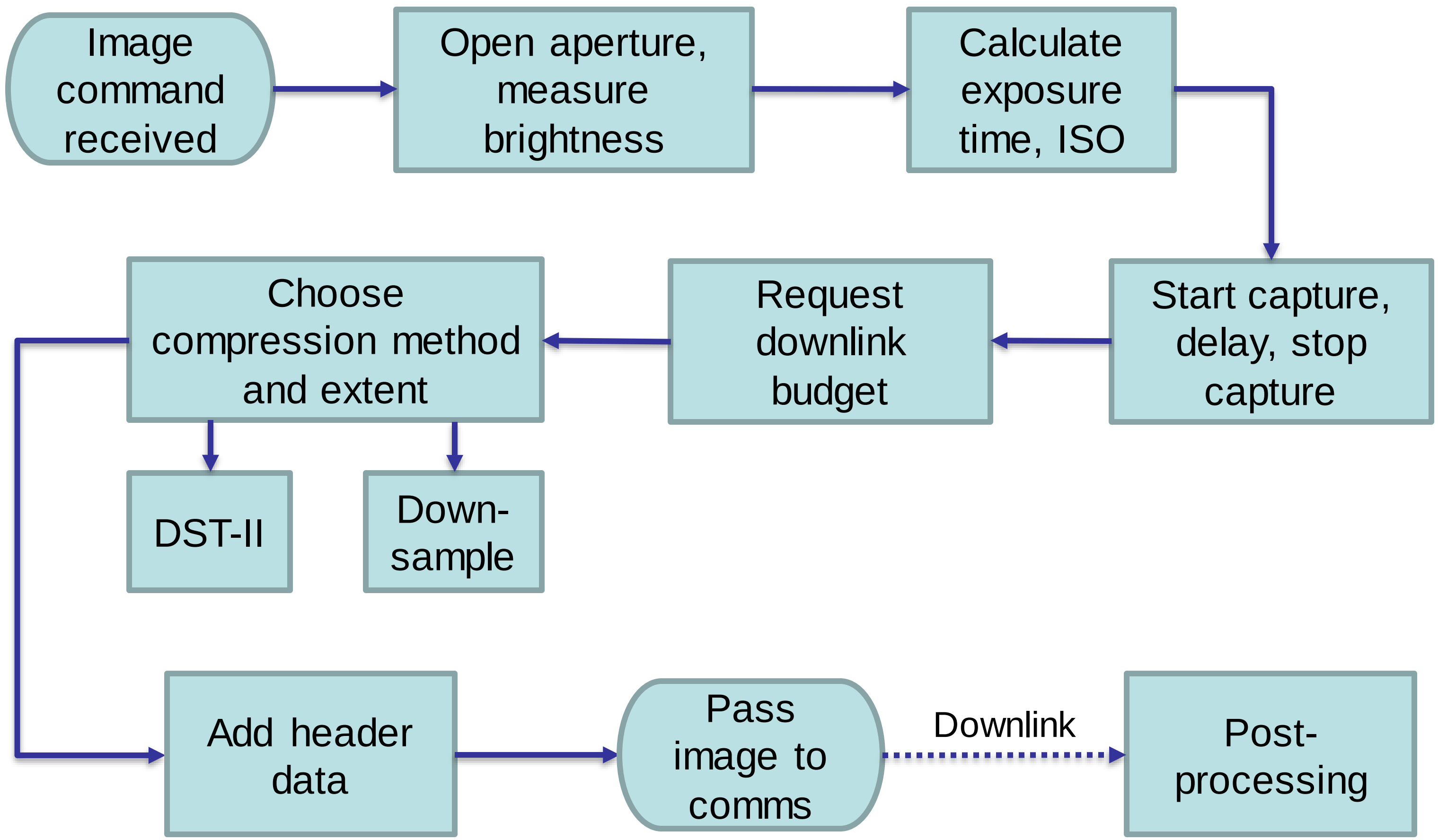


Bi-Cubic Interpolation

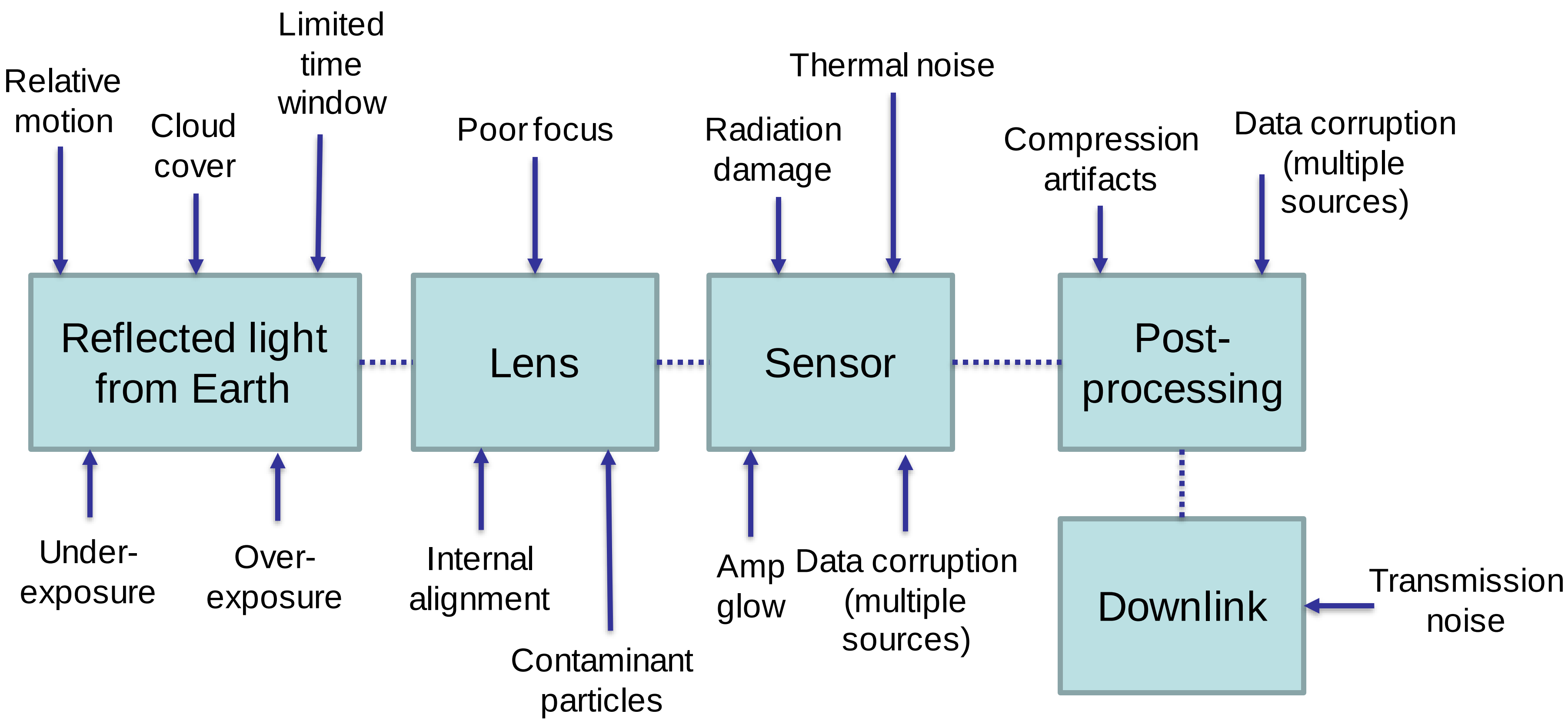


Images:: https://www.cambridgeincolour.com/

Payload: Control Sequence

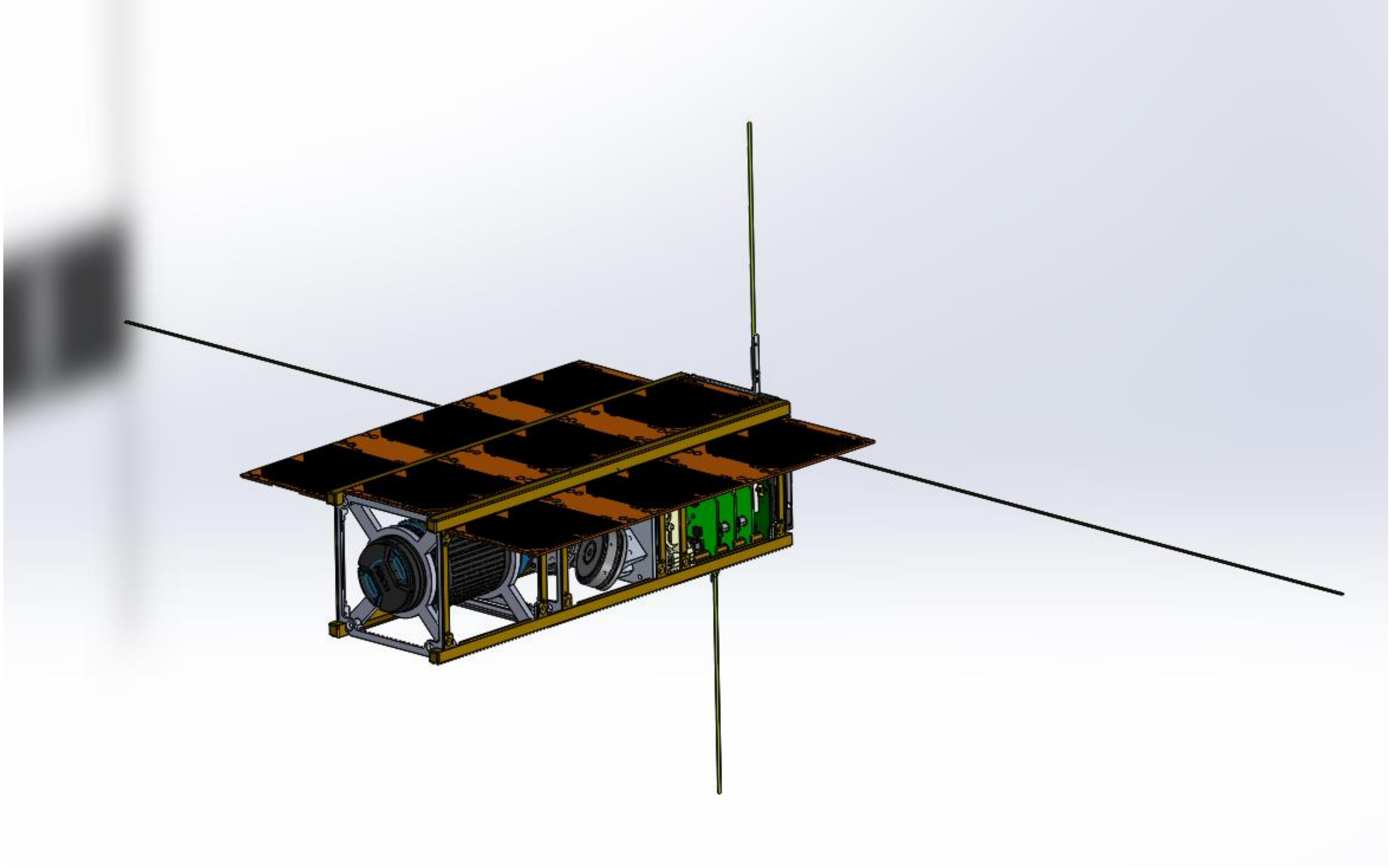


Payload: Sources of Risk



Spacecraft Structure

Spacecraft Structure: Rendering



Spacecraft Structure: Dimensional Analysis

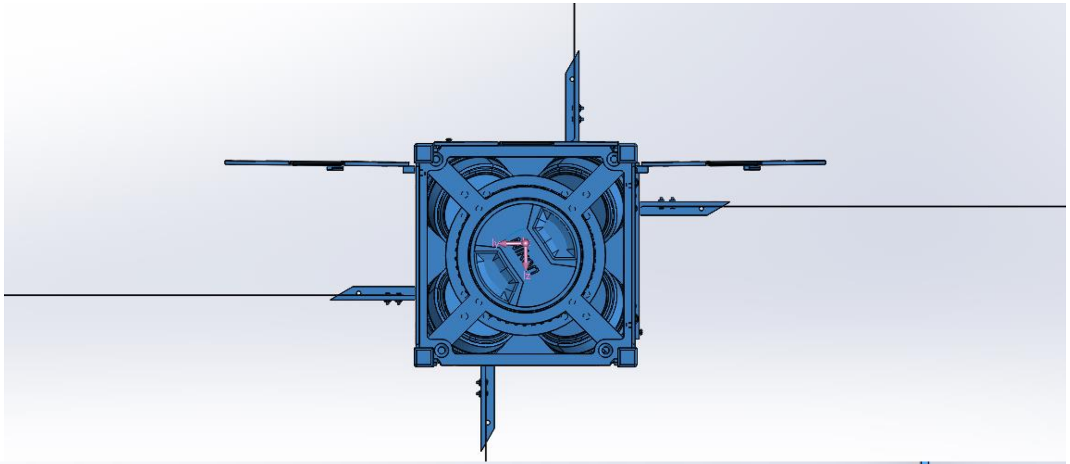
Total Mass: 3039 (g)
Center of Mass:
X-Axis: $-\ 4.42\ mm$
Y-Axis: $+0.99\ mm$
Z-Axis: $-12.01\ mm$
(With respect to center of total structure)
(At time of simulation)

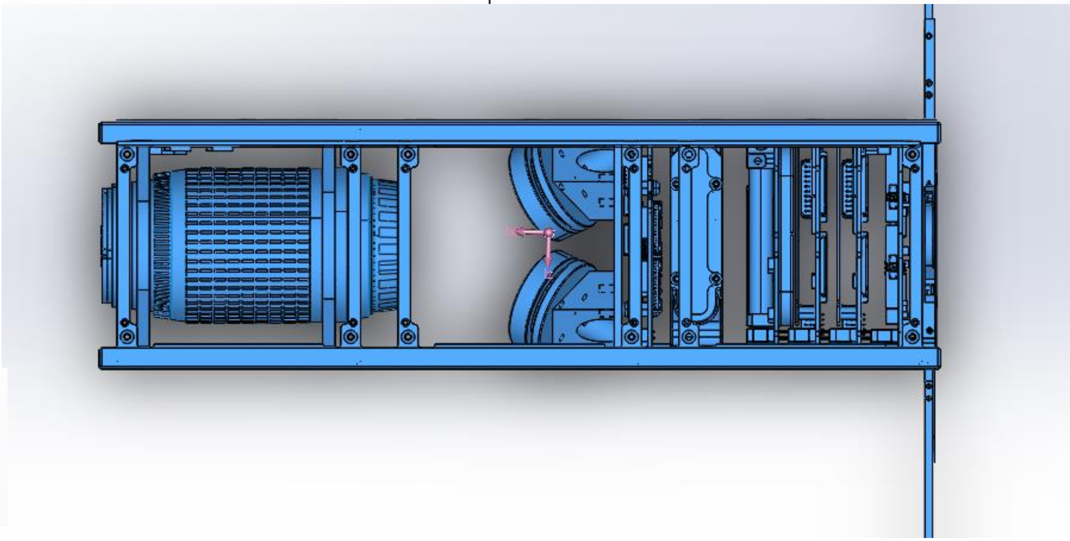
Moments of Inertia ($g \cdot mm^2$):

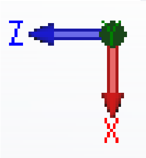
$Lxx\ =\ $ 34809656.77
$Lxy\ =\ $ −35700.19
$Lxz\ =\ $ −707908.38

$Lyx\ =\ $ −35700.19
$Lyy\ =\ $ 32728235.27
$Lyz\ =\ $ −21259.43

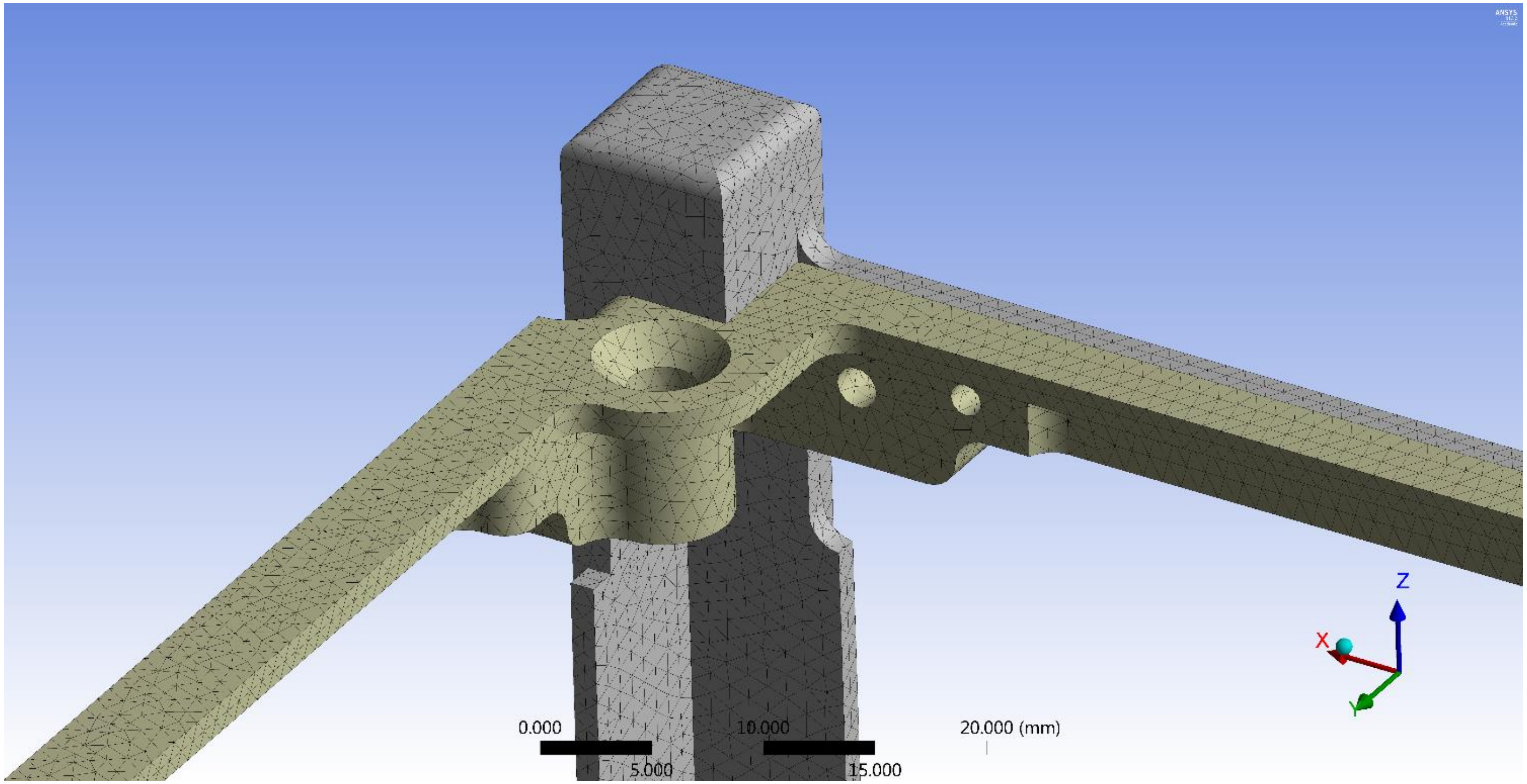
$Lzx\ =\ $ −707908.38
$Lzy\ =\ $ −21259.43
$Lzz\ =\ $ 8768625.87





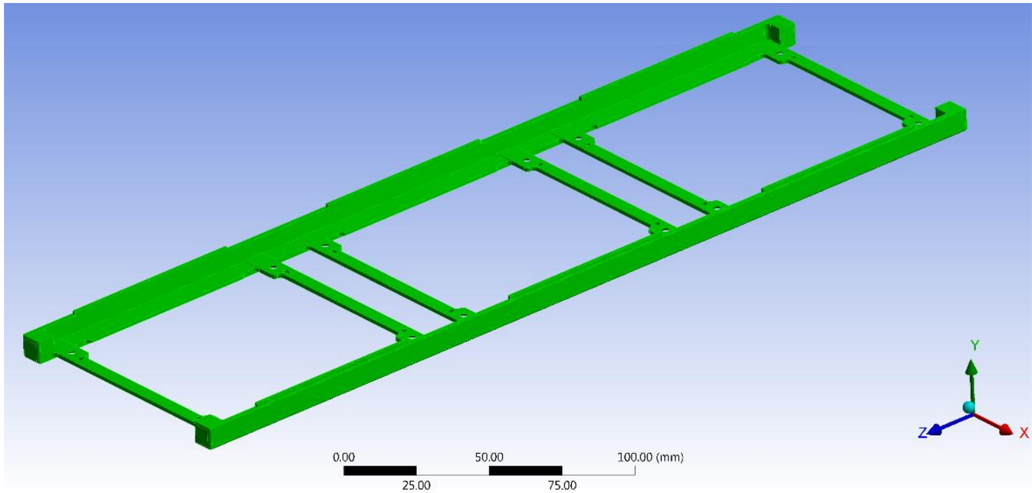


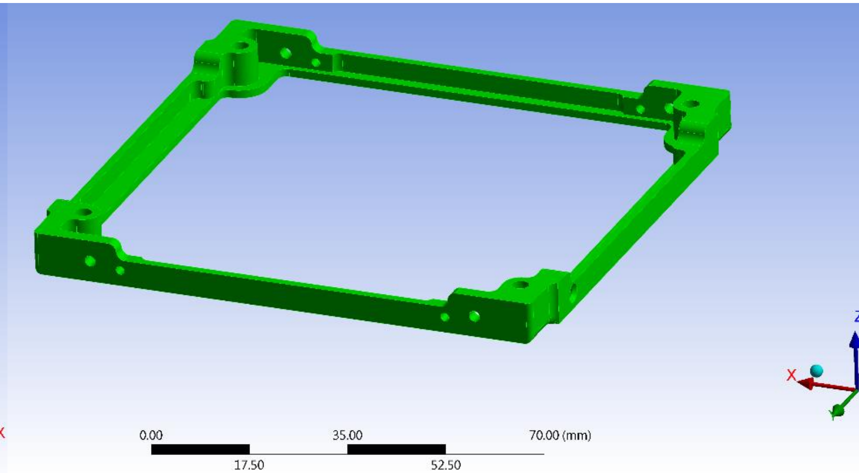
Spacecraft Structure: Modeling



Mesh Size: $1.0\ mm$
Nodes: $1{,}495{,}408$
Elements: $917{,}249$

Spacecraft Structure: Frame Material





	Main Structure	Inner Structure
Material	7075-T6 Plate	7075-T6 Plate
Finish	Type III Hard Anodize	Type III Hard Anodize
Dimension	$340.5\ mm\ x\ 100.0\ mm$	$95.4\ mm\ x\ 98.4\ mm$ $(100.00\ mm\ x\ 100.00\ mm\ Outer)$
Mass	$7.5845x10^{-2}\ kg\ x\ 2$	$1.9891x10^{-2}\ kg\ x\ 6$

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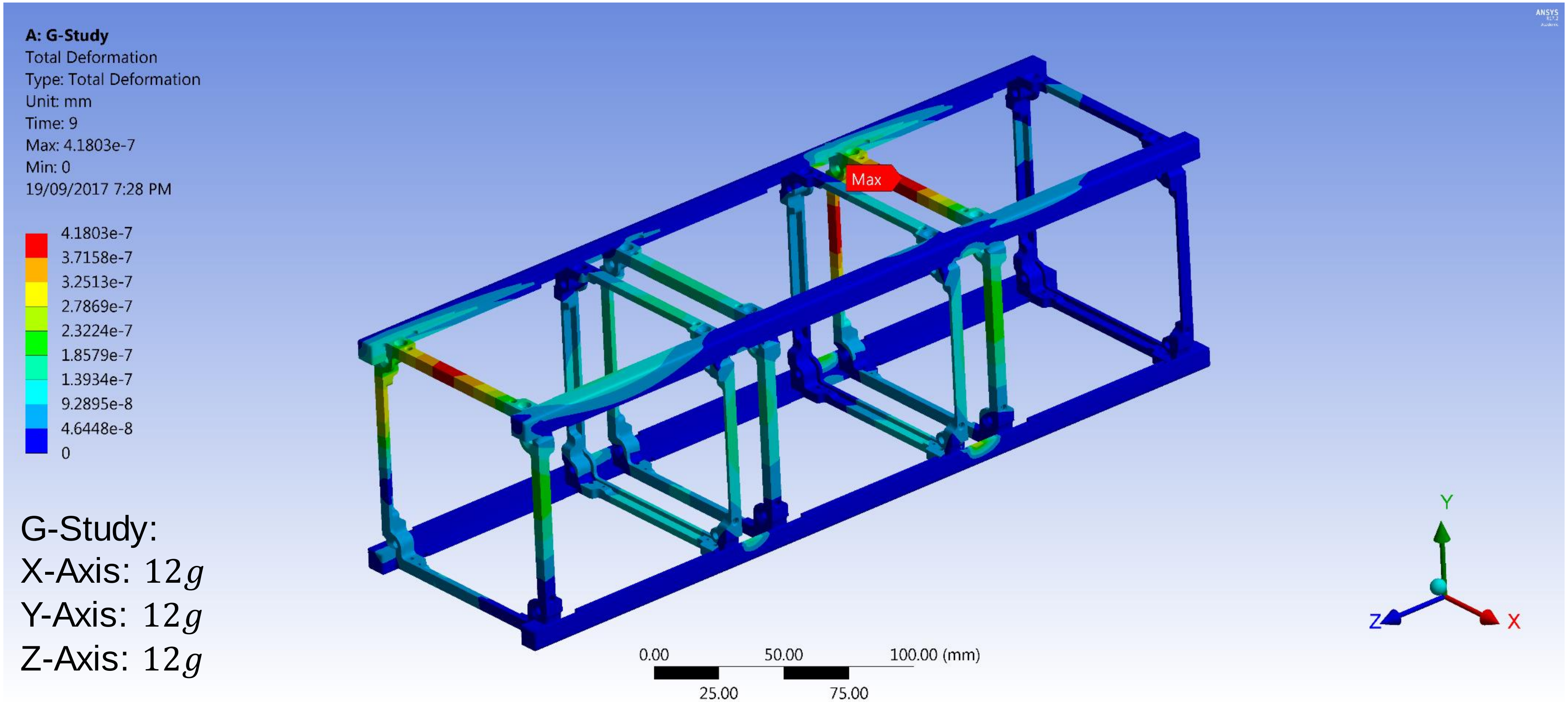
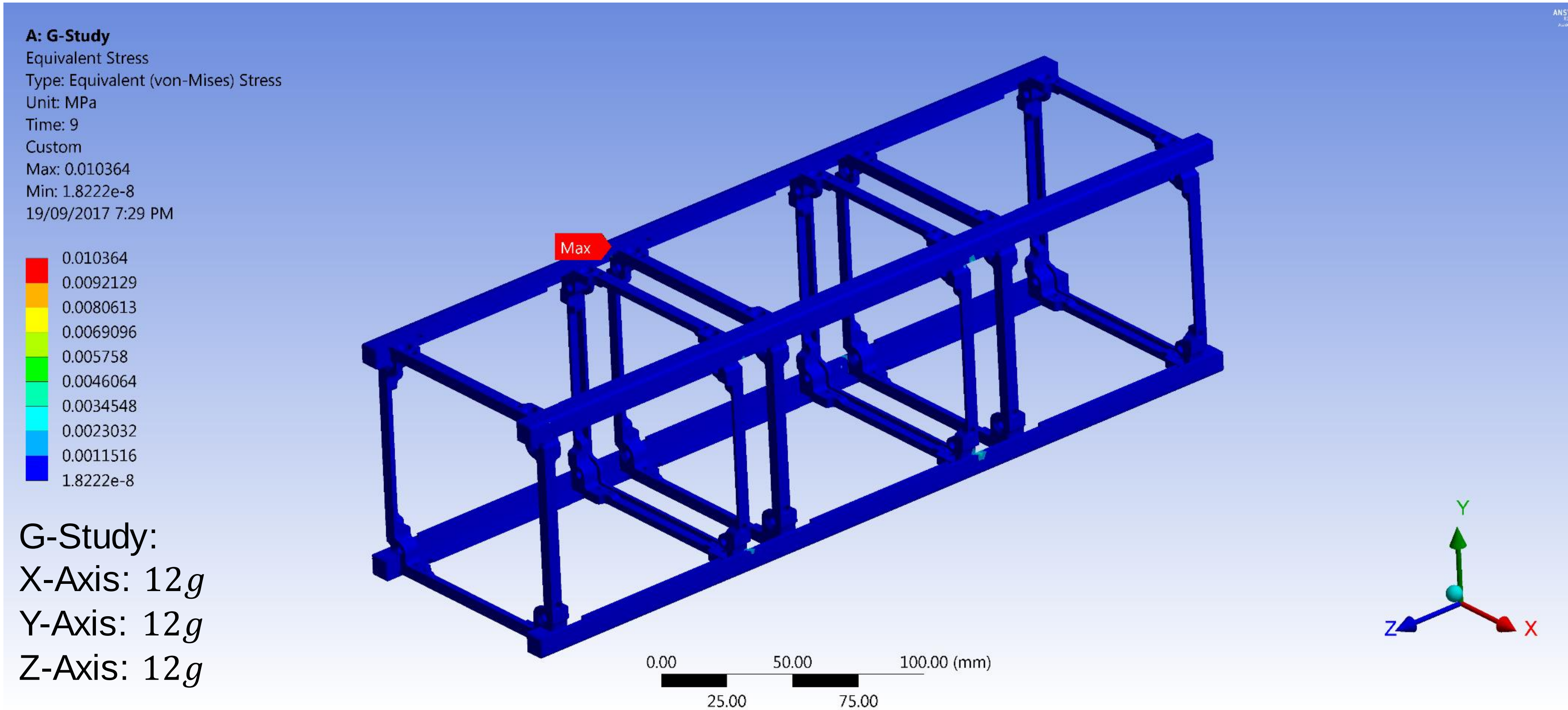
Spacecraft Structure: Static Analysis (1/2)



G-Study:
X-Axis: $12g$
Y-Axis: $12g$
Z-Axis: $12g$

Maximum Deformation:
Rib 2: $4.18x10^{-7}mm$

Spacecraft Structure: Static Analysis (2/2)

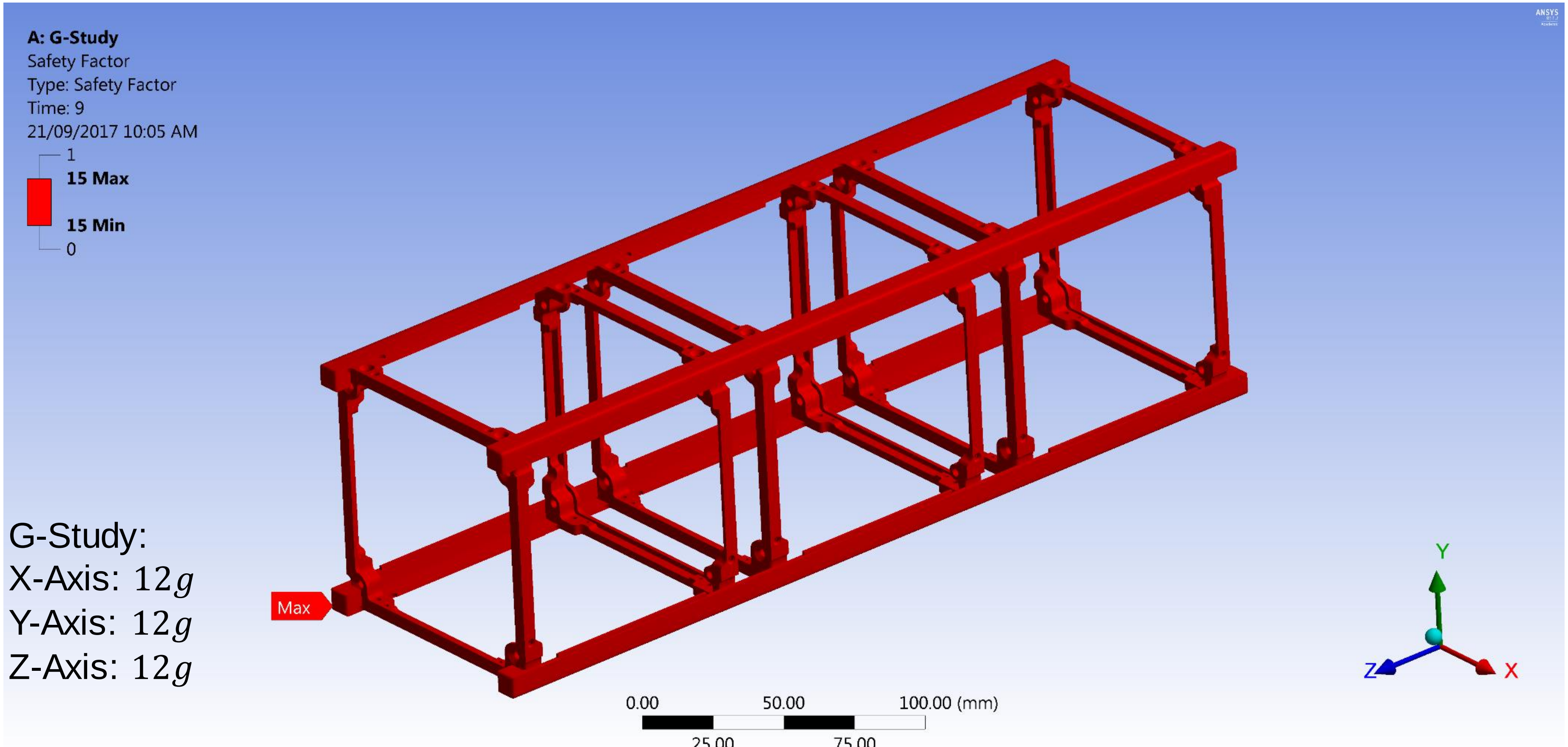


G-Study:
X-Axis: $12g$
Y-Axis: $12g$
Z-Axis: $12g$

Maximum Stress:
Rib 4: $0.01\ MPa$

[DIETR-0310] Launch Quasi-static Acceleration Test

Spacecraft Structure: Safety Factor

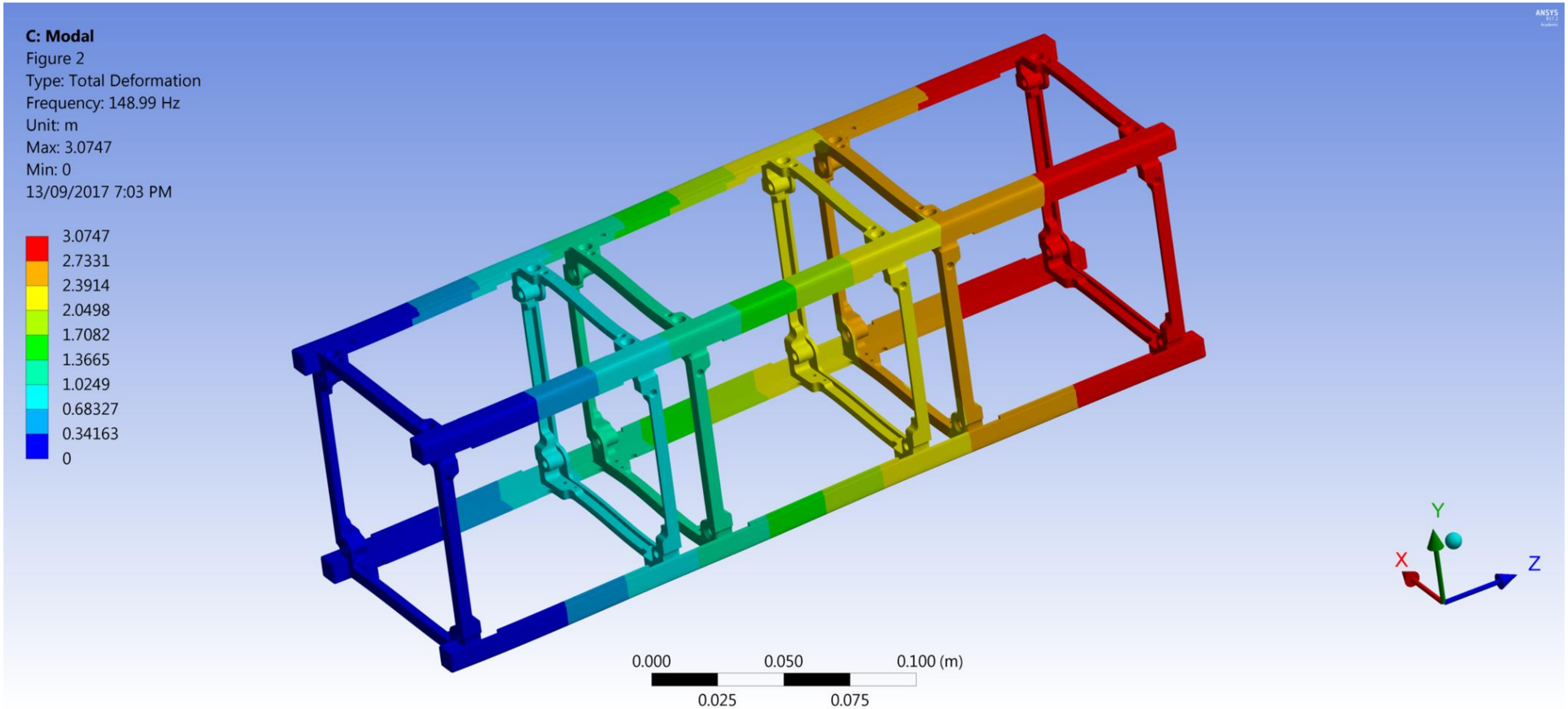


G-Study:
X-Axis: $12g$
Y-Axis: $12g$
Z-Axis: $12g$

Safety factor: 15

[DIETR-0310] Launch Quasi-static Acceleration Test

Spacecraft Structure: Normal Modes Analysis (1/2)

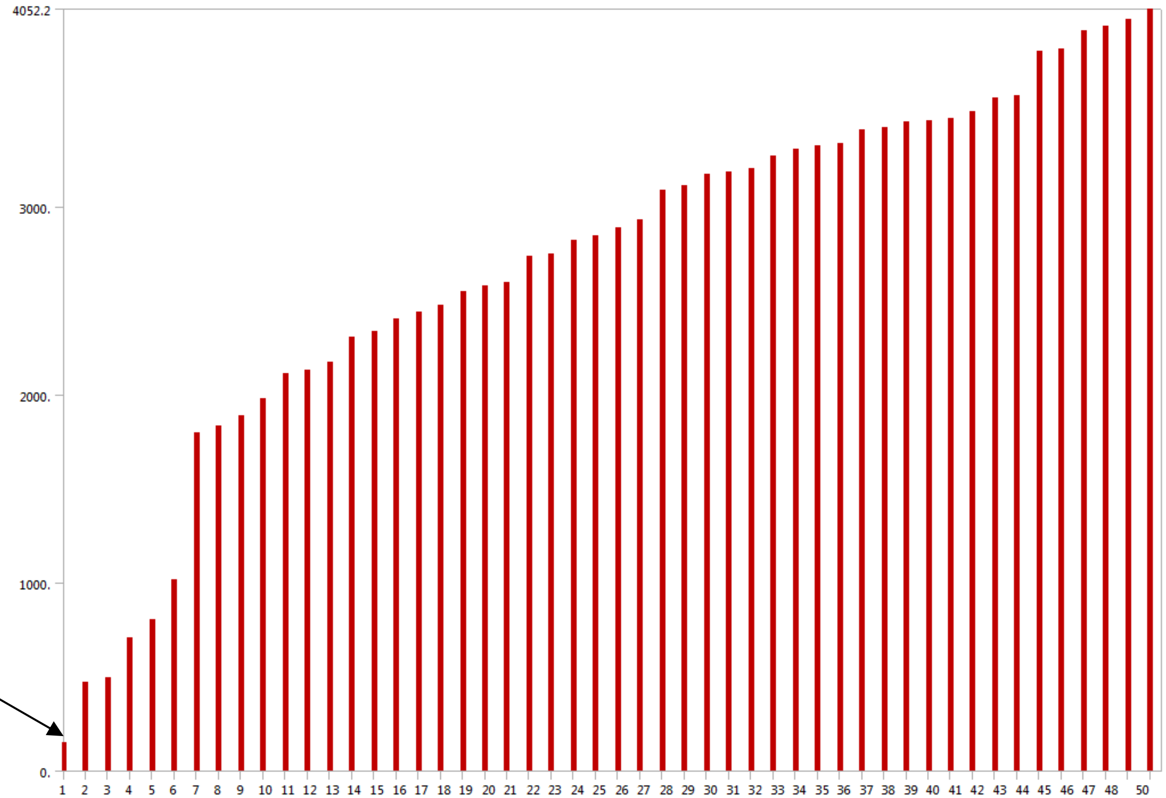


Modal-Study:
Mode 1: $148.99\ Hz$

[DIETR-0200] Fundamental Frequency

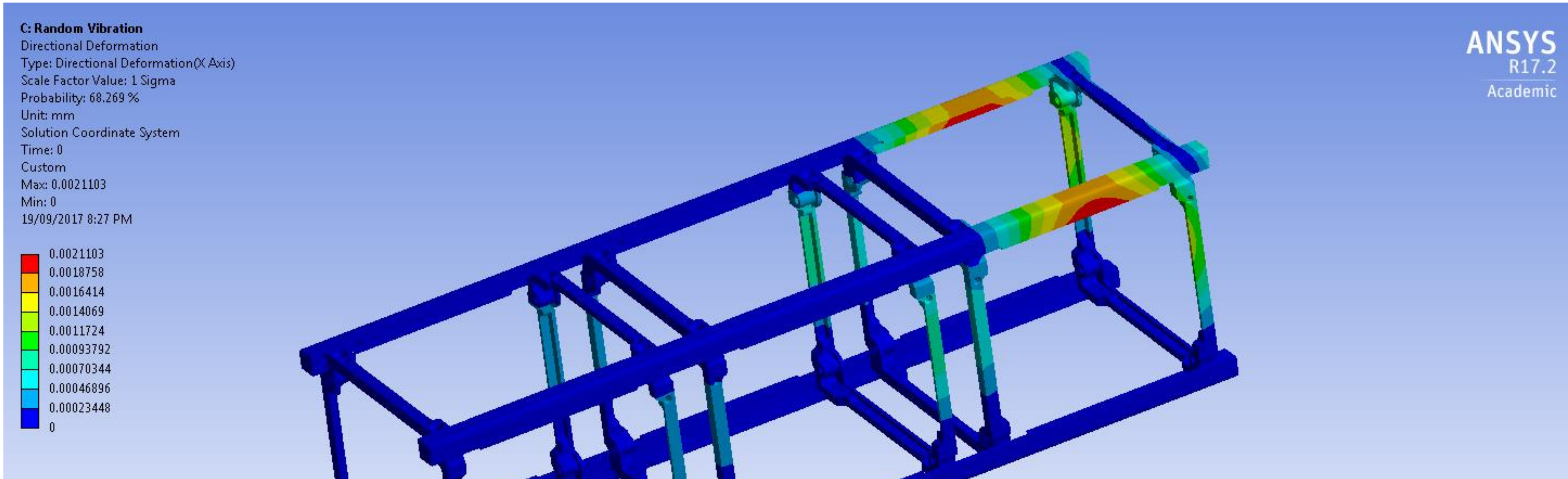
Spacecraft Structure: Normal Modes Analysis (2/2)

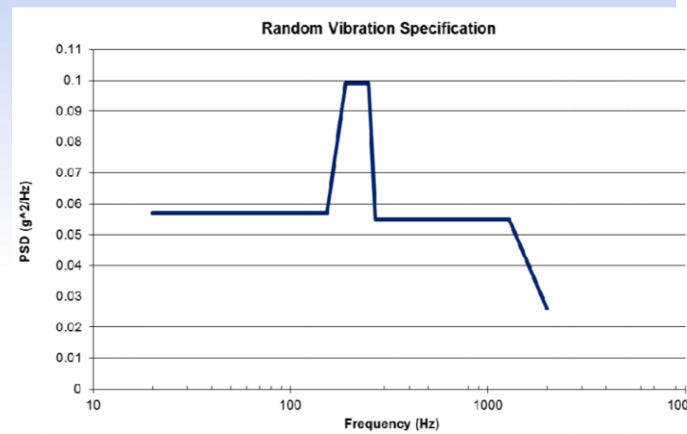
148.99 Hz



Modal-Study: First 50 Modes of vibration

Spacecraft Structure: Launch Vibration Study (1/3)



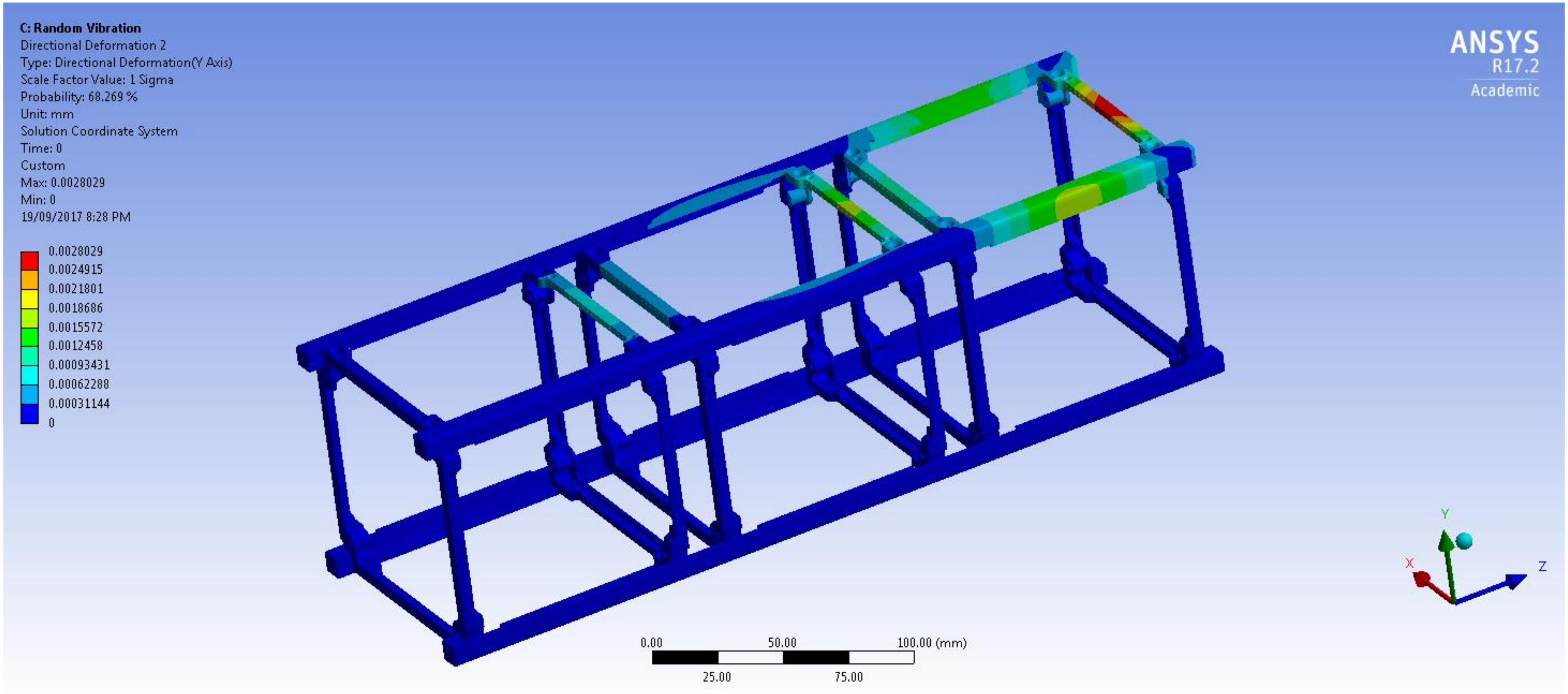


Launch Vibration-Study: X-Axis

Maximum Deformation:
Rib 2: $0.0021\ mm$

[DIETR-0320] Launch Vibration Test

Spacecraft Structure: Launch Vibration Study (2/3)

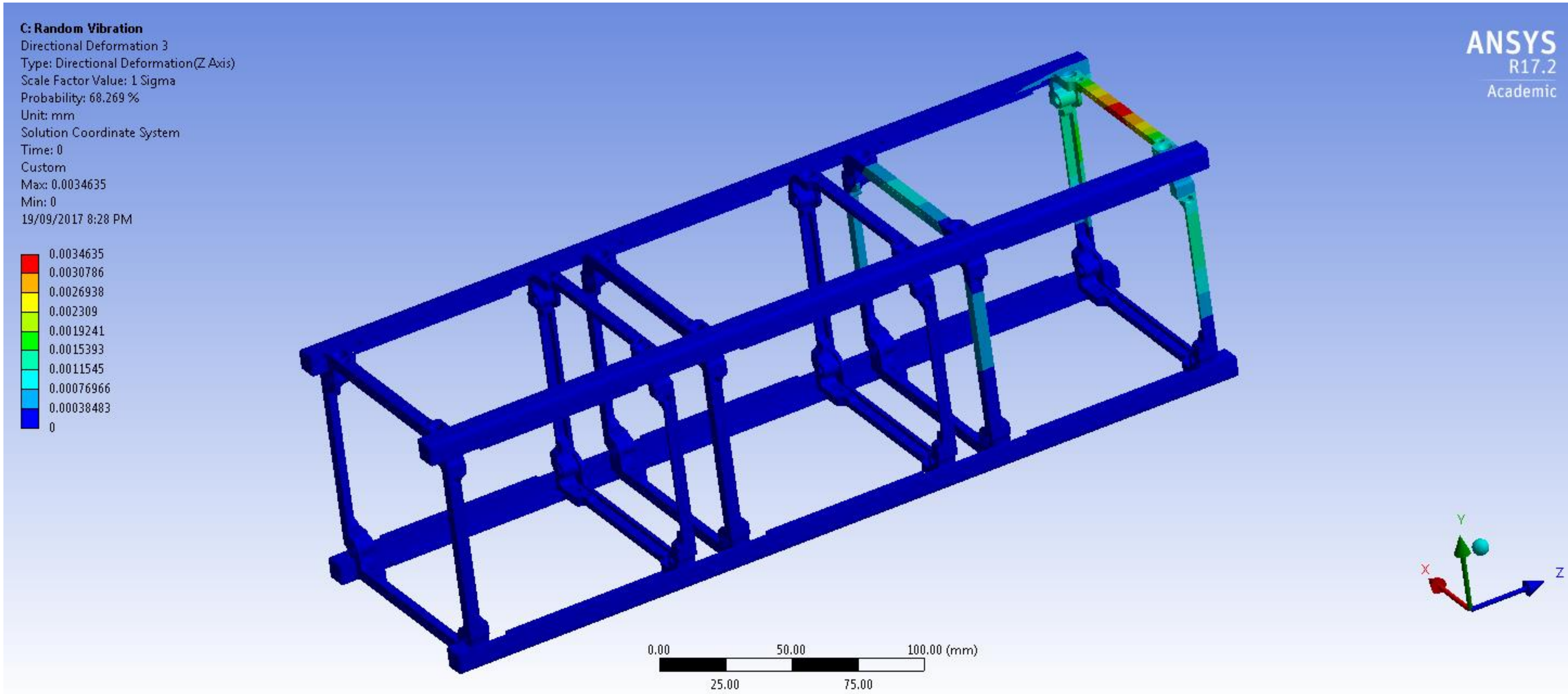


Launch Vibration-Study: Y-Axis

Maximum Deformation:
Rib 1: $0.0028\ mm$

[DIETR-0320] Launch Vibration Test

Spacecraft Structure: Launch Vibration Study (3/3)



Launch Vibration-Study: Z-Axis

Maximum Deformation:
Rib 1: $0.0035\ mm$

[DIETR-0320] Launch Vibration Test

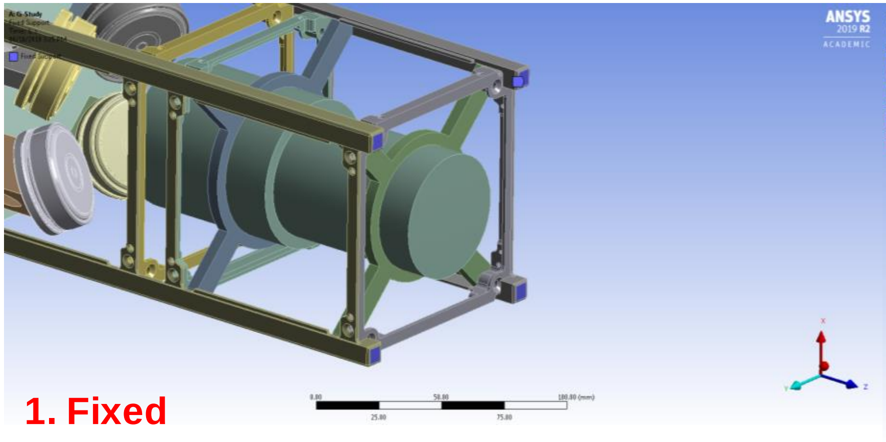
Spacecraft Structure: New Simulations (1/2)

New simulations have been created and ran but failed to converge in time for this presentation. Feedback from judges at CSDC-4 has been considered and implemented.

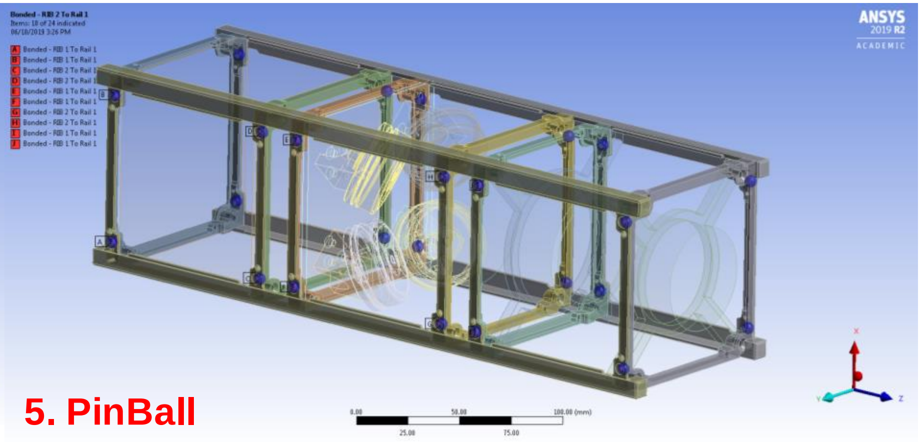
Conditions:

1. A Fixed Top Support (Contacting PPOD Door).
2. Force applied to the bottom of each leg representing the deployment spring (44.4 N).
3. Acceleration applied to all bodies. (Cycle of ±12 g’s, X,Y,Z)
4. Room to move in PPOD (0.1 mm allowed between each PPOD Rail and Frame Rail)
5. Bonded Pinball Radius applied to each Frame bolt hole (2.0 mm)
6. Frictional Contact applied between Frame Ribs and Frame Rails (Coefficient of 0.17)

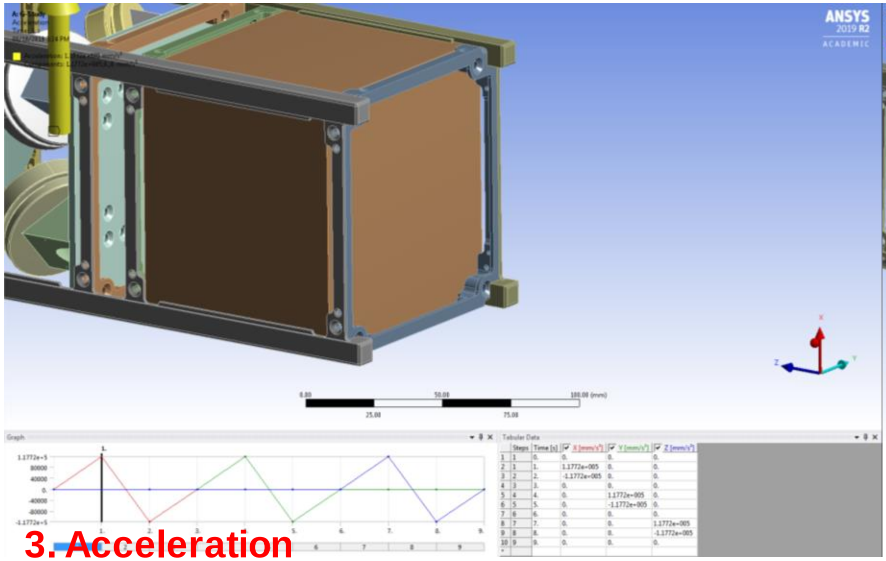
Spacecraft Structure: New Simulations (2/2)



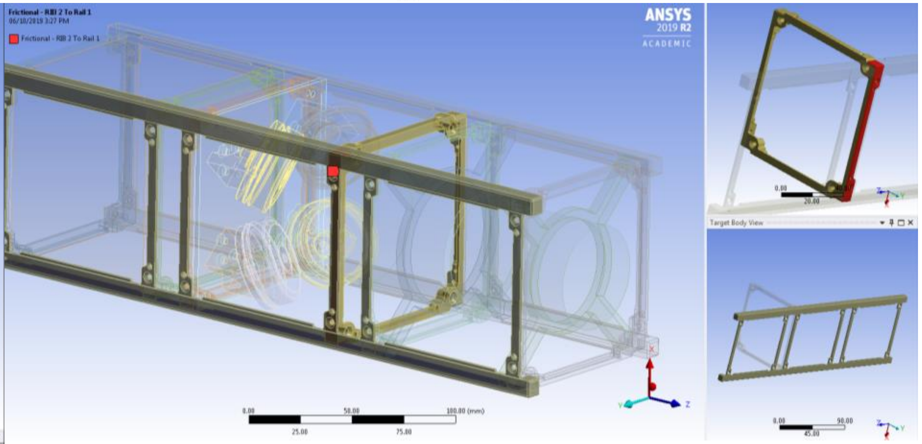
1. Fixed



5. PinBall



3. Acceleration



6. Friction

[DIETR-0320] Launch Vibration Test

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Spacecraft Structure: Mass Budget

Component	Manufacturer	Nominal Mass (grams)	Source	Margin(%)	Qty	Total
Structure						
Aluminum Frame (7075-T65)	In-House	304	Measured	0	1	304.00
Deployment Springs	MasterCarr	0.5	Measured	0	2	1.00
Deployment switch	MasterCarr	1	Measured	0	1	1.00
Power						
Solar Cells	ISIS	150	Datasheet	5	3	157.50
EPS +Battery	ISIS	360	Datasheet	5	1	378.00
Spring Hinges	In-House	20	TBD	10	6	132.00
Burn Wire + Resistor	In-House	5	TBD	5	1	5.25
Comunications						
UHF/VHF Antenna	ISIS	100	Datasheet	5	1	105.00
Comunications Board	ISIS	75	Datasheet	5	1	78.75
Telemetry						
Magnetometer	BOSCH	50		10	1	55.00
Attitude Determination & Control						
Maxon EC45 motor	Maxon	75	Datasheet	5	4	315.00
Reaction Wheel Mounting Board	In-House	150	Measured	5	1	157.50
Reaction Wheel Control Board	In-House	95	Measured	5	1	99.75
Magnetorquer Board	ISIS	196	Datasheet	5	1	205.80
On-Board Computer						
On Board Computer	ISIS	95	Datasheet	5	1	99.75
Payload -1						
200 mm all metal lens	Nicon/Pentax	520		15	1	598.00
Adaptor Ring	Nicon/Pentax	23		5	1	24.15
Stepper Motor (28BYJ-48)	Arduino	25	Datasheet	5	1	26.25
Stepper Motor Drivewr Board	Arduino	5	Datasheet	5	1	5.25
Sensor Cooler (TECD14) + Driver	Thorlabs	100	Datasheet	5	1	105.00
ZWOASI1600 Sensor	ZWO	410	Datasheet	5	1	430.50
					Total Mass	3284.45

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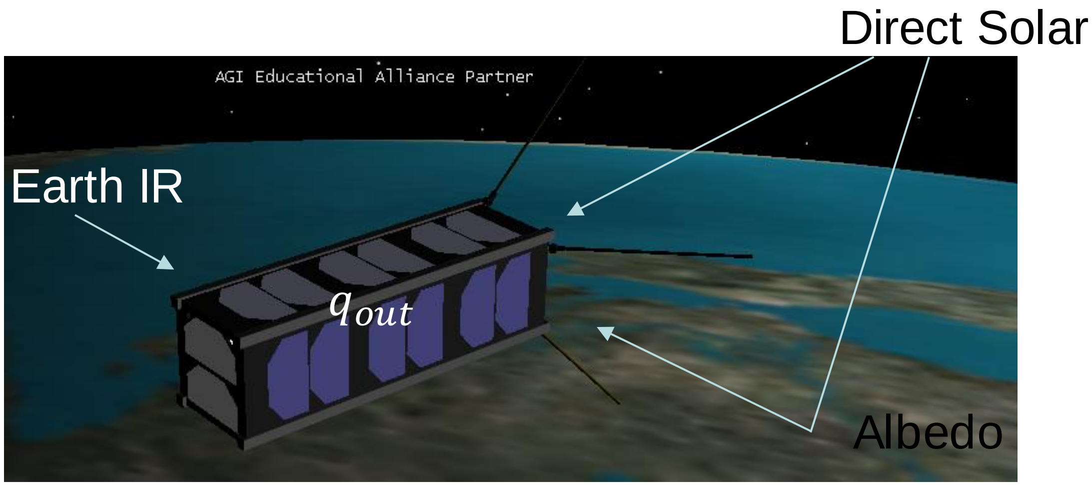
CSDC

Thermal Analysis

Thermal Analysis: Overview



Internal Sources	Sinks
Batteries/EPS	Primary/Secondary Structure
OBC	Radiation to space
Reaction Wheels	
Comms Radio & Amp	

Thermal Analysis: Margins

Component	Margin
Clydespace EPS	-40 to 85 °C
Clydespace Batteries	-10 to 50 °C
TI Transceiver	-40 to 85 °C
Reaction Wheels	-40 to 100 °C
Reaction Wheels Controller	-30 to 60 °C
Magnetorquers	-40 to 70 °C
Sun Sensors	0 to 70 °C
Imaging Sensor	-5 to 45 °C
Imaging Sensor Radiator	Up to 90 °C

Thermal Analysis: Setup

- Thermal maximum is taken during daylight in a 400 km circular orbit
- Thermal minimum is taken during eclipse in an 800 km orbit

- Largest single face of satellite is 30 cm x 30 cm (0.09 m^2)
- Overall satellite surface area is 0.26 m^2
- Thermal emissivity of QUBESat is average of emissivity of gold anodized aluminum (0.82), triple junction solar cells (0.85), and AZ93 white paint (0.92)
- Absorptance of QUBESat is average of absorptance of aluminum (0.48), solar cells (0.92) and paint (0.15)

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Thermal Analysis: Case Study

Source	Thermal Maximum	Thermal Minimum
Solar Flux	188.16 W	0 W
Earth Albedo Flux	49.98 W	0 W
Earth IR Flux	46.71 W	41.65 W
Free Molecular Heating Flux	1.02 W	0.02 W

Source	Thermal Maximum	Thermal Minimum
EPS	5.11 W	0.2 W
Reaction Wheels	20 W	0.15 W
Magnetorquer	0.4 W	0.2 W
Comms Radio + Amplifier	5.7 W	0.01 W

Thermal Maximum	Thermal Minimum
127.7 °C	-30.9 °C

Thermal Analysis: Temperature Margins

Component	Thermal Maximum	Thermal Minimum
EPS	+42.7 °C	9.1 °C
Batteries	+77.7 °C	-20.9 °C
Reaction Wheels	27.7 °C	9.1 °C
Magnetorquers	+57.7 °C	9.1 °C
Imaging Sensor	+82.7 °C	-25.9 °C

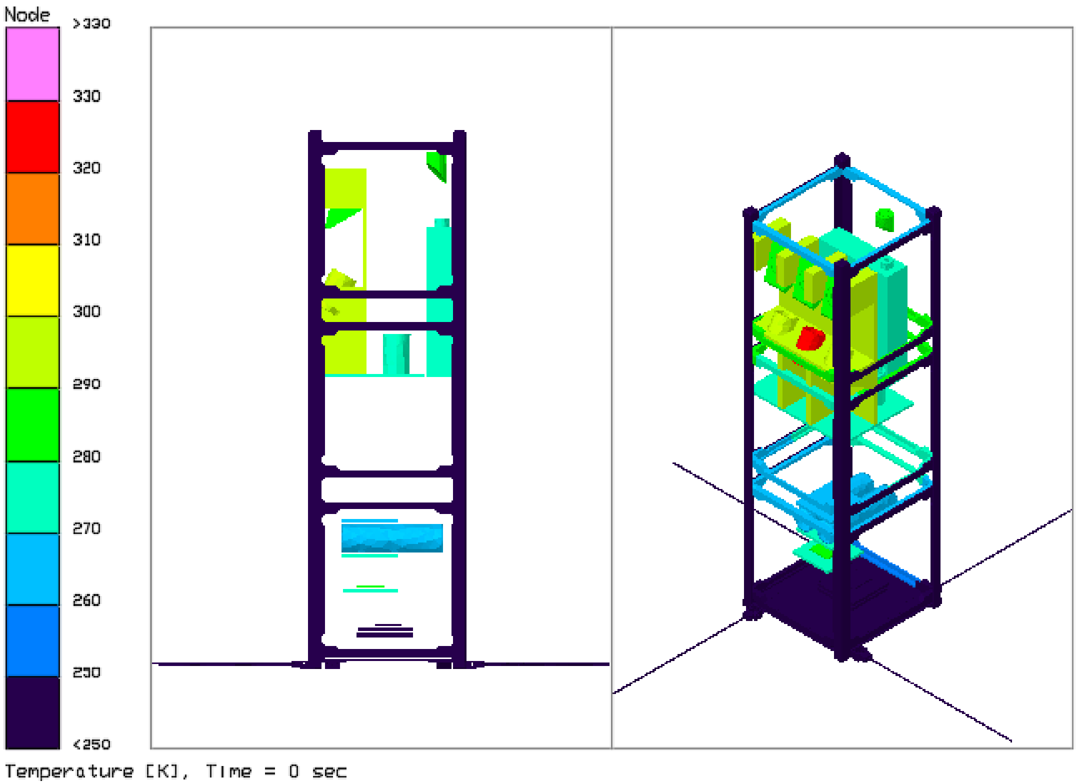
Thermal Analysis: Strategies & Next Steps

- Preliminary first-principles analysis suggests cooling solution required
- Due to the deployable solar panels, significant spacecraft surface area is available for radiative heat dissipation
- Specific components can be targeted with MLI and active heating/cooling solutions as required
  - Batteries and imaging sensor will require heaters

- Additional analysis required, thermal mathematical model to be created

Thermal Analysis: Mathematical Model

- Conduction and radiation (Monte Carlo Ray-Tracing)
- Tetrahedron mesh
- Conduction and radiation contacts between internal components inner secondary structure



- Previous results (2017):

Thermal Max:

- $T_{transceiver}$ = 85 °C

Thermal Min:

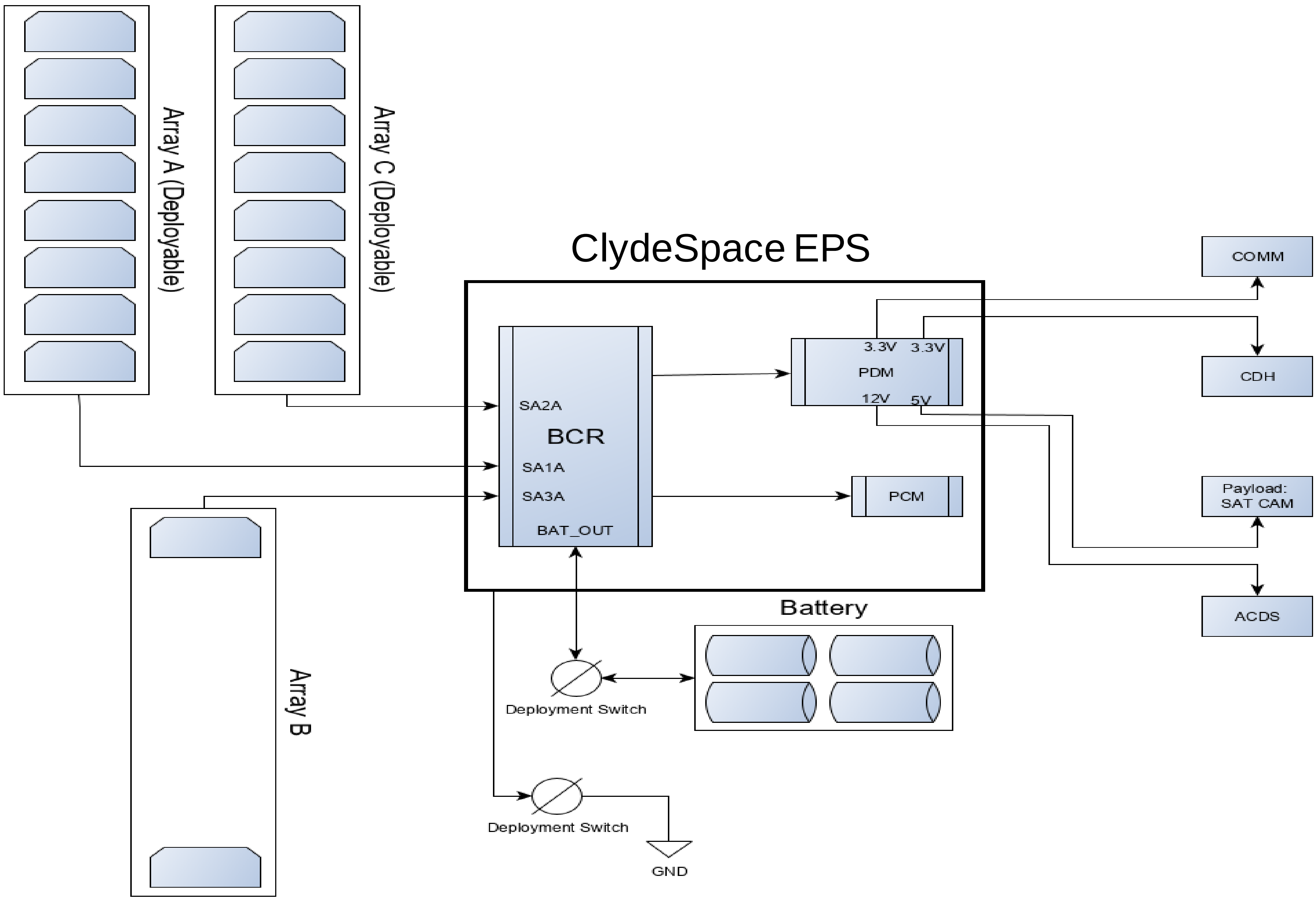
- $T_{battery}$ = -7 °C

Power Subsystem

Power Subsystem: Overview

- Deploy solar arrays after detumble
- Generate enough power for all components in satellite from deployable solar arrays
- Efficiently store and manage generated power by configuring EPS
- Overcurrent monitoring

Power Subsystem: SAT Block Diagram



Power Subsystem: EPS

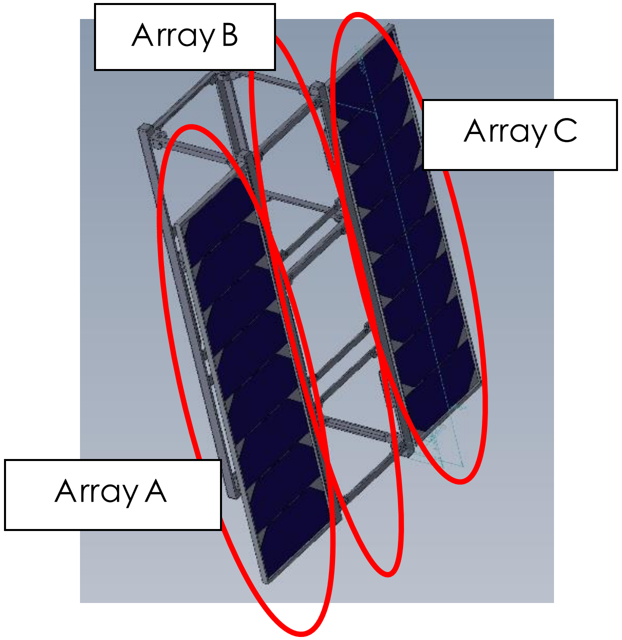
- EPS selected was 3rd Generation EPS from ClydeSpace
  - Cheaper than ASTERLabs EPS
  - Purchased and used for CSDC-4
  - Confident in encoding system

Image credit: https://www.aac-clyde.space/

Supplier	Part Name	Native Cost	Cost (CAD)	Notes
ClydeSpace	3rd Generation EPS	3000 EUR	4505.00	Price in Euro (Additional levys, duties)
ASTERLabs	NanoPowerP31uX	4600 USD	5808.00	No batteries, Price in USD

Power Subsystem: Power Generation

- Orbit (LEO ISS orbit)
  - Orbit length (hrs): 1.54
  - Sunlight hrs/orbit: 0.96
  - Orbit average Power: 22.7 Wh
- Solar Cells
  - Three solar arrays, two deployable after detumble
  - 18 AzurSpace QJ Solar Cells

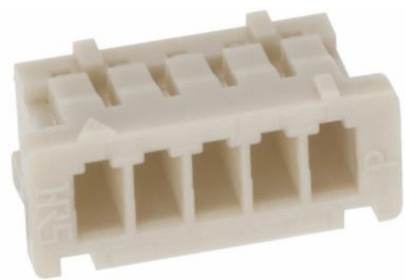


Power Subsystem: Storage

- Batteries
  - 4 lithium ion 18650 cells
  - 3.7V each
  - 11,840 mWh capacity
  - 25 W maximum unregulated output
  - 20 W maximum regulated output
  - Largest DOD is 78%

Power Subsystem: Regulation and Distribution

- Power regulations and Distribution
  - 10 regulated switchable PDMs and non-switchable high current rails
  - Power distribution through system power bus (or internal harness if needed)
  - Internal harness connections:
    1. Solar array to EPS
    2. All other connections



1

2

Power Subsystem: Power Budget

Subsystem	Component	Max Power (mW)	LEOP	Default(Wait)	Default(ACDS)	Default(Power)	Default(Pass)	Pass	Safe
			Operational Mode - Percentage of Max Power						
ADCS	Orientation Sensor	44.28	100	100	100	100	100	100	0
	Sun Sensor	20	100	100	100	100	100	100	0
	Reaction Wheel Motors + Controller x 4	97826	0	0	1	3	3	1	0
	Magnetorquer x 3	600	50	0	100	0	0	0	0
CDH	OBC	1386	100	100	100	100	100	100	10
Comms	Antenna Front End Amplifier	7200	100	0	0	0	0	100	0
	Transciever IC x2	324	50	50	0	0	0	80	0
Power	EPS	200	100	100	100	100	100	100	10
	Solar Panels	-23600	0	33	0	100	0	0	0
Payload	Payload and COMM MCU	462	100	25	0	0	0	100	0
	Camera	500	0	0	0	0	0	100	0
	Lens logic and focus motors	250	100	0	0	0	0	0	
	TEC cooler	24000	0	0	0	0	0	100	
Mechanical	Heat Sinks	6000	0	0	0	0	0	0	0
Deployment	Burn Wire (Antenna)	1000	100	0	0	0	0	0	0
	Burn Wire (Solar Panel)	1000	100	0	0	0	0	0	0

	ISS LEO Orbit	Sun-Synch Orbit
Orbit length (hrs)	1.54	1.54
Sunlight length	0.9625	1.54
	Power Generation Capabilities (mW)	23600

Note:
-COMMS Transmission are a maximum 90

Power Subsystem: Energy Use per Orbit Budget

				Energy Used per Orbit (mWh)						
Subsystem	**Component**	**Max Power (mW)**		**LEOP**	**Default(Wait)**	**Default(ACDS)**	**Default(Power)**	**Default(Pass)**	**Pass**	**Safe**
	Orientation Sensor	44.28		68	68	68	68	68	68	0
	Sun Sensor	20		31	31	31	31	31	31	0
	Reaction Wheel Motors + Controller x 4	97826		0	0	1507	4520	4520	1507	0
ADCS	Magnetorquer x 3	600		462	0	924	0	0	0	0
CDH	OBC	1386		2134	2134	2134	2134	2134	2134	213
	Antenna Front End Amplifier	7200		11088	0	0	0	0	11088	0
Comms	Transciever IC x2	324		249	249	0	0	0	399	0
	EPS	200		308	308	308	308	308	308	31
Power	Solar Panels	-23600	NOTE: Used Sunlight Length (ISS)	0	-7496	0	-22715	0	0	0
	Payload and COMM MCU	462		711	178	0	0	0	711	0
Payload	Camera	500		0	0	0	0	0	770	0
	Lens logic and focus motors	250		385	0	0	0	0	0	
	TEC cooler	24000			0			0		
Mechanical	Heat Sinks	6000		0	0	0	0	0	0	0
	Burn Wire (Antenna)	1000		1540	0	0	0	0	0	0
Deployment	Burn Wire (Solar Panel)	1000		1540	0	0	0	0	0	0
	ISS LEO Orbit	**Sun-Synch Orbit**	***Total per orbit (mWh)***	18517	-4527	4972	-15654	7061	17017	244
Orbit length (hrs)	1.54	1.54	***AvgPower (mW)***	12024	-2940	3229	-10165	4585	11050	159
Sunlight length	0.9625	1.54	**DOD per Orbit (ISS) (%)**	39	-10	10	-33	15	36	1
	Power Generation Capabilities (mW)	23600	Total Generated Power per ISS Orbit (mWh)	22715						
			Total Generated Power per S-S Orbit (mWh)	36344						
			Battery Capacity (mWh)	47360						

Attitude Determination & Control System (ADCS)

QUEEN'S SPACE ENGINEERING TEAM

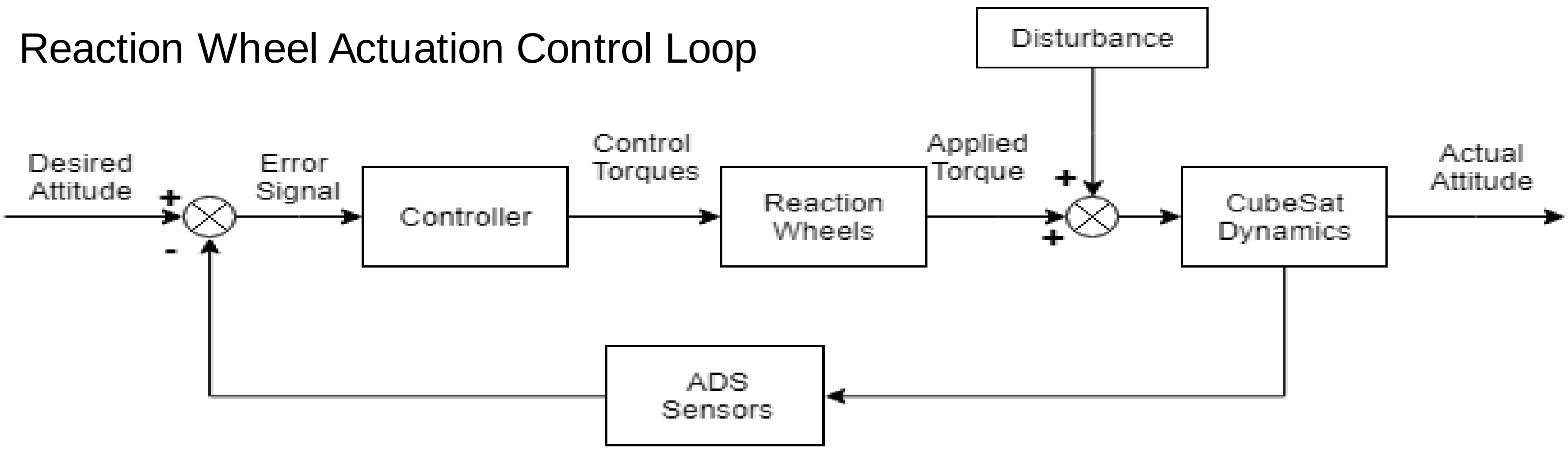
ADCS: Overview

- Detumble QUBESat after deployment
- Receive attitude request from OBC
- Slew to a desired roll angle for picture taking or power generation
- Maintain attitude determination and control in the event of sensor or actuator failure
- Desaturate reaction wheels when needed

ADCS: Control Modes

Mode	Description	Required accuracy (deg)
Magnetic Detumble	Use B-Dot algorithm and magnetorquers to slow angular velocity	N/A
Power Generation	Use reaction wheel actuation to orient satellite towards sun	10
Fine Pointing/Picture	Use reaction wheel actuation to slew satellite to a reference attitude.	0 - 6.5

Reaction Wheel Actuation Control Loop



ADCS: External Disturbance Torques (1/2)

- Gravity gradient torque
  - Unequal gravitational force on different parts of satellite
  - Force long axis to rotate towards nadir
- Earth's magnetic field torque
  - Collisions with charged particles cause the CubeSat to develop charge
  - Can interact with Earth's magnetic field

ADCS: External Disturbance Torques (2/2)

- Atmospheric drag torque
  - Atmosphere can create drag force on the CubeSat in LEO
  - Different drag coefficients create torque
- Solar radiation pressure torque
  - Photons strike the CubeSat and create SRP

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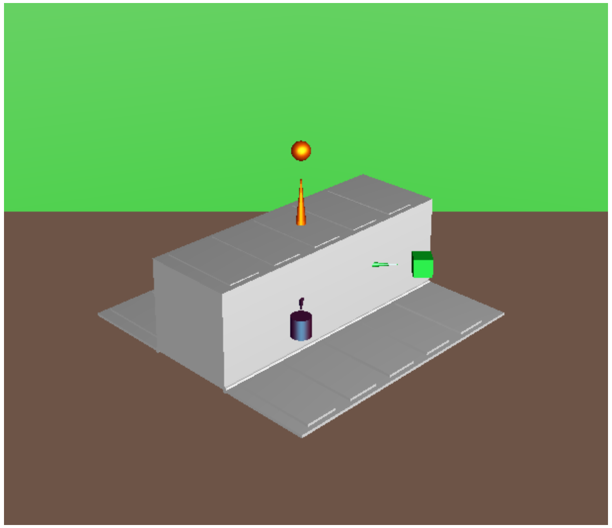
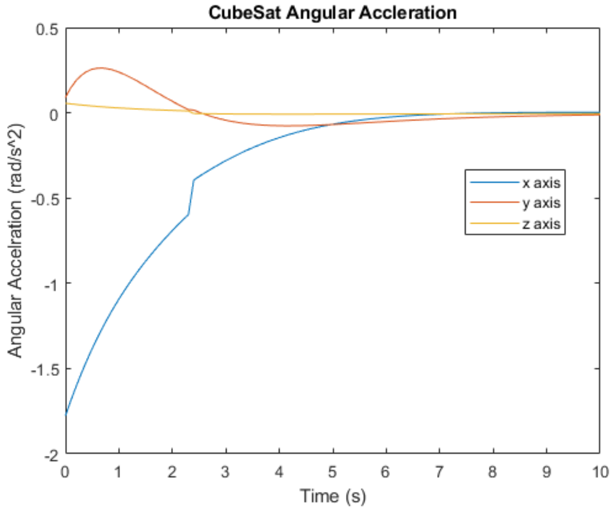
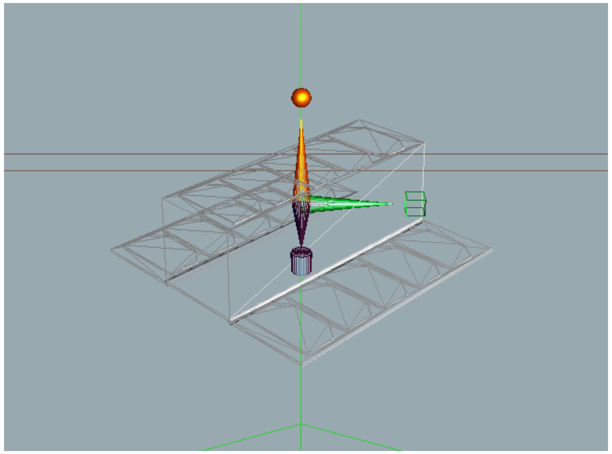
ADCS: Modelling Tools (1/2)

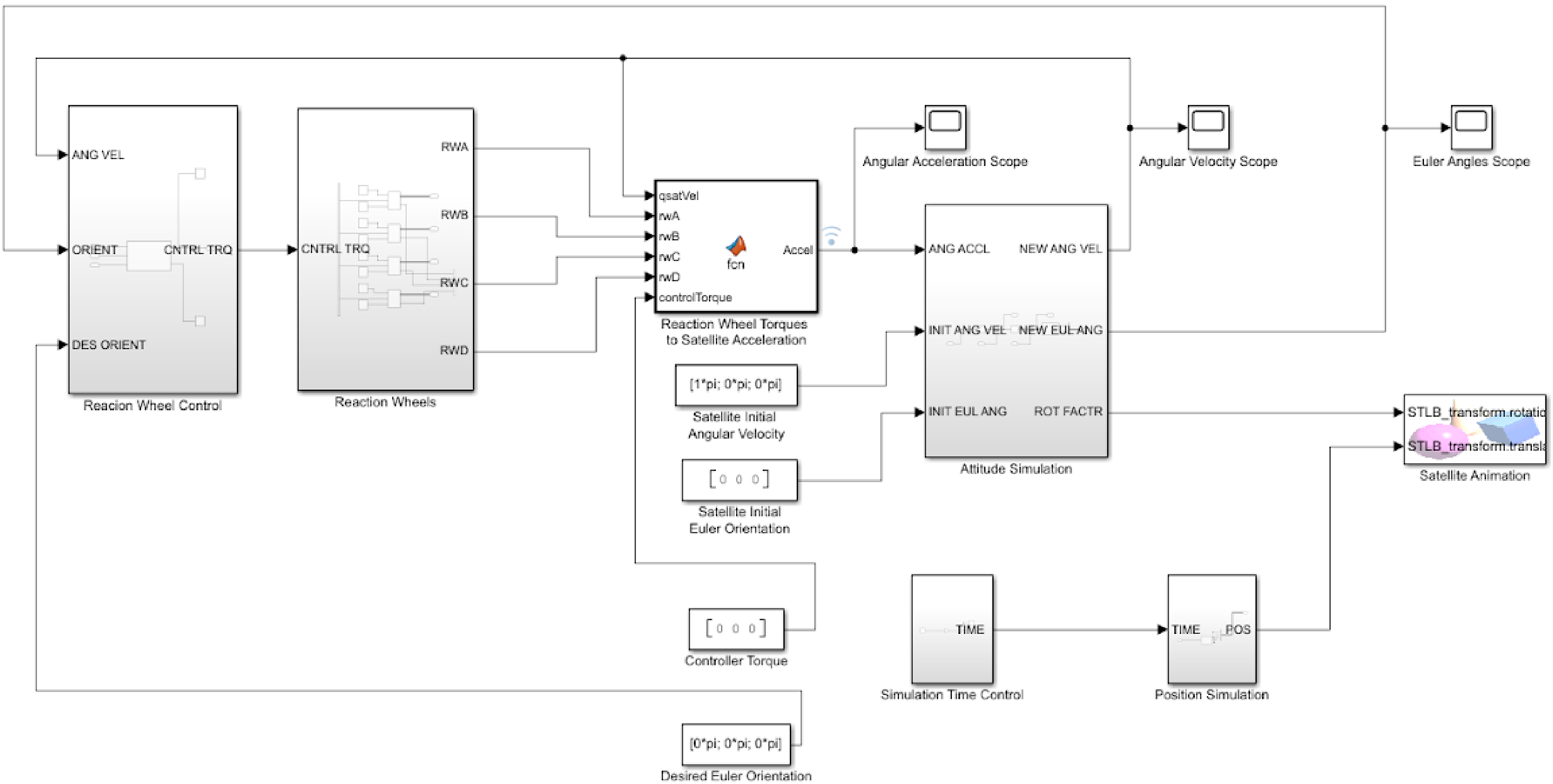
- Simulink ADCS model using reaction wheels and PID controller
- Real-time 3D visualization and attitude data







ADCS: Modelling Tools (2/2)

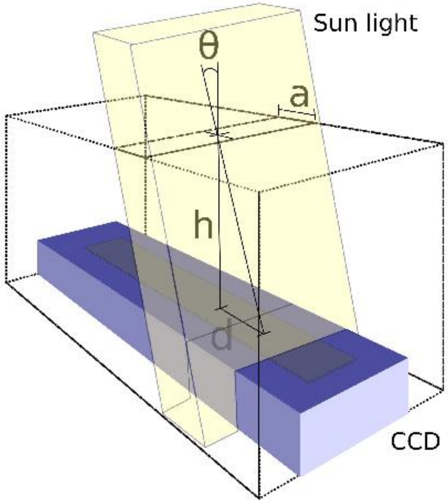


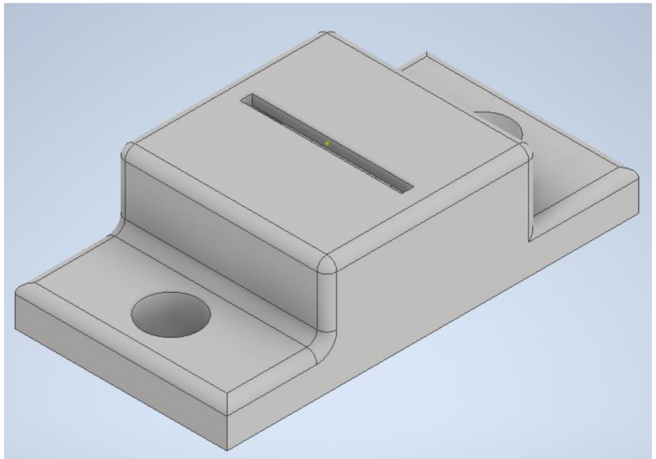
ADCS: Sensors and Actuators

- Attitude sensors
  - Sun sensing: 8 custom sun sensors, 2 on each side: +X, +Y, -X, -Y
  - Adafruit BNO055 Absolute Orientation Sensor:
    - Gyroscope: *Drift error can accumulate over time*
    - Magnetometer: *Can be used to reset attitude*
- Attitude control
  - Reaction wheels: Maxon COTS motors
  - 4-wheel configuration: full control if single wheel fails
  - 3 perpendicular Magnetorquers
  - Wheels can become saturated, magnetorquers needed for momentum dumping

ADCS: Sensors (1/3)

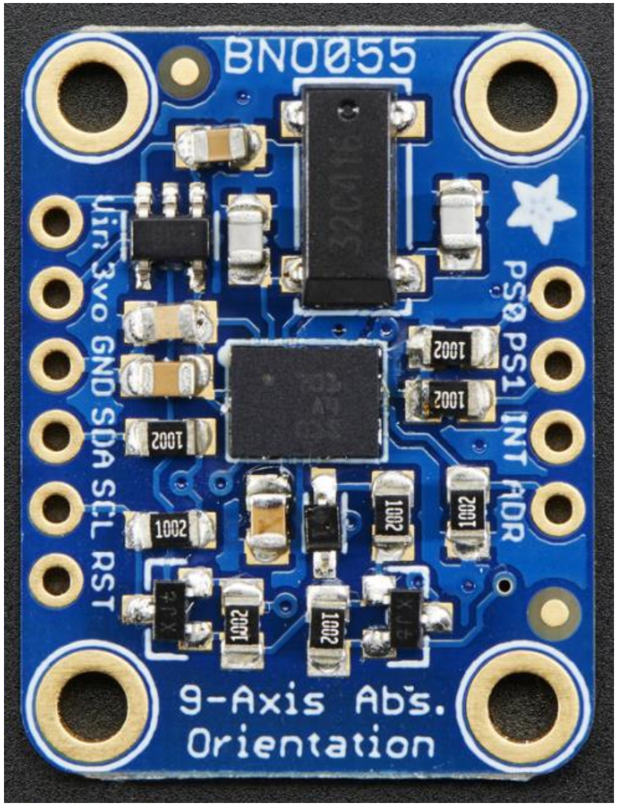
- Sun sensor
  - Determine direction of sun relative to satellite
  - Composed of two perpendicular linear photodiode arrays with custom covers
  - Works when the satellite is not in eclipse
  - Need map sensor output at different angles





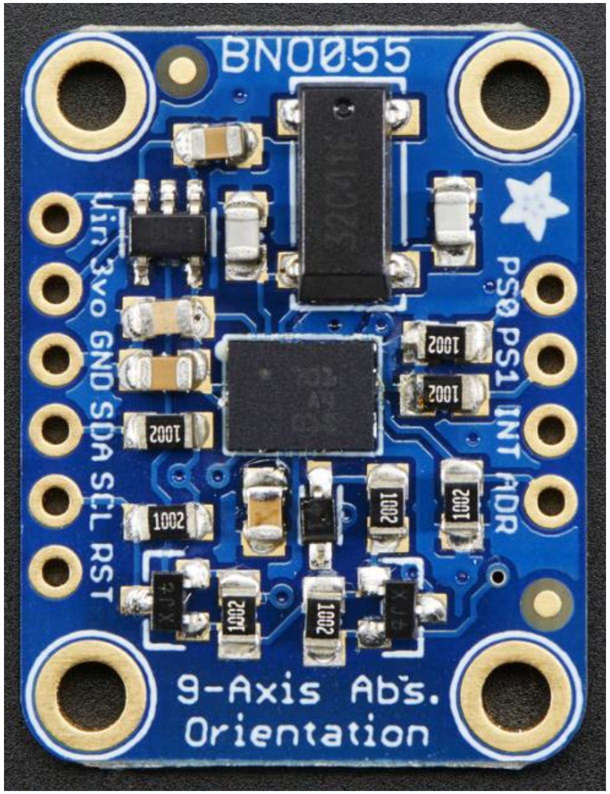
ADCS: Sensors (2/3)

- BNO055 Magnetometer
  - Measures the magnetic field at satellite location
  - Magnetic fields generated by the electronics can affect readings
  - BNO055 must be properly calibrated to avoid this



ADCS: Sensors (3/3)

- BNO055 Gyroscope
  - Measures changes in satellite angular velocity
  - Accurate initially, but can drift after extended durations
  - Combine data with other sensors



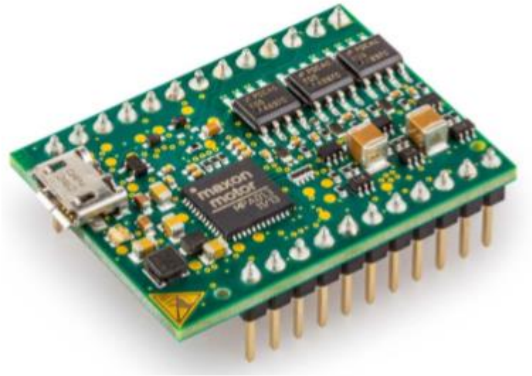
ADCS: Attitude Determination Truth Table

Gyroscope	Magnetometer	Sun Sensor	Overall accuracy (deg)
✓	✗	✗	< 1
✗	✓	✗	5
✗	✗	✓	10
✓	✓	✗	4
✓	✗	✓	10
✗	✓	✓	2
✓	✓	✓	< 1
✗	✗	✗	N/A

ADCS: Actuators (1/4)

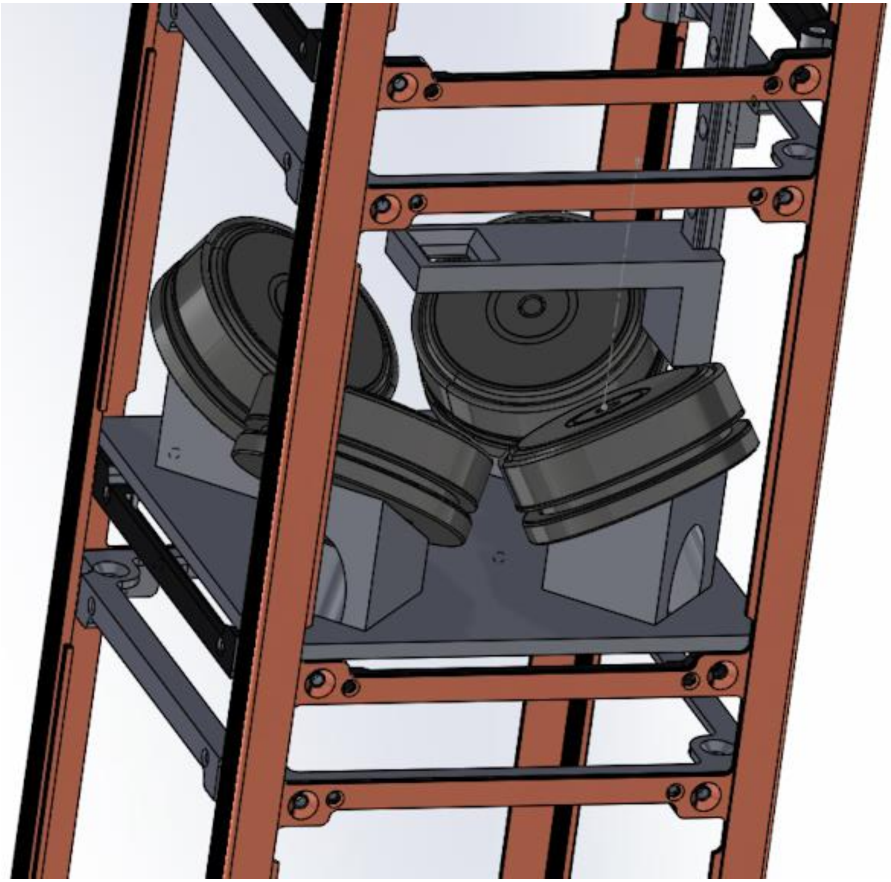
- Maxon EC 45 flat motor
  - Maxon Escon Module 24/2
  - DC power in to 3 phase switching out
  - One controller per wheel

Mass	75 g
Nominal torque	55 mNm
Nominal voltage	12 V
Max efficiency	76%
Inherent rotor inertia	92.5 gcm^2
Torque constant	25.5 mNm/A



ADCS: Actuators (2/4)

- 4x Maxon motors in pyramid configuration
  - Full control is maintained if a single motor breaks
  - 4-wheel nominal roll torque: **90 mNm**
  - 4-wheel nominal roll slew rate: **2.5 deg/s**
  - Control is limited as reaction wheels become saturated



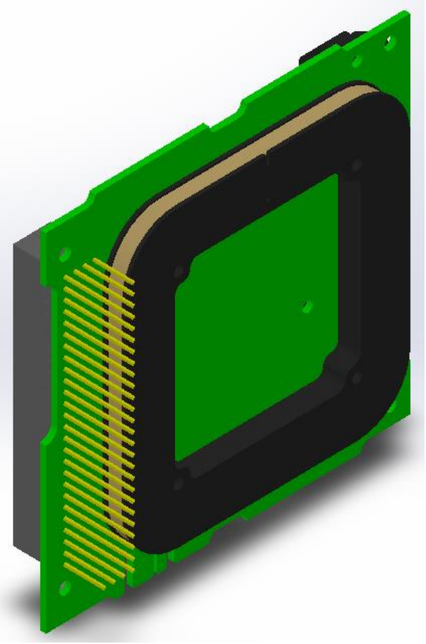
ADCS: Actuators (3/4)

- Magnetorquer rods and coil
  - Used for magnetic attitude control
  - Magnetic dipole interacts with Earth's magnetic field
  - Needed for detumble and wheel desaturation

Image: cubesatshop.com NCTR-M002 Magnetorquer Rod, MT01 Compact Magnetorquer

ADCS: Actuators (4/4)

- Magnetorquer assembly with three-axis control
  - Detumble with "B-Dot" algorithm
  - Desaturate reaction wheels
  - NCTR-M002 rod magnetic moment: **0.2 Am^2**
  - MT01 Compact Magnetorquer coil magnetic moment: ~**0.19 Am^2**



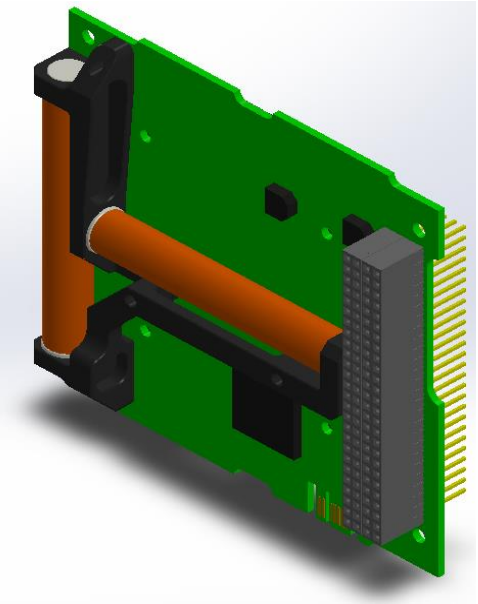


Image: cubesatshop.com ISIS Magnetorquer board

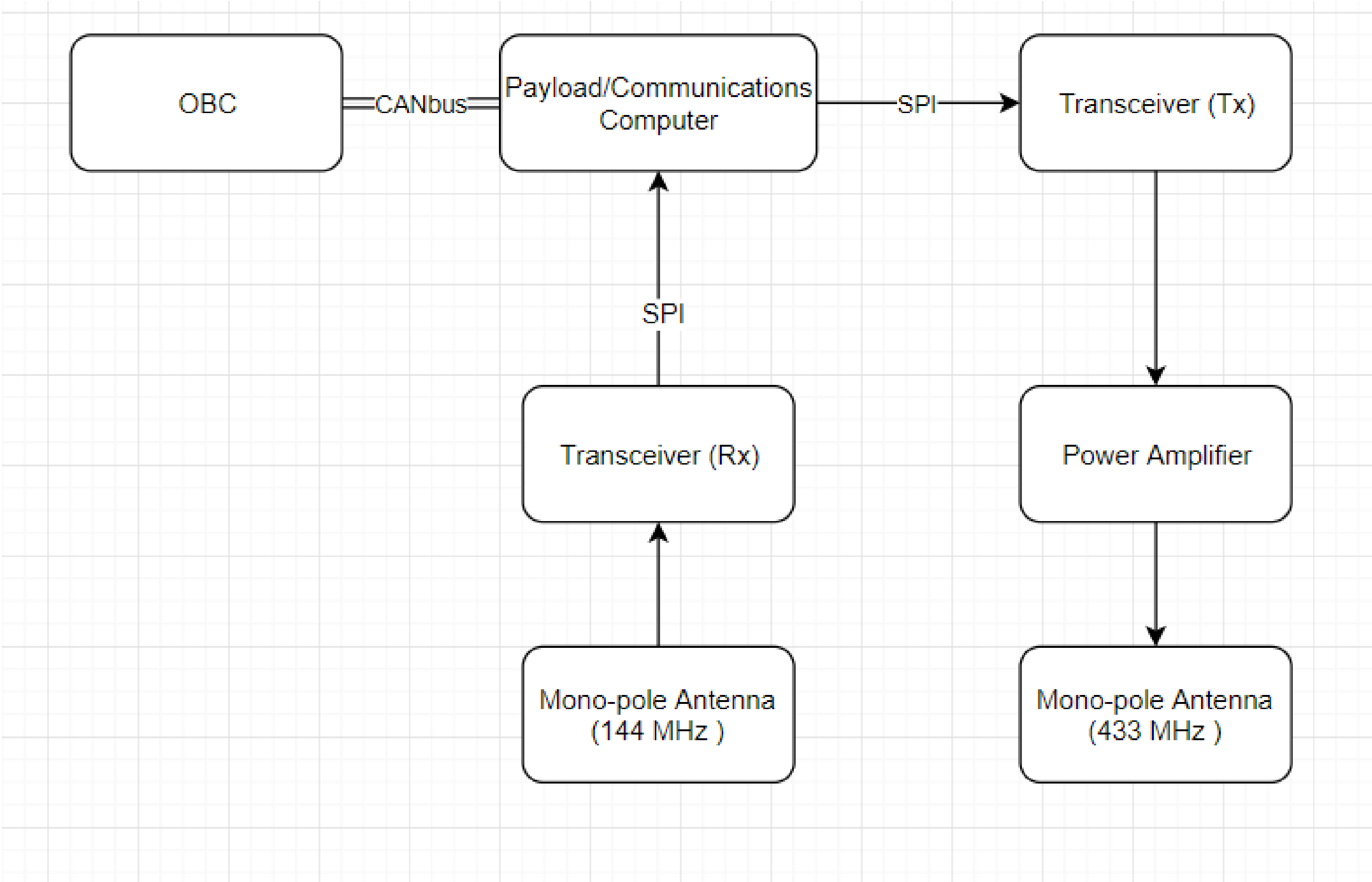
Communications Systems

QUEEN'S SPACE ENGINEERING TEAM

Communications Systems: Overview

- Downlink will be operating at 433 MHz
  - Used to transmit images and telemetry
  - Images will be downlinked in 90 seconds
- Uplink will be operating at 144 MHz
  - Used to trigger pictures, adjust attitude, and update the RTC
- All calculations for communications were based on using the Royal Military College of Canada's setup base station

Communications Systems: Satellite Functional Flow



Communications Systems: Base Station Hardware

- RMC a dual polarity Yagi-Uda antenna with 15dBi of gain and tracking
- 75 W of transmit power
- 9600 bps transceiver

Communications Systems: Link Budgets

UPLINK		DOWNLINK		Units	Note
Item	**Value**	**Item**	**Value**		
Power Transmitted RMC	48.75	Power Transmitted QSAT	32.5	dbm	
TX Antenna Gain	15	TX Antenna Gain	0	dbi	
Rx Antenna Gain	0	Rx Antenna Gain	15	dbi	
Communications Distance	2400	Communications Distance	2400	Km	(1)
Operation Frequency	144	Operation Frequency	433	MHz	
Space Loss	-143.09	Space Loss	-152.66	dbm	(2)
Antenna Pointing Offset Loss	-0.2	Antenna Pointing Offset Loss	-0.2	dbm	
System Implementation Loss	-1	System Implementation Loss	-1	db	
Loss from Polarization	0	Loss from Polarization	0	db	
Atmospheric Loss	-2.76	Atmospheric Loss	-2.76	db	(3)
QSAT Receiver Sensitivity	-123	RMC/ARO Receiver Sensitivity	-123	dbm	(4)
Power Received @ QSAT	**-83.3**	**Power Received @ RMC/ARO**	**-109.12**	**dbm**	
Link Margin	**39.7**	**Link Margin**	**13.88**	**dbm**	

(1) Distance was chosen as a rough maximum distance for the downlink margin, also allows for approximately 1 hour of communications time per day.

(2) Space loss calculated as $20\log_{10}(\frac{\lambda}{4\pi d})$

(3) Atmospheric loss estimated for O_2 and H_2O absorption.

(4) No values where given for the sensitives of the equipment used at RMC or by the amateur radio operators so they were approximated to be the same as the satellite transceiver.

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Communications Systems: Data Sources

Subsystem	Data	Bits/Sample	Samples/min	Samples / Day	Bits/Day	kBytes/Day	Recording Frequency (4)	Recorded kBytes/Day	Notes
Payload	Image	864000	0.11111	159.9984	138238617.6	17279.827	1	17279.8272	(1)(2)
	Orientation X	32	60	86400	2764800	345.6	0.033	11.4048	(3)
	Orientation Y	32	60	86400	2764800	345.6	0.033	11.4048	
	Orientation Z	32	60	86400	2764800	345.6	0.033	11.4048	
	Orientation W	32	60	86400	2764800	345.6	0.033	11.4048	
ADCS	Orientation Sensor Temperature	10	1	1440	14400	1.8	0.5	0.9	
	Solar Cell Voltage	10	1	1440	14400	1.8	0.5	0.9	
	Solar Cell Current	10	1	1440	14400	1.8	0.5	0.9	
	Solar Cell Temperature	10	1	1440	14400	1.8	0.5	0.9	
	Battery Voltage	10	1	1440	14400	1.8	0.5	0.9	
	Battery Current	10	1	1440	14400	1.8	0.5	0.9	
	Battery Temperature	10	1	1440	14400	1.8	0.5	0.9	
	5V Bus Current	10	1	1440	14400	1.8	0.5	0.9	
	3.3V Bus Current	10	1	1440	14400	1.8	0.5	0.9	
	12V Bus Current	10	1	1440	14400	1.8	0.5	0.9	
Power	Current Direction	10	1	1440	14400	1.8	0.5	0.9	
	Year Timestamp	12	60	86400	1036800	129.6	0.016	2.0736	
	Month Timestamp	4	60	86400	345600	43.2	0.016	0.6912	
	Day Timestamp	8	60	86400	691200	86.4	0.016	1.3824	
	Hour Timestamp	8	60	86400	691200	86.4	0.016	1.3824	
	Minute Timestamp	8	60	86400	691200	86.4	0.016	1.3824	
Comp	Second Timestamp	8	60	86400	691200	86.4	0.016	1.3824	
							Total Excluding Images:	63.8136	
							Total:	17343.6408	

(1) Image capture frequency was based on a estimated maximum of 10 images for a 90 minute orbit
(2) Image size based on maximum possible downlink at 9600bps for 90 seconds
(3) Orientation data measured as a quaternion value consisting of 4 32 bit floating point numbers
(4) Frequency that collected data is stored on the satellite and downlinked to mission controlled

Communications Systems: Data Throughput

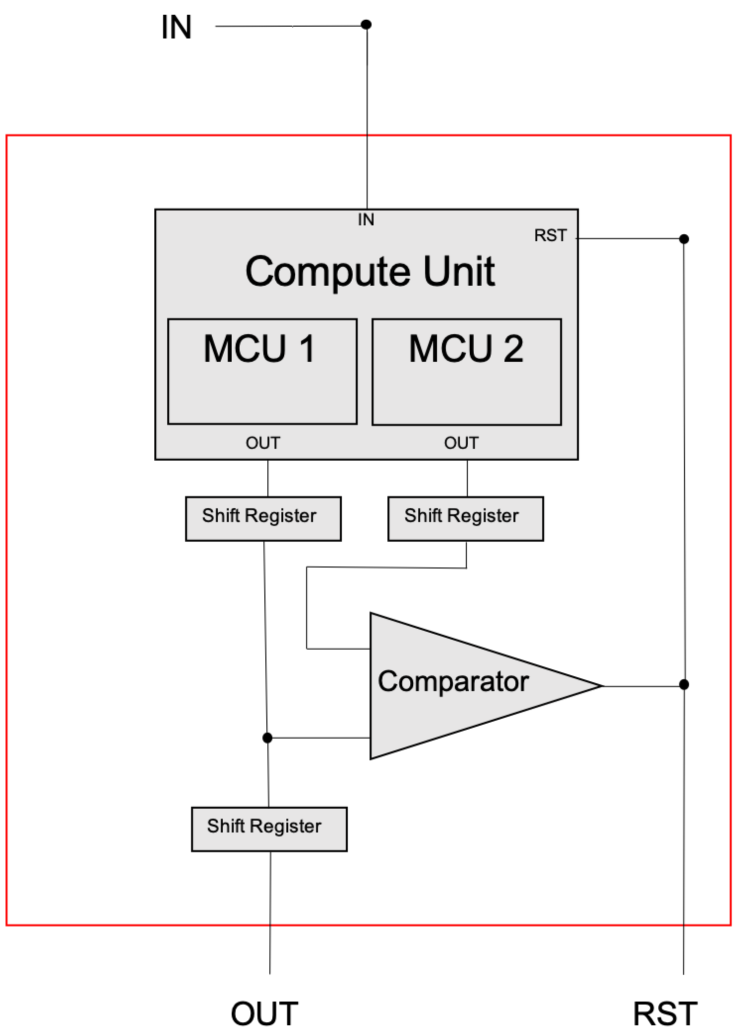
- Total data downlinked per day to the ground station will be 63.8 kB consisting of telemetry.
  - Downlinks will occur twice per day
- At 9600 bps 108 kB can be downlinked in 90 seconds to the ARO.
  - A maximum of 10 images can be taken per orbit yielding a maximum throughput of 17079.8 kb of image data per day.

On Board Computer (OBC)

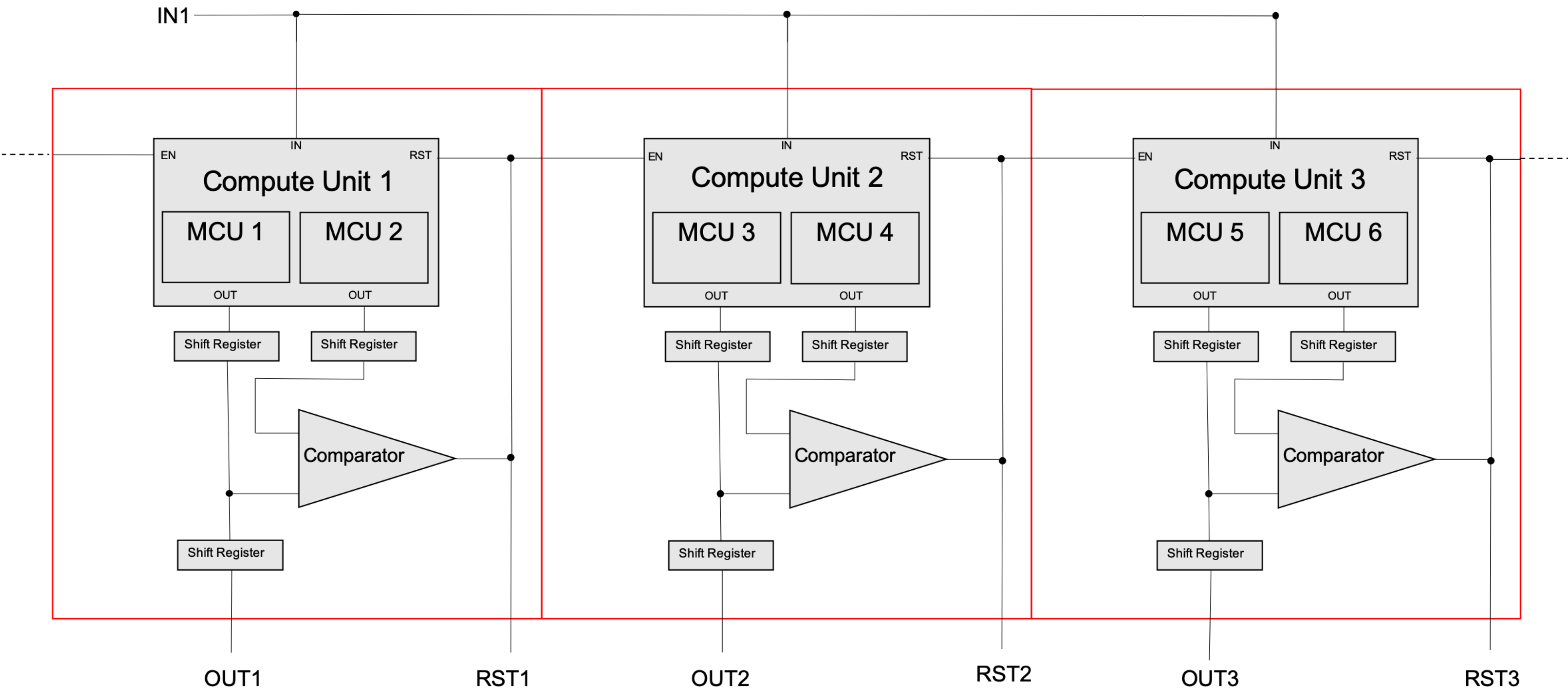
OBC: Overview

- Detect and mask soft and hard errors
- Recovery in the case of hard errors
- Diagnosis of other subsystem’s health
- Treatment and recovery in the event that another subsystem faults
- Receive attitude request and send to the ADCS

OBC: Single-String Architecture



OBC: Multi-String Architecture

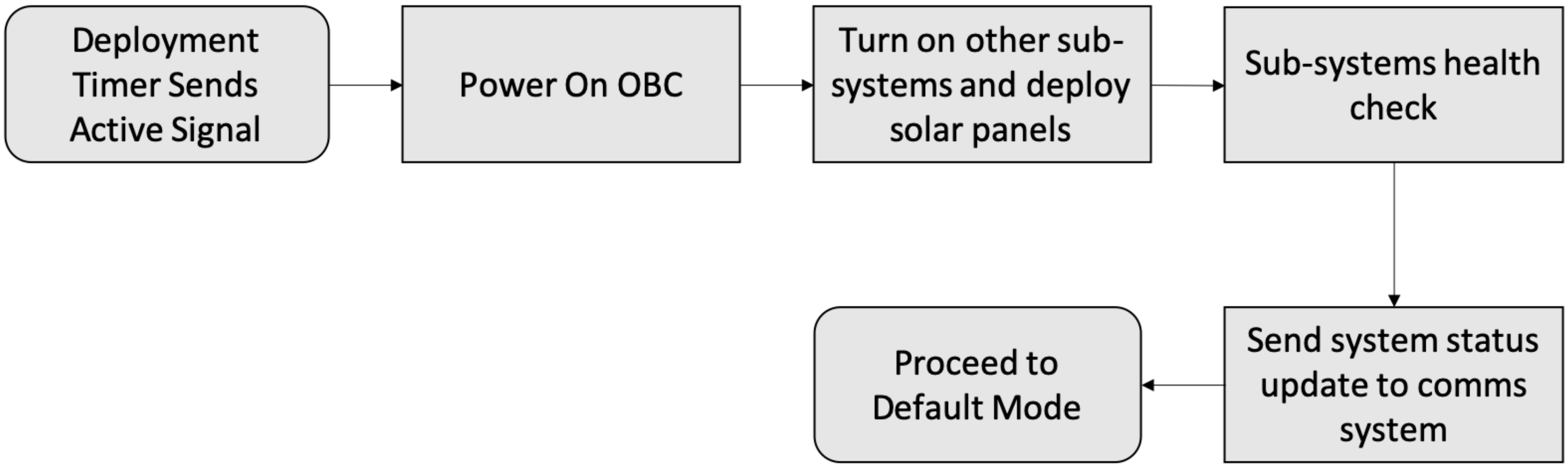


OBC: MCU (STM32L)

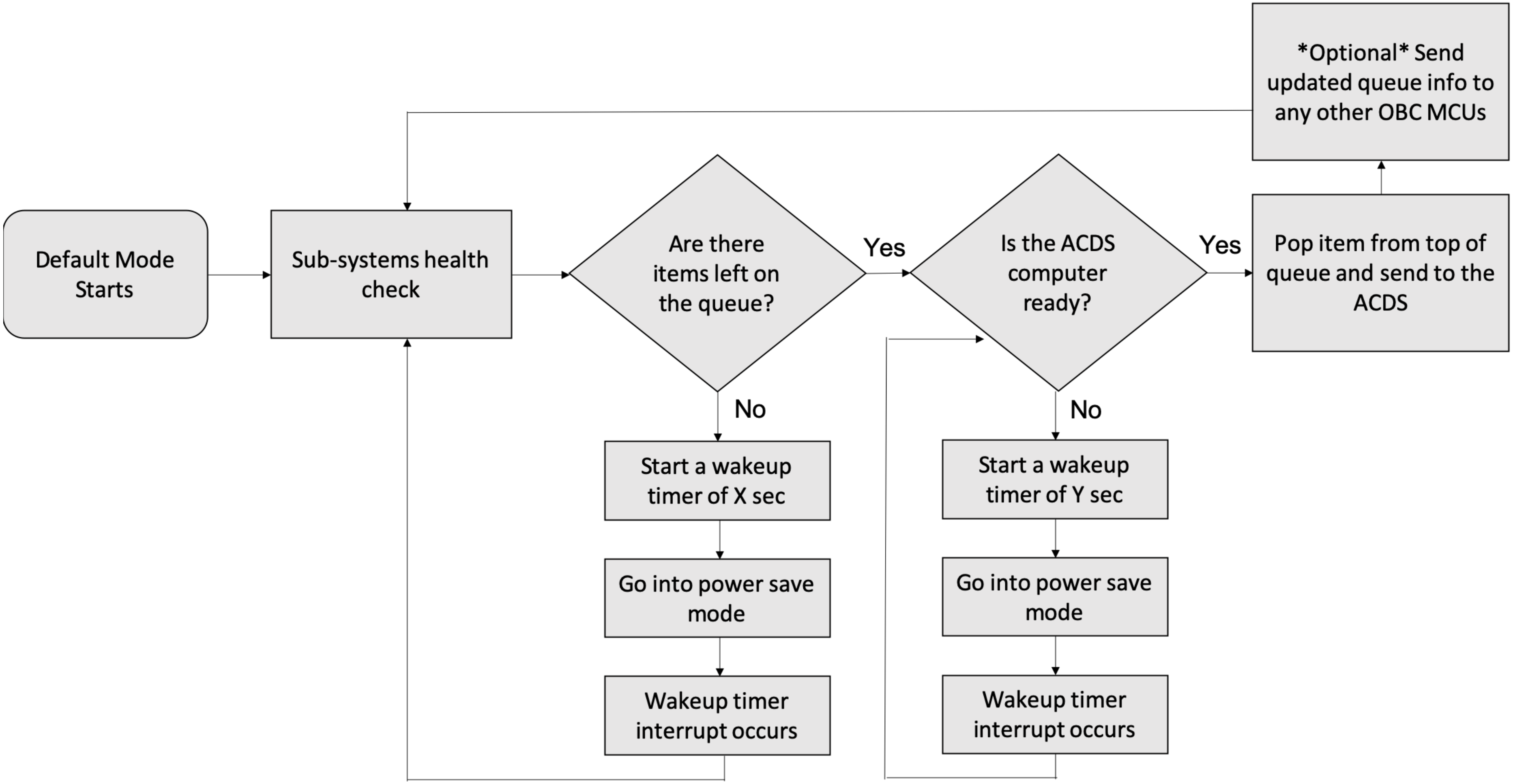
Low cost, ultra low power MCU. Has flight heritage.

CPU	ARM Cortex M4, 80 MHz
RAM	40-320 KB
Storage	256-1024 KB (flash)
Data Acquisition & Control	82 Digital IO, 2 Internal Comparators, 2 Internal DAC, 24 Channel ADC
Interfaces	10/100 Ethernet 5x USART 1x UART 3x SPI 3x I2C 1x CAN
Onboard Devices	RTC, 2x WDG, 11x 16-bit timers, SysTick
Operation Temperature	-40 °C to 85 °C
Current Draw (lowest power mode – run mode per MHz	0.03µA - 100µA/MHz
Supply Voltage	1.71V to 3.6V
Package	LQFP 32 to 144

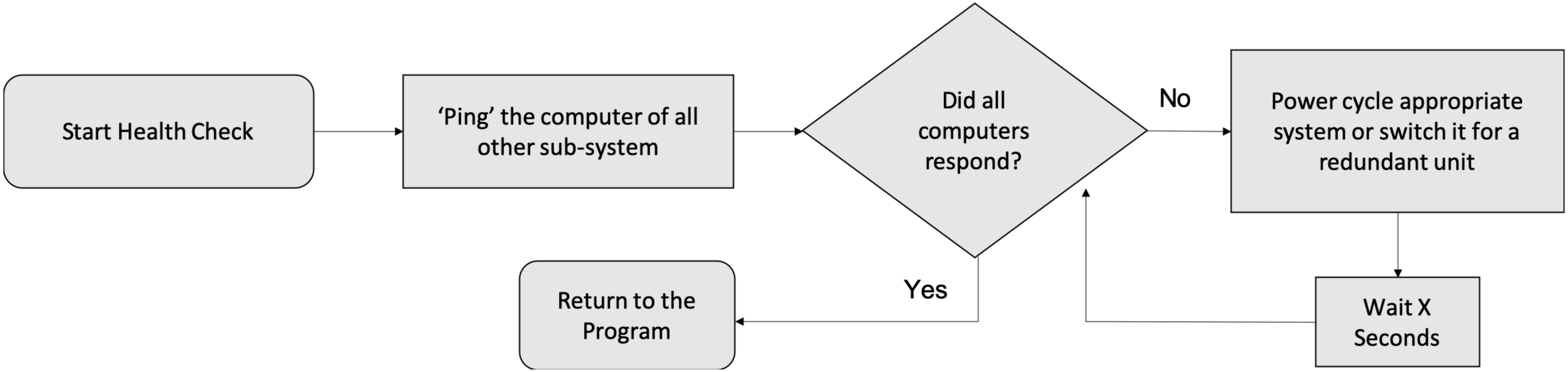
OBC: LEOP Software



OBC: Default Mode Software



OBC: Subsystem Health Check Software



Assembly, Integration & Testing (AI&T)

QUEEN'S SPACE ENGINEERING TEAM

AI&T: Payload

Test	Description	Involved Subsystems	Start Date	End Date
Lens control	Writing control library to control USM components in lens housing	Lens, OBC	Dec 2019	Jan 2020
Camera control interface	Interface closed source ZWO driver with STM32 microcontroller	Image sensor, OBC	Dec 2019	Dec 2020
Thermal stability control	Testing thermal stability in a vacuum with ambient temperature control	Heat pipes, control circuit, image sensor	Mar 2020	Mar 2020
Image compression performance	On target testing of compression algorithms against expected test images	OBC	Jan 2020	Jan 2020
System integration	Command image capture with all systems – automatic thermal control, exposure and gain settings and compression ratio	All	Apr 2020	Apr 2020

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Image compression performance	On target testing of compression algorithms against expected test images	OBC	Jan 2020	Jan 2020
System integration	Command image capture with all systems – automatic thermal control, exposure and gain settings and compression ratio	All	Apr 2020	Apr 2020

QUEEN'S SPACE ENGINEERING TEAM

AI&T: Payload

Test	Description	Involved Subsystems	Start Date	End Date
Lens control	Writing control library to control USM components in lens housing	Lens, OBC	Dec 2019	Jan 2020
Camera control interface	Interface closed source ZWO driver with STM32 microcontroller	Image sensor, OBC	Dec 2019	Dec 2020
Thermal stability control	Testing thermal stability in a vacuum with ambient temperature control	Heat pipes, control circuit, image sensor	Mar 2020	Mar 2020
Image compression performance	On target testing of compression algorithms against expected test images	OBC	Jan 2020	Jan 2020
System integration	Command image capture with all systems – automatic thermal control, exposure and gain settings and compression ratio	All	Apr 2020	Apr 2020

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Test	Description	Involved Subsystems	Start Date	End Date
Lens control	Writing control library to control USM components in lens housing	Lens, OBC	Dec 2019	Jan 2020
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Thermal stability control	Testing thermal stability in a vacuum with ambient temperature control	Heat pipes, control circuit, image sensor	Mar 2020	Mar 2020
Image compression performance	On target testing of compression algorithms against expected test images	OBC	Jan 2020	Jan 2020
System integration	Command image capture with all systems – automatic thermal control, exposure and gain settings and compression ratio	All	Apr 2020	Apr 2020

QUEEN'S SPACE ENGINEERING TEAM

CSDC

AI&T: Mechanical & Structure

Test	Description	Involved Subsystems	Start Date	End Date
Deployment	Ensure OBC and EPS power on when switch is released; Test OBC timer prior to antenna and solar panel deployment	OBC, EPS	Oct-2019	Dec-2019
Vibration*	Simulate launch sequence natural modules with vibration table	Primary and Secondary Structure	Oct-2019	Dec-2019
Thermal Vacuum**	Operate basic functions in vacuum and low/high temperatures-depending on securing sufficient chamber	All	Mar-2020	April-2020

*Shaker table at Queens available

**Vacuum chamber at RMC to be used

AI&T: Mechanical & Structure

Test	Description	Involved Subsystems	Start Date	End Date
Deployment	Ensure OBC and EPS power on when switch is released; Test OBC timer prior to antenna and solar panel deployment	OBC, EPS	Oct-2019	Dec-2019
Vibration*	Simulate launch sequence natural modules with vibration table	Primary and Secondary Structure	Oct-2019	Dec-2019
Thermal Vacuum**	Operate basic functions in vacuum and low/high temperatures-depending on securing sufficient chamber	All	Mar-2020	April-2020

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AI&T: Mechanical & Structure

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Vibration*	Simulate launch sequence natural modules with vibration table	Primary and Secondary Structure	Oct-2019	Dec-2019
Thermal Vacuum**	Operate basic functions in vacuum and low/high temperatures-depending on securing sufficient chamber	All	Mar-2020	April-2020

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**Vacuum chamber at RMC to be used

AI&T: Mechanical & Structure

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Vibration*	Simulate launch sequence natural modules with vibration table	Primary and Secondary Structure	Oct-2019	Dec-2019
Thermal Vacuum**	Operate basic functions in vacuum and low/high temperatures-depending on securing sufficient chamber	All	Mar-2020	April-2020

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**Vacuum chamber at RMC to be used

AI&T: Power

Test	Description	Involved Subsystems	Start Date	End Date
EPS Interface and Control Development	Use Arduino I2C bus to interface with EPS and retrieve telemetry, measure outputs from PDM and PCM, integrate Arduino code in OBC system and repeat above tests	Solar Arrays, EPS, Batteries	Oct 2019	Feb 2020
Solar Array and Battery PCB	Test Solar Cell and Battery PCB's to confirm operation (simulated load, multimeter check)	Solar Arrays, Batteries	Nov 2019	Jan 2020
Output Power Consumption	Ensure power consumption of subsystems and operational modes is within nominal ranges	All	Feb 2020	April 2020
Connector Harnesses	For subsystem components not connected through system power bus; cables and connectors must be made, connected, and tested	EPS	Feb 2020	April 2020

AI&T: Power

Test	Description	Involved Subsystems	Start Date	End Date
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QUEEN'S SPACE ENGINEERING TEAM

CSDC

AI&T: ADCS Sensors

Test	Description	Involved Subsystems	Start Date	End Date
Magnetometer calibration	Calibrate relative to Earth's field and confirm readings using Helmholtz cage	BNO055	Nov 2019	Feb 2020
Gyroscope calibration	Calibrate gyroscope based on data sheet information	BNO055	Nov 2019	Nov 2019
Sun sensor calibration	Map out sensor output at different angles to light source	Sun sensor	Nov 2019	Nov 2019
Magne-tometer and sun sensor	Determine orientation relative to imposed magnetic field and light source	BNO055, sun sensor	Nov 2020	Feb 2020
Magne-tometer and gyroscope	Determine orientation relative to imposed magnetic field and gyroscope readings	BNO055	Nov 2020	Feb 2020

AI&T: ADCS Sensors

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AI&T: ADCS Actuators

Test	Description	Involved Subsystems	Start Date	End Date
Magne-torquer	Impose magnetic field using Helmholtz cage. Use magnetorquers to create torque	Magne-torquers	Feb 2020	Feb 2020
Reaction wheels, individual	Test functionality of each wheel	Reaction wheels	Nov 2019	Nov 2019
Reaction wheels, group	Test attitude control of reaction wheel unit. Test 3- and 4-wheel modes	Reaction wheels	Jan 2020	Jan 2020
Desaturation	Run reaction wheels to maximum RPM. Decrease angular momentum using magnetorquers	Reaction wheels and magne-torquers	Feb 2020	Feb 2020

AI&T: ADCS Actuators

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AI&T: ADCS System

Test	Description	Involved Subsystems	Start Date	End Date
Housed magne-torquer	Test attitude control of magnetorquers	Magne-torquers	Apr 2020	Apr 2020
Detumbling	Test detumbling capabilities of the magnetorquers	Magne-torquers	Apr 2020	Apr 2020
Housed reaction wheel	Test attitude control of reaction wheels. Test 3- and 4-wheel modes	Reaction wheels	Apr 2020	Apr 2020
Desaturation	Desaturate reaction wheel momentum using magnetorquers	Reaction wheels, magne-torquers	Apr 2020	Apr 2020
Full ADCS	Slew to correct satellite orientation relative to an imposed magnetic field and light source	All ADCS subsystems	Apr 2020	Apr 2020

AI&T: ADCS System

Test	Description	Involved Subsystems	Start Date	End Date
Housed magne-torquer	Test attitude control of magnetorquers	Magne-torquers	Apr 2020	Apr 2020
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QUEEN'S SPACE ENGINEERING TEAM

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AI&T: Communications (1/2)

Test	Description	Involved Components	Start Date	End Date
Antenna	Ensure the antenna characteristics are compatible with the communications system and make appropriate adjustments	Antenna Prototypes, Vector Network Analyzer	Jan 2020	Jan 2020
Link (433 MHz)	Verify a connection can be made between the satellite communications system and a simulated ground station	STM32 MCU, Transceivers, Antennas, ground station	Jan 2020	Jan 2020
Link (144 MHz)	Verify a connection can be made between the satellite communications system and a simulated ground station	STM32 MCU, Transceivers, Antennas, ground station	Jan 2020	Jan 2020
Image Downlink	Verify images can be successfully downlinked to the simulated ground station and test maximum image size	Camera, STM32 MCU, Transceivers, Antennas, ground station	Feb 2020	Feb 2020

AI&T: Communications (1/2)

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Link (144 MHz)	Verify a connection can be made between the satellite communications system and a simulated ground station	STM32 MCU, Transceivers, Antennas, ground station	Jan 2020	Jan 2020
Image Downlink	Verify images can be successfully downlinked to the simulated ground station and test maximum image size	Camera, STM32 MCU, Transceivers, Antennas, ground station	Feb 2020	Feb 2020

AI&T: Communications (2/2)

Test	Description	Involved Components	Start Date	End Date
Ground station	Verify communication can be achieved between the satellite and the RMC ground station	STM32 MCU, Antennas, Transceivers, Amplifier, Ground station	March 2020	March 2020
Antenna Release Mechanism	Verify burn wires capable of releasing antenna array upon deployment	STM32 MCU, Deployment mechanism, Antennas, EPS	Apr 2020	Apr 2020
Distance	Test that a communications link can be made at long distances >1km	STM32 MCU, Transceivers, Antennas, ground station	Feb 2020	Feb 2020

AI&T: Communications (2/2)

Test	Description	Involved Components	Start Date	End Date
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Distance	Test that a communications link can be made at long distances >1km	STM32 MCU, Transceivers, Antennas, ground station	Feb 2020	Feb 2020

AI&T: Communications (2/2)

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Distance	Test that a communications link can be made at long distances >1km	STM32 MCU, Transceivers, Antennas, ground station	Feb 2020	Feb 2020

AI&T: On Board Computer (OBC)

Test	Description	Involved Subsystems	Start Date	End Date
Lock-Step	Testing the interconnection between MCUs in the OBC to ensure they're synchronized	Full OBC	Nov 2019	Jan 2020
Communication	Test communications with other sub-systems over CAN BUS	OBC, all other MCUs	Jan 2020	Mar 2020
Simulated Radiation Upset	Induce simulated upsets by altering the contents of a single MCU's memory. Expect this to cause a system reset and for the OBC to not output data	OBC, stand in CAN reader	Jan 2020	Mar 2020
Total Ionizing Dose	Place the OBC in a Cobalt-60 source such as that at McMaster	OBC, stand in CAN reader	Jan 2020	Mar 2020
Radiation Upset	Place the OBC in a high-power proton beam	OBC, stand in CAN reader	Jan 2020	Mar 2020

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QUEEN'S SPACE ENGINEERING TEAM

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QUEEN'S SPACE ENGINEERING TEAM

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QUEEN'S SPACE ENGINEERING TEAM

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Risk Management

Risk Management: Payload (1/2)

Risk	Effect	Mitigation
High vibration during launch	Lens out of focus or misaligned	• Focus can be adjusted/reset using USM in lens ring • Vibrational analysis of lens mount to determine critical modes • Low off-gas adhesives used where necessary
Sensor damage due to radiation	Increased sensor noise, burnt out pixels	• Close lens aperture and power off sensor when not in use • CMOS sensors are less susceptible to radiation damage than CCDs

Risk Management: Payload (1/2)

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Risk Management: Payload (2/2)

Risk	Effect	Mitigation
Rotation during image capture	Motion blur in images	• Large aperture lens used to minimize • Maximize image sensor gain • Tighten ADCS accuracy constraints
Sensor cooling adds more heat than the radiator can handle	Heat transfer, heat build up on sensor, high dark current noise	• Extensive thermal modelling • Perform vacuum testing • Use very short exposure times

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Risk Management: Power

Risk	Effect	Mitigation
Solar Cell/EPS channel failure	Power generation diminished or failure	• Four sperate channel connections on three different battery charge regulators (BCR's) • Redundant, one fails the other may still function
Battery/EPS BCR failure	Energy Storage Diminished or failure	• Two separate battery paths (two paths, two cells in series each) PCB to system power bus • Redundant, one battery fails, the other is functional • Design and test heaters and temperature sensors for battery longevity

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Risk Management: ADCS

Risk	Effect	Mitigation
Reaction wheel failure	Inaccuracies in attitude control	• Implement a 3-wheel control mode for if 1 wheel fails
Residual dipole created by torque rods	Possible inaccuracies in magnetometer readings	• Position magnetorquers so that components are not affected • Calibrate magnetometer accordingly • Implement a demagnetization method

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Risk Management: Communications

Risk	Effect	Mitigation
Failure to establish comm-unications	Will be unable to communicate with ground station and ARO	• Critical Failure
Failure to deploy antennas	Will be unable to communicate with ground station and ARO	• UV sensitive wire will be used for the deployable antennas so it will degrade over time if the burn wire fails
Comm-unications MCU error	Corruption of data, inability to communicate	• OBC will attempt to restart the MCU
Transmission errors	Images or telemetry could become unreadable	• Transmission can be reattempted

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CSDC

Risk Management: OBC

Risk	Effect	Mitigation
Hard errors in mission critical components	Cannot send messages to ACDS if no backups exist	• Expected radiation dose simulations using SPENVIS or other, and compared to tests
SEUs in Data or computer state	This can cause a corruption of the OBC's data or an inability to execute some portion of the OBC's software.	• Lock-step and watchdog timers will detect such events and reboot the appropriate MCU to return it to normal operating condition.

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Anomaly Mitigation

Anomaly Mitigation: Payload (1/2)

Anomaly	Detection	Response
CMOS noise	Noisy image output, particularly black regions	• Increase sensor cooling
Thermal warping	Warped/blurry images	• Tighten thermal constraints • Post-processing correction
Image noise	Sensor operating above recommended temperature	• Increase sensor cooling • Post-processing correction
Amp glow	Bright patches consistent across images	• Increase sensor cooling
Motion blur	Streaked, blurred images	• Post-processing correction

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Anomaly Mitigation: Payload (2/2)

Anomaly	Detection	Response
Overexposure	Loss of image detail Image sensor saturation	• Reduce aperture • Shorten exposure time
Underexposure	Loss of image detail	• Increase aperture • Increase exposure time
Radiation damage to sensor	Hot pixels appear in image	• Cool sensor • Limited mission duration
Lens contaminants	Fuzzy or warped spots in images	• Clean room
Optical Aberration	Blurred image	• Buy high end telephoto lens

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CSDC

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QUEEN'S SPACE ENGINEERING TEAM

CSDC

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Anomaly Mitigation: Communications

Anomaly	Detection	Response
Unable to transmit	Timeout No 'data received' signal	• Re-attempt on next cycle
Internal comms. noise	Increased data noise	• Restart Communications MCU

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Anomaly Mitigation: OBC

Anomaly	Detection	Response
Single event latch-up	Power system detects over current	• Power cycle of the appropriate unit is triggered
Data corruption	Lock-step error detection will observe any corrupted data that the OBC attempts to use	• The use of corrupted data will result in a system power cycle as per the architecture previously shown
Low storage memory	OS will be written to detect this prior to memory being fully filled	• On subsequent passes of the ground station data will be offloaded and memory will then be freed
Process not responding	Watchdog timeout signal	• Initiate power cycle

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QUEEN'S SPACE ENGINEERING TEAM

Concept of Operations (CONOPS)

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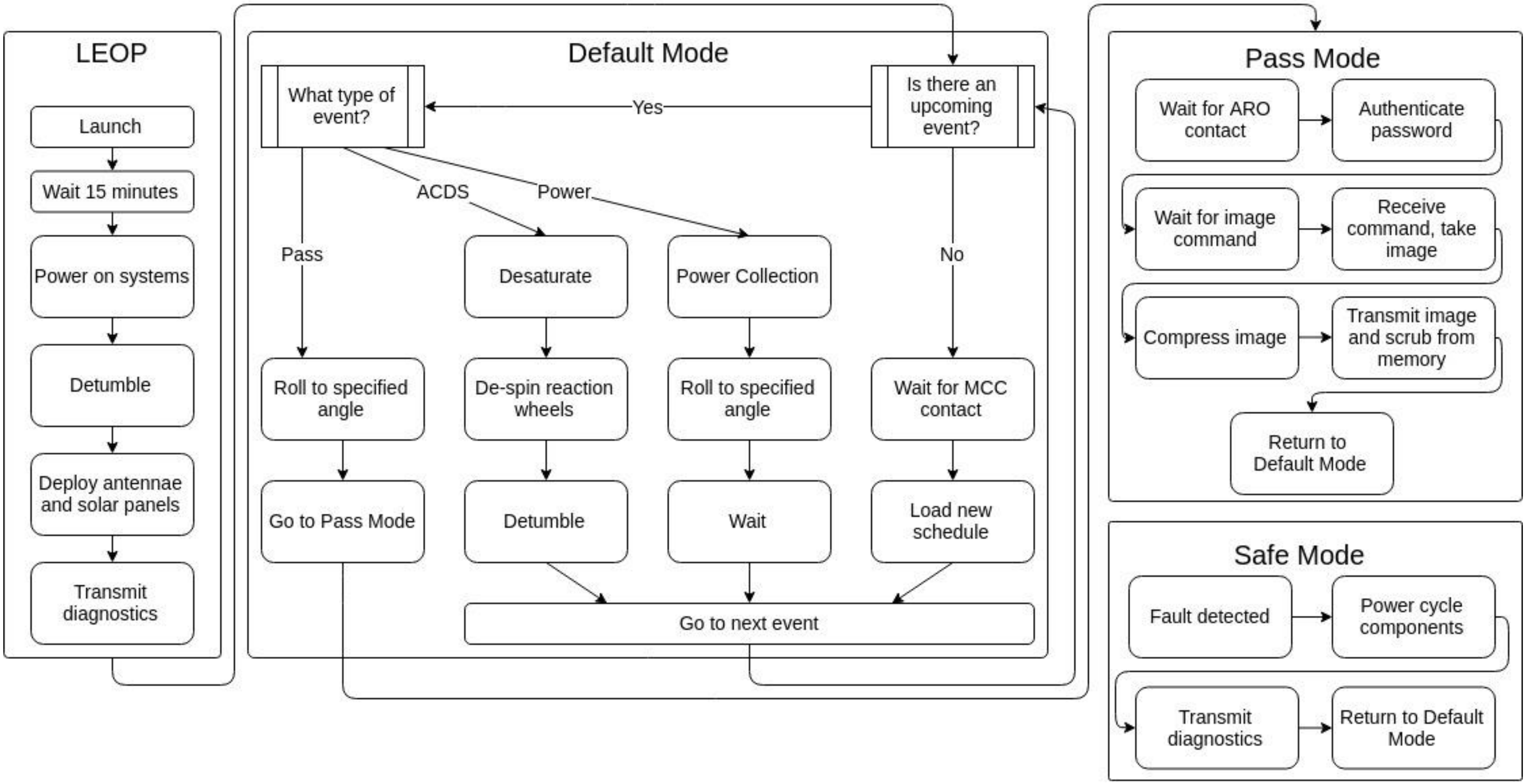
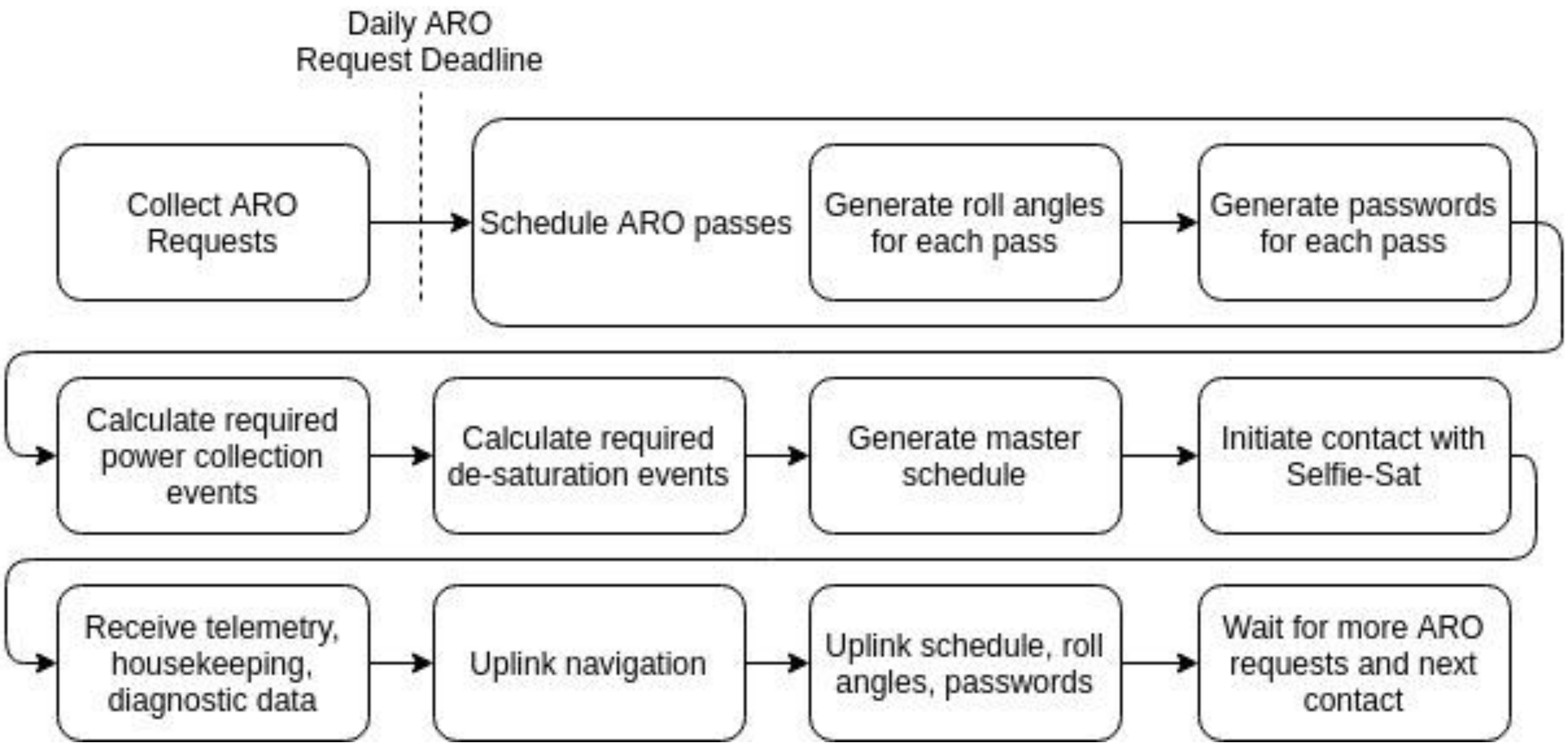
Concept of Operations: Space Segment Overview

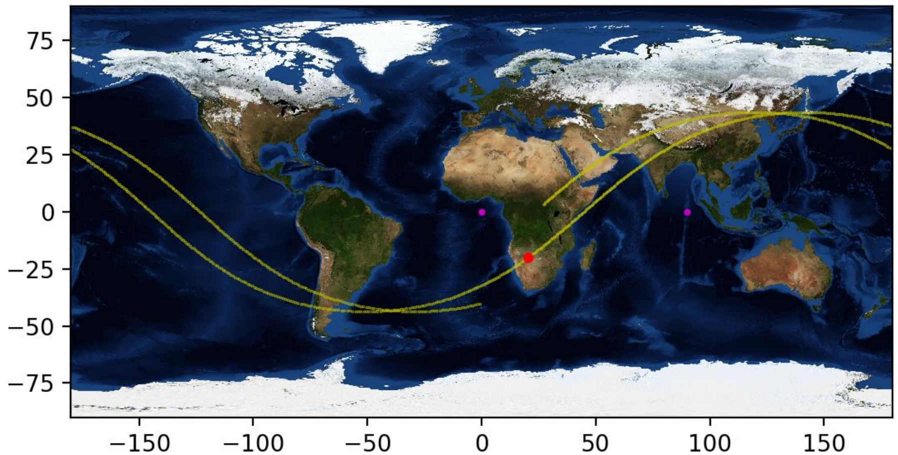


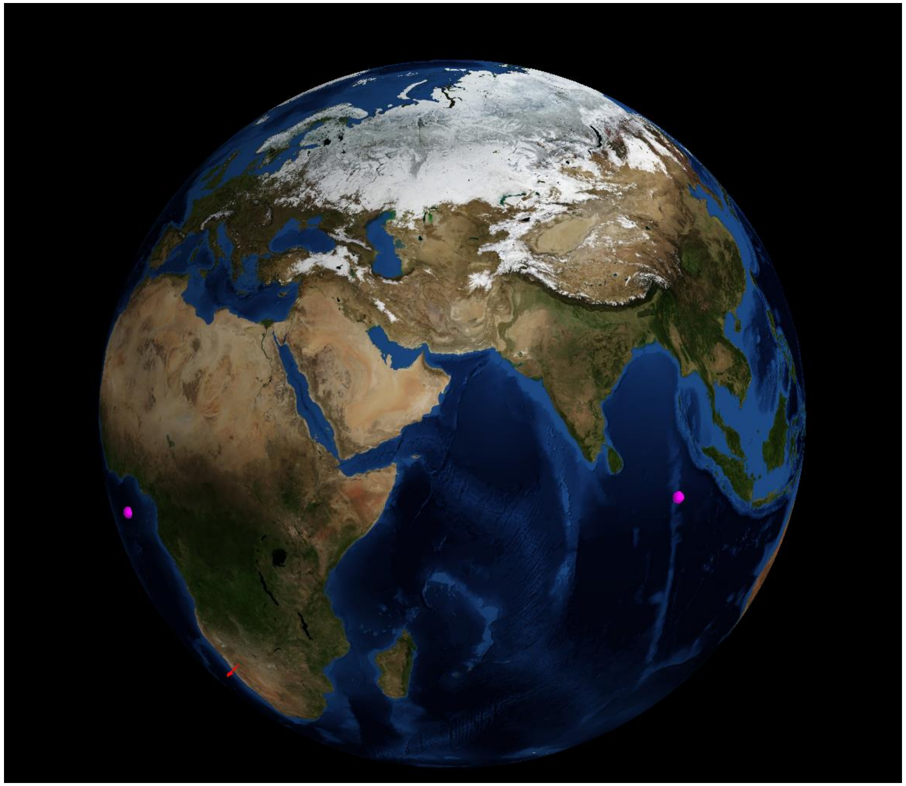
Concept of Operations: Ground Segment Overview



Concept of Operations: Scheduling Algorithm (1/2)

- Python simulation written from scratch for orbit prediction and image scheduling





Concept of Operations: Scheduling Algorithm (2/2)

1. Greedy Algorithm chooses the order of photos to be taken in the order that they appear
2. If a photo appears too close to another, they are removed from the queue
3. The removed photos are fed through the algorithm again to be added to the end of the queue

Concept of Operations: Initialization Sequence (1/2)

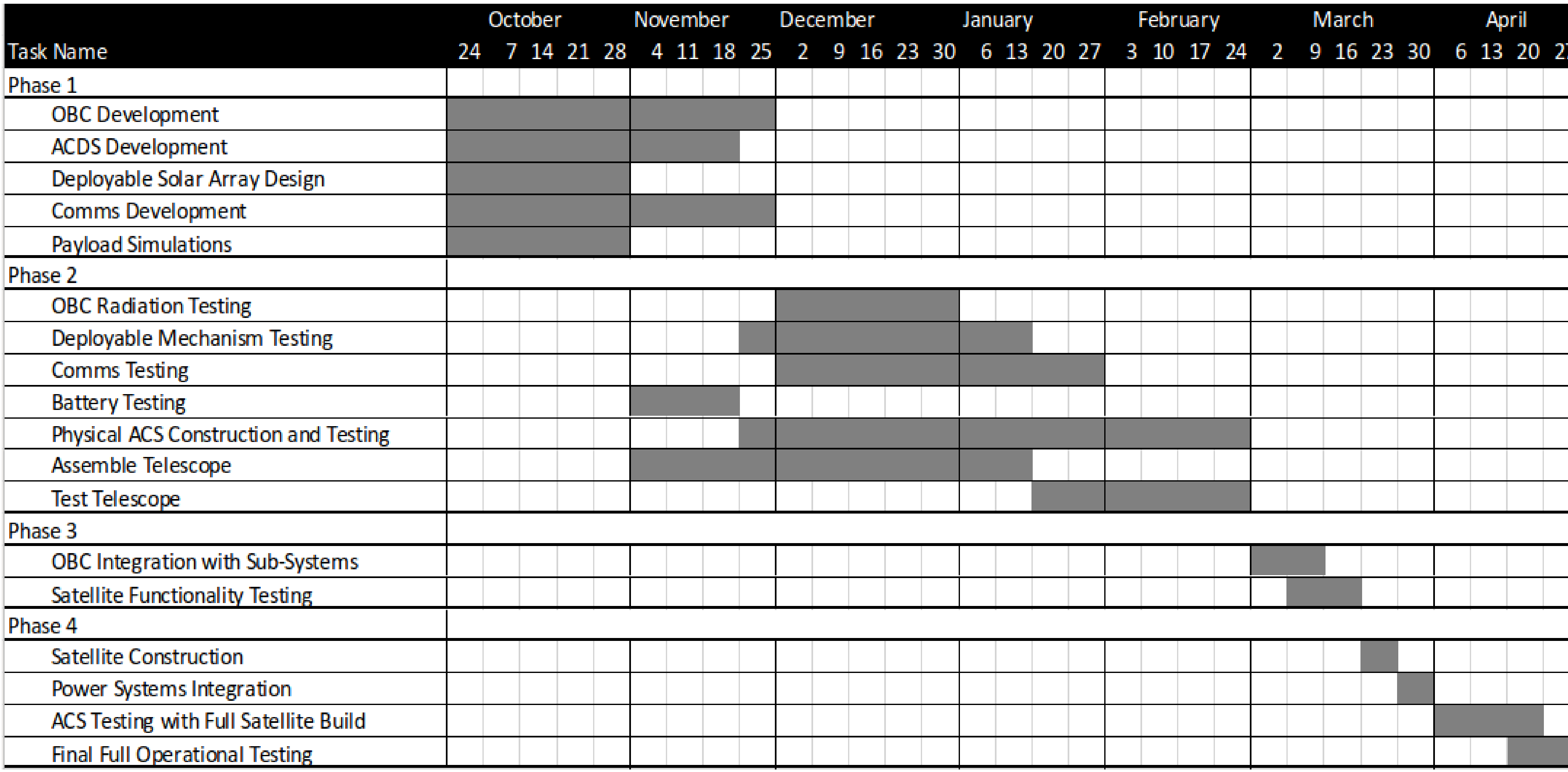
Test	Description	Involved Subsystems
Launch	EPS power on when launched from PPOD	EPS
Power On	Power on OBC, communications system, and the magnetorquers after 15 minutes	OBC, Communications, ADCS
Detumble	Use passive attitude control (I.e. magnetorquers) to detumble satellite	ADCS
Deployment	Solar array deployment, antenna deployment	Structure, EPS, Solar Arrays, Antenna
Telemetry	Collect and save telemetry at specified frequencies, broadcast presence over communications system	OBC, Communications, EPS
Handshake	Establish data link between ground station and satellite	OBC, Communications, EPS

Concept of Operations: Initialization Sequence (2/2)

Test	Description	Involved Subsystems
Power	Enter Default – Power mode to refill batteries and test this default mode	ADCS, EPS, OBC
ADCS	Enter Default – ADCS mode to de-spin motor and test the validity of our detumble mode	ADCS, EPS, OBC
Payload (Pass)	Upon test pass orientate satellite using uplinked data from ground, take image, downlink to test ARO	ADCS, OBC, Telescope, Comms
Default	Return to default mode and begin regular operation	All

Program Management

Program Management: Schedule



QUEEN'S SPACE ENGINEERING TEAM

Program Management: Team Dynamics

- QSET is an open-access team
  - Potential difficulties in ensuring deadlines are met
- Knowledge gap
  - Second time at CSDC
  - Only 3 returning members from previous competition
  - Steep learning curve in space technology
- Facility and Equipment Access
  - Highly dependent on partnership with professors at Queen's University and Royal Military College for lab usage

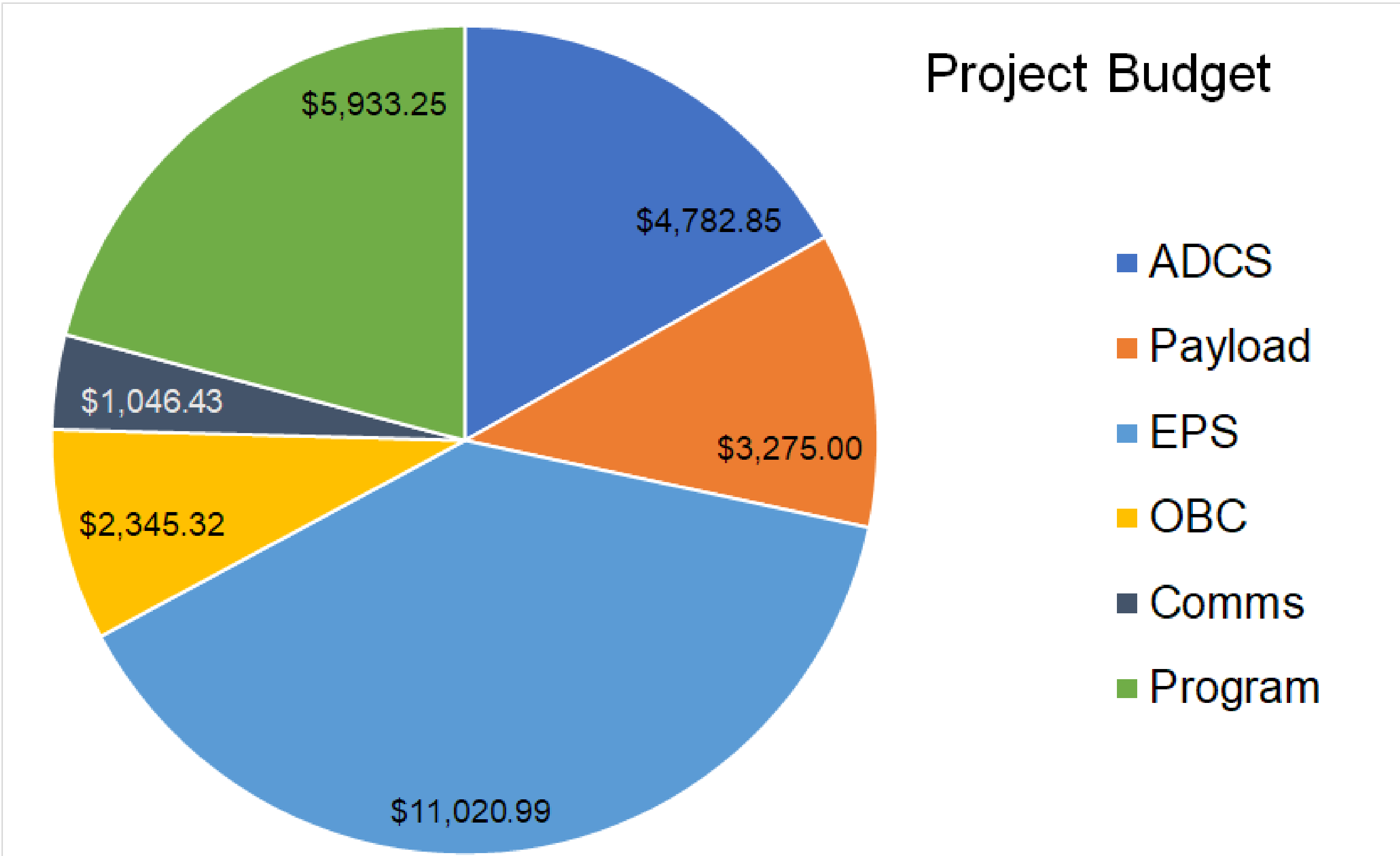
Program Management: New Member Training

- Implemented a new member training program
  - 12-week integration where students learn basic technical skills and broaden their understanding of space science
  - Provide skills that are not covered in the first-year engineering curriculum
  - Prepare student with a basis of knowledge to work on complex projects in the winter semester
  - Gain a more thorough understanding of the team's structure and projects
  - All with the purpose of increasing retention rates amongst new members and improving team dynamics

Program Management: Technology Risks

- ADCS Development
  - Significant undertaking with few sub-team members of mechanical and electrical background
- Payload optics
  - Selecting high quality consumer components allow more time for integration and testing
- Deployable mechanisms
  - New undertaking for QSET, potential for failure due to inexperience in design

Program Management: Budget Overview



Total	**$28,403.84**

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Program Management: Project Income

- Based on 2018-2019 QSET Fiscal Year

Revenue Source	Amount
Dean's Donation Fall	$13,000.00
Dean's Donation Winter	$8,500.00
QYEA Gael's Den cheque 2019	$4,000.00
Student Fees	$8,693.13
IEEE	$1,000.00
INVISTA	$2,943.60
Previous balance (2018-2019)	$5,133.73
Subtotal	**$43,270.46**

QUEEN'S SPACE ENGINEERING TEAM

Educational Outreach

Educational Outreach: Science Rendezvous

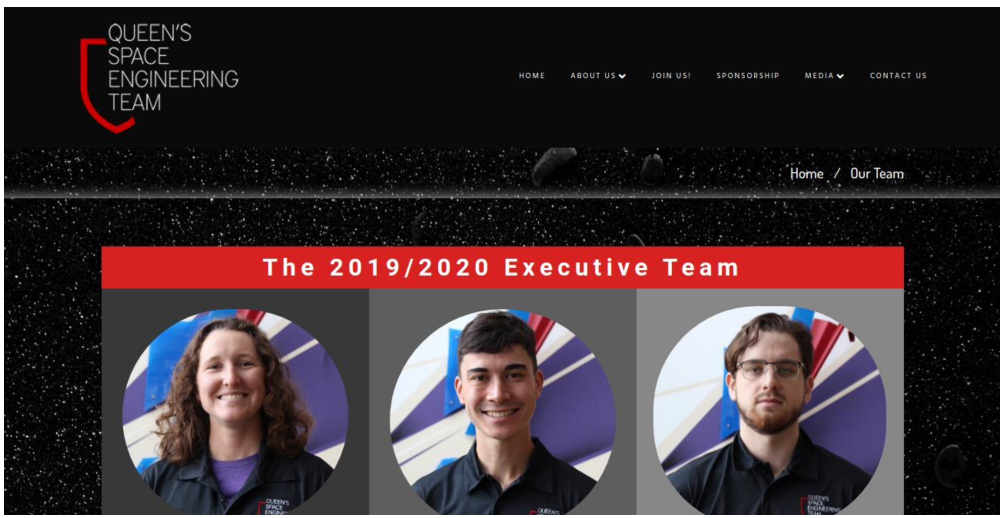
- Science Rendezvous is an annual Canada-wide event bringing people in STEM fields to present in their communities
- QSET presented their decade of work in space-related technologies to thousands of students and families in Kingston in May 2019
- Local media and Science Rendezvous organizers were present at the event

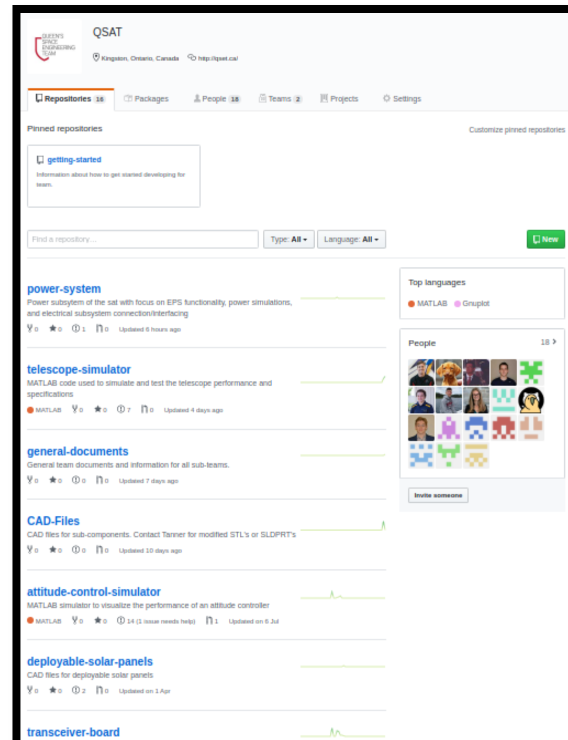
Educational Outreach: Other (1/3)

- WiSE Girl Guide Badge Day (ages 7-13) March 23, 2019
- Orientation week showcase on Queen's campus to over 700 first-year engineering students Sept. 2018 and 2019
- High school students toured our workspace where we displayed our ongoing projects


Educational Outreach: Other (2/3)

- Showcased work at the 2019 Queen’s Space Conference to ~150 attendees and presenters
- Publicly documents all team work on QSET webpages (www.qset.ca and github.com/queens-satellite-team)





Educational Outreach: Other (3/3)

- Art of Research Photo Contest
  - Open to the public at the Isabel Bader Centre for the Performing Arts in Kingston

- Shell Experiential Learning Opportunities Symposium at Queen's University
  - Presented to Shell representatives for funding opportunities in spring 2019

Summary

Summary: Accomplishments (1/2)

- General
  - Partnered with RMC for ground station access
- Payload
  - Robust design chosen to minimize design work and maximize integration and testing
  - Industry standard components allow for low-cost prototyping
- Structure & Thermal
  - CAD model ready for prototyping
  - Models predict viable thermal operation and vibrational integrity
  - Overall 3.9 kg mass (incl. margin)

Summary: Accomplishments (2/2)

- Power & Communications
  - Designed EPS system to handle power requirements of payload
  - Antenna simulations underway
  - Preliminary code for some MCU functionality
- ADCS
  - Designed and built Simulink attitude control simulation
  - Purchased functional hardware
- Outreach
  - Wide variety of outreach projects, building relationships with local schools and camps to provide educational workshops
  - Plans to continue relationship with ScienceQuest, Science Rendezvous, and the Engineering Society of Queen's University

Summary: Next Steps & Required Assistance (1/3)

- Overall
  - Test initialization procedure
  - Access to vacuum chamber; no facility for thermal testing
  - Management of risk in team dynamics
  - Shift from design phase into system construction and testing
- Payload
  - Performance and thermal analysis of sensor system
  - Further modelling of copper heat pipes for passive cooling
  - Image compression and downlink procedures
  - Adaptor and harness for lens and sensor

Summary: Next Steps & Required Assistance (2/3)

- Structure & Thermal
  - Battery heating/lamp cooling tests
  - Manufacture and prototype to confirm models
- Power Subsystem
  - Design solar panel PCB
  - Determine battery cycle curves & confirm power usage
  - Design a battery pack PCB and battery heating and monitoring system

Summary: Next Steps & Required Assistance (3/3)

- Communications
  - Order communications components
  - Develop code for message encoding and interfacing with components
  - Develop PCBs for communications systems
- ADCS
  - Model sun sensing capabilities
  - Implement and test magnetorquers
  - Sensor and actuator calibration
- OBC
  - Dummy load testing
  - Ensure watchdog and error-correction functionality

Acknowledgments

Dr. Josh Marshall
Thomas Sears

Matthew Bowen
Tanner Rellinger
Eric Larmer
Matthew Duke
Andrew Cramp
Piper Steffen
Cal Graham
Ted Ecclestone
Isaac Jahncke
Emma Paczkowski
Sydney Caulfeild
Rylen Sampson
Sarah Reese
Anthony Steele
Emma Howard
Lily de Loe
Connor Dunham
Michael Baril

QUEEN'S SPACE ENGINEERING TEAM

Thank you!

Supplementary Information

Thermal Analysis: Calculations (1/7)

- Determine orbital parameters
  - Set to 400 km circular for thermal maximum and 800 km circular for thermal minimum
- Determine power dissipation for spacecraft components
  - Maximum and minimum power dissipation for all components listed in *Thermal Analysis: Component Power Dissipation* slide
  - Thermal maximum is assumed to take place during communications with an ARO. Therefore, the imaging sensor is not drawing power, while the comms transceiver and amplifier are operating at maximum power dissipation
- Determine the operational and non-operational temperature requirements (temperature margins). Presented on Slide 51
- Select a simplified geometric shape for thermal calculations
  - QUBESat is taken as a 3U cubesat with deployable panels totaling 0.26 m^2 for all calculations involving total surface area, and the largest face of 30 cm x 30 cm is taken for calculations involving a single flat plate

Thermal Analysis: Calculations (2/7)

- Determine the thermal heating environment
  - Identify operational phases with maximum heating and cooling
    - Maximum heating occurs at 400 km in daylight
    - Maximum cooling occurs at 800 km in eclipse
- Calculate the environmental heat absorbed by the spacecraft
  - Direct solar heating in watts (*Solar Flux* slide)
  - Reflected solar heating in watts (*Albedo Flux* slide)
  - Earth emissions in watts (*Earth IR Flux* slide)
  - Free molecular heating in watts (*FMH* slide)
- Solve for temperature extremes (*Solving for Temperatures* slide)
- Compare with component margins and determine required thermal control methods

Thermal Analysis: Calculations, Solar Flux (3/7)

$$q_{Sun} = Q_{sun} A_s \alpha_s \mu_i$$

- Q_{sun}: Solar flux density taken at its maxima of 1419 W/m^2
- A_s: Total satellite surface area
- α_s: Absorptance of spacecraft surface in the solar spectrum
  - Taken at 0.52 (average of solar cells, aluminum, white paint)
- μ_i: Solar aspect coefficient, the percentage of satellite area exposed to solar flux. Taken as 1.

Thermal Analysis: Calculations, Albedo Flux (4/7)

$$q_{albedo} = Q_{sun} A_s \alpha_s a F_x$$

- Q_{sun}, A_s, α_s: same as previous
- a: Albedo coefficient for the Earth
  - Taken as 0.30, the average
- F_x: view factor
  - The diminishing value of albedo with altitude
  - R_e is Earth's radius
  - H is satellite altitude

$$F_a = \frac{R_e^{\,2}}{(R_e + H)^2}$$

Thermal Analysis: Calculations, Earth IR Flux (5/7)

$$q_{Earth\_IR} = Q_{IR\_surface} A_s F_x \varepsilon_{IR}$$

- $Q_{IR\_surface}$: The average Earth infrared flux density at the surface
  - Taken as the average, 236 W/m^2
- A_s: Satellite surface area as before
- F_x: View factor as before
- ε_i: Spacecraft IR emissivity
  - Taken at 0.86 (average between solar cells, aluminum, and white paint)

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CSDC

Thermal Analysis: Calculations, FMH (6/7)

$$q_{FMH} = \frac{1}{2}\alpha_{FMH}\rho V^3 A_{FMH}$$

- α_{FMH}: Accomodation coefficient, percentage efficiency of heat transfer between atmospheric molecule and spacecraft surface
  - Taken as 1
- ρ: Atmospheric density
  - MSISE-90 model used
  - 5.04e-11 km/m^3 at 400 km in altitude
  - 9.59e-13 km/m^3 at 800 km in altitude
- V: Velocity of spacecraft
  - 7,669 m/s at 400 km
  - 7,452 m/s at 800 km
- A_{FMH}: Area of spacecraft exposed to FMH
  - Taken as largest face, 30 cm x 30 cm

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Thermal Analysis: Calculations, Solving for Temperatures (7/7)

- Using the steady state heat balance equation for an isothermal object, the temperature in each thermal case is found:

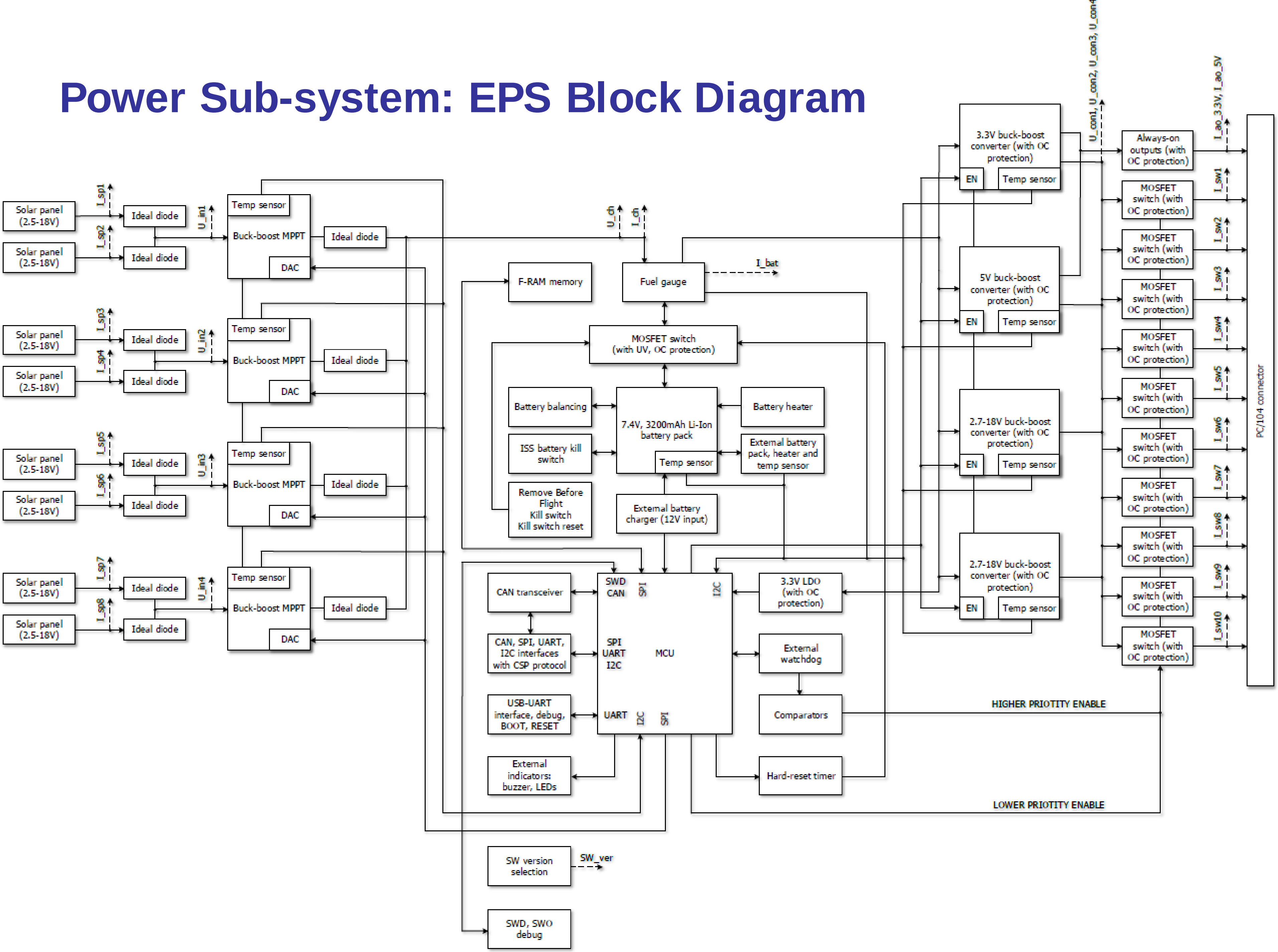
$$T = \left(\frac{q_{Sun} + q_{albedo} + q_{Earth\_IR} + q_{FMH} + q_{\text{internal}}}{\varepsilon_{IR} A_s \sigma} \right)^{1/4}$$

- Where σ is the Stefan-Boltzmann constant

Thermal Analysis: Component Power Dissipation

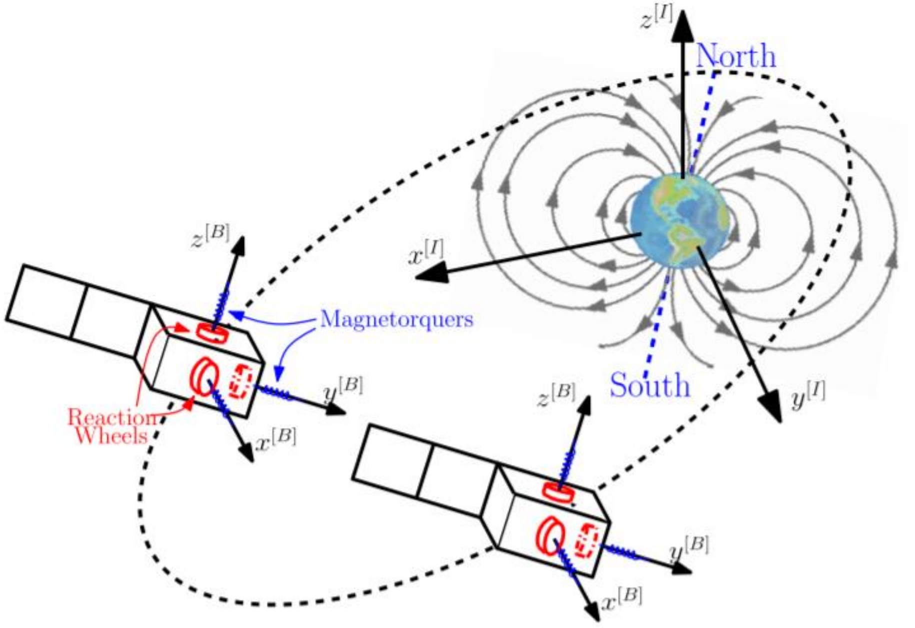
Subsystem	Component	Source Hot Case	Source Cold Case
Power	Clyde Space EPS	5.11 W	0.2 W
Power	Clyde Space Battery pack	0.1 W	0.3 W to 0.9 W
ADCS	Reaction Wheels	5 W x 4 wheels	0.035 W x 4 wheels
ADCS	Motor Controller	0.2688 W	0.0256 W
ADCS	Magnetorquer Rods	0.2 W	0.1 W
Comms	Transeiver (cc1120 Tx)	0.092 W	0.0039 W
Comms	Transeiver (cc1120 Rx)	0.066 W	0.0039 W
Comms	Power Amp (RF5110G)	5.63 W	0 W
Payload	Image sensor	2 W	0W
Payload	TEC cooler		

Power Sub-system: EPS Block Diagram



Magnetic Detumbling

- Satellite must detumble upon entering orbit
- Magnetorquers must also be used for reaction wheel desaturation
- Magnetic detumbling involves the use of magnetometers to generate torques proportional to measured changes in the local magnetic field
- The “B-Dot” algorithm is commonly used for magnetic detumbling



Program Budget - ADCS

Item	Qty	Unit	Unit Cost	Taxes/Shipping	Cost
SIMULINK 3D Animation License	4	ea	$29.00	$0.00	$116.00
Gimbal	1	n/a	$300.00	$0.00	$300.00
Magnetorquer Rods	2	ea	$1,582.02	$632.81	$3,796.85
STM32 MCU	2	ea	$50.00	$20.00	$120.00
Reaction Wheel Mount	1	n/a	$400.00	$0.00	$400.00
Wiring and Connectors	n/a	n/a	$50.00	$0.00	$50.00
Subtotal					**$4,782.85**

Program Budget - Payload

Item	Qty	Unit	Unit Cost	Taxes/Shipping	Cost
Canon 135mm f/2.0 USM	1	ea	$1,000.00	$150.00	$1,150.00
Aluminum housing/radiator	1	n/a	$500.00	$100.00	$600.00
Test bed (for calibration/verification of theory)	1	n/a	$100.00	$20.00	$120.00
ZWO ASI1600MM (mono) image sensor	1	ea	$1,000.00	$200.00	$1,200.00
Camera mount (machining/printing)	1	n/a	$100.00	$20.00	$120.00
STM32 MCU	1	ea	$50.00	$10.00	$60.00
30mm TEC cooler	1	ea	$20.00	$5.00	$25.00
Subtotal					**$3,275.00**

Program Budget - EPS

Item	Qty	Unit	Unit Cost	Taxes/Shipping	Cost
Spring Hinge	4	ea	$36.55	$29.24	$175.44
PCBs Manufacturing	150	per square inch	$10.00	$0.00	$1,500.00
7075 Aluminium 12'x12'x1/4'	1	ea	$79.50	$15.90	$95.40
Solar Cells	20	ea	$363.06	$450.00	$7,711.20
Wire/cable 26 AWG 500'	1	ea	$116.54	$15.15	$131.69
Solar Cell female connectors	80	ea	$0.17	$2.72	$16.32
pins	400	ea	$0.07	$5.60	$33.60
crimper	1	ea	$1,049.61	$136.45	$1,186.06
Solar Cell male connectors	60	ea	$0.99	$11.88	$71.28
Misc. Hardware	n/a	n/a	$100.00	n/a	$100.00
Subtotal					**$11,020.99**

QUEEN'S SPACE ENGINEERING TEAM

Program Budget - OBC

Item	Qty	Unit	Unit Cost	Taxes/Shipping	Cost
PCBs	20	ea	$50.00	$130.00	$1,130.00
MCU/Processor	15	ea	$50.00	$97.50	$847.50
Capacitors	50	ea	$0.80	$5.20	$45.20
Resistors	50	ea	$0.15	$0.98	$8.48
MISC ICs	30	ea	$5.00	$19.50	$169.50
Solder	1	n/a	$50.00	$6.50	$56.50
Connectors and Ports	30	ea	$2.00	$7.80	$67.80
Wire	3	n/a	$6.00	$2.34	$20.34
Subtotal					**$2,345.32**

Program Budget - Comms

Item	Qty	Unit	Unit Cost	Taxes/Shipping	Cost
Transeiver	5	ea	$5.17	$3.36	$29.21
Power Amp.	3	ea	$12.40	$4.84	$42.03
PCB	3	ea	$50	$19.5	$169.5
Coax	2	ea	$15.00	$3.90	$33.90
Antenna	2	n/a	$30.00	$15.60	$135.60
Misc. Components	1	n/a	$40.00	$5.20	$45.20
Digital Logic Analyzer	1	ea	$263.00	$34.19	$297.19
Amateur radio operator certificate	1	n/a	$60.00	$7.80	$67.80
Travel to certificate testing location	1	n/a	$200.00	$26.00	$226.00
Subtotal					**$1,046.43**

QUEEN'S SPACE ENGINEERING TEAM

Program Budget – Other Costs

Item	Qty	Unit	Unit Cost	Taxes/Shipping	Cost
CDR - Rental Vehicle	1	ea	$330.99	$46.76	$377.75
Gas	1	n/a	$300.00	$0.00	$300.00
Food	5	ea	$180.00	$0.00	$900.00
Hotel	1	n/a	$500.00	$0.00	$500.00
DFL - Rental Vehicle	2	ea	$330.99	$46.76	$755.50
Gas	2	n/a	$300.00	$0.00	$300.00
Food	10	ea	$180.00	$0.00	$1,800.00
Hotel	2	n/a	$500.00	$0.00	$1,000.00
Subtotal					**$5,933.25**

Program Budget – Total

Budget Type	Cost
ADCS	$4,782.85
Payload	$3,275.00
EPS	$11,020.99
OBC	$2,345.32
Comms	$1,046.43
Other Costs	$5,933.25
Total	**$28,403.84**

Uplinked Commands

- Command library – one file for each command