space structures laboratory

CoreSat Systems Engineering

Fabien Royer

September 11th , 2017

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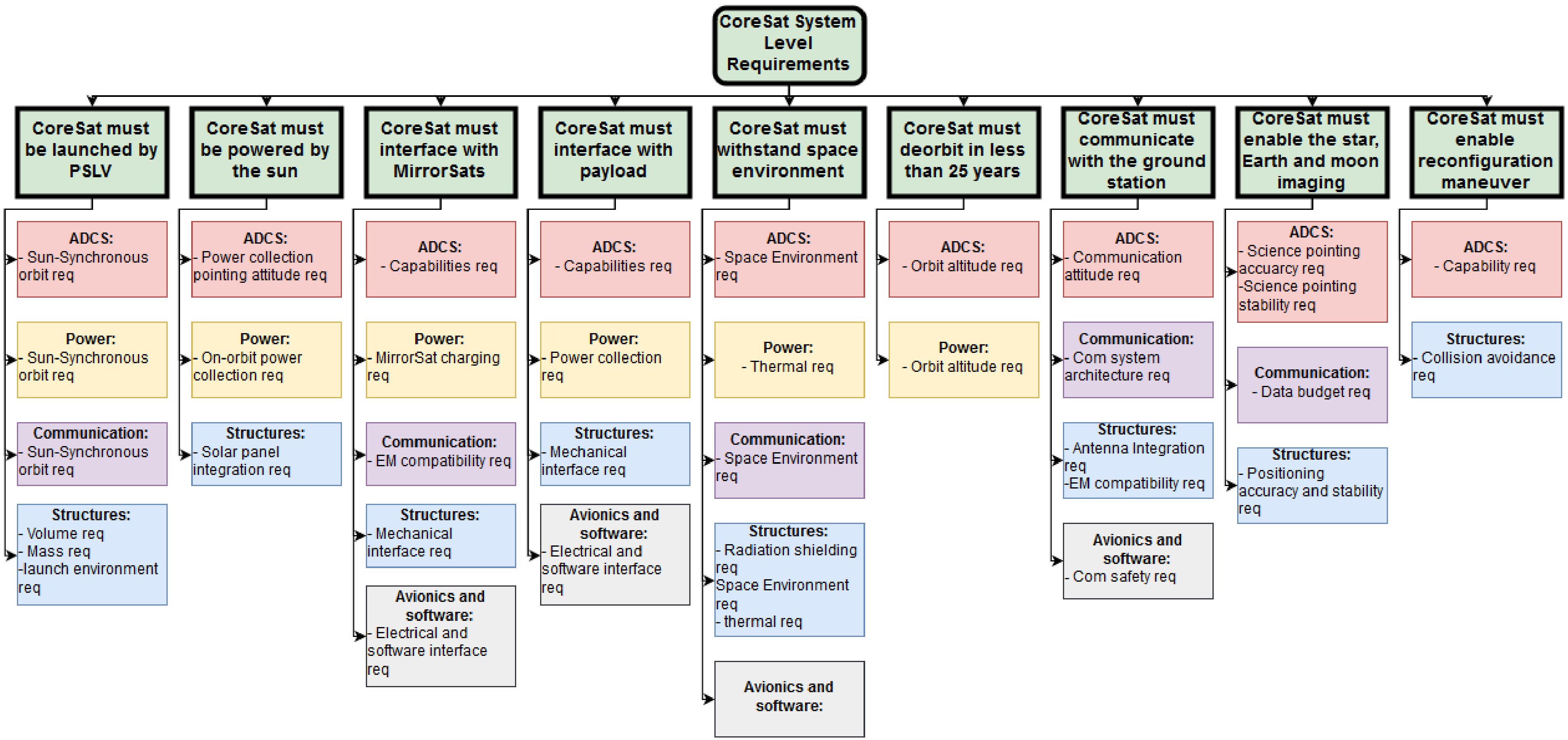
Outline

1) Overview of high level requirements
2) Orbit and lifetime analysis
3) On-orbit maximum power collection
4) Mass budget
5) Communication analysis
6) Mission Scenario
7) Open Issues and Planned Work

High Level Requirements

High level requirement flow-down:

- Subsystem requirements will be presented in dedicated presentations



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Lifetime Analysis and Orbit Selection

Potential Scenarios:

1) Boom does not deploy

- worst configuration: narrow configuration, undeployed, side

2) MirrorSats separations do not occur

- worst configuration: narrow configuration, side

3) 1 MirrorSat separate and do not redock

- worst configuration: narrow L, side or tumbling MirrorSat alone

4) 1 MirrorSat separate and redock

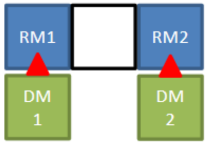
- worst configuration: L configuration, side or tumbling MirrorSat

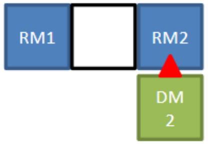
5) 2 MirrorSats separate and do not redock

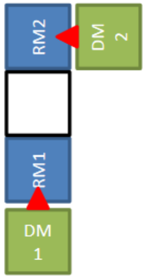
- worst configuration: CoreSat side or tumbling MirrorSat

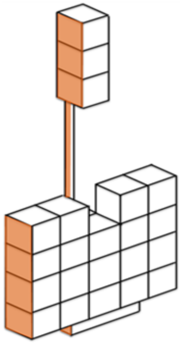
6) 2 MirrorSats separate and redock

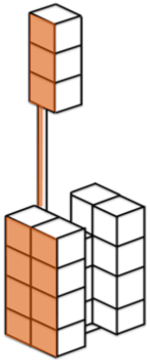
- worst configuration: I configuration, side











Lifetime Analysis and Orbit Selection

Hypotheses:

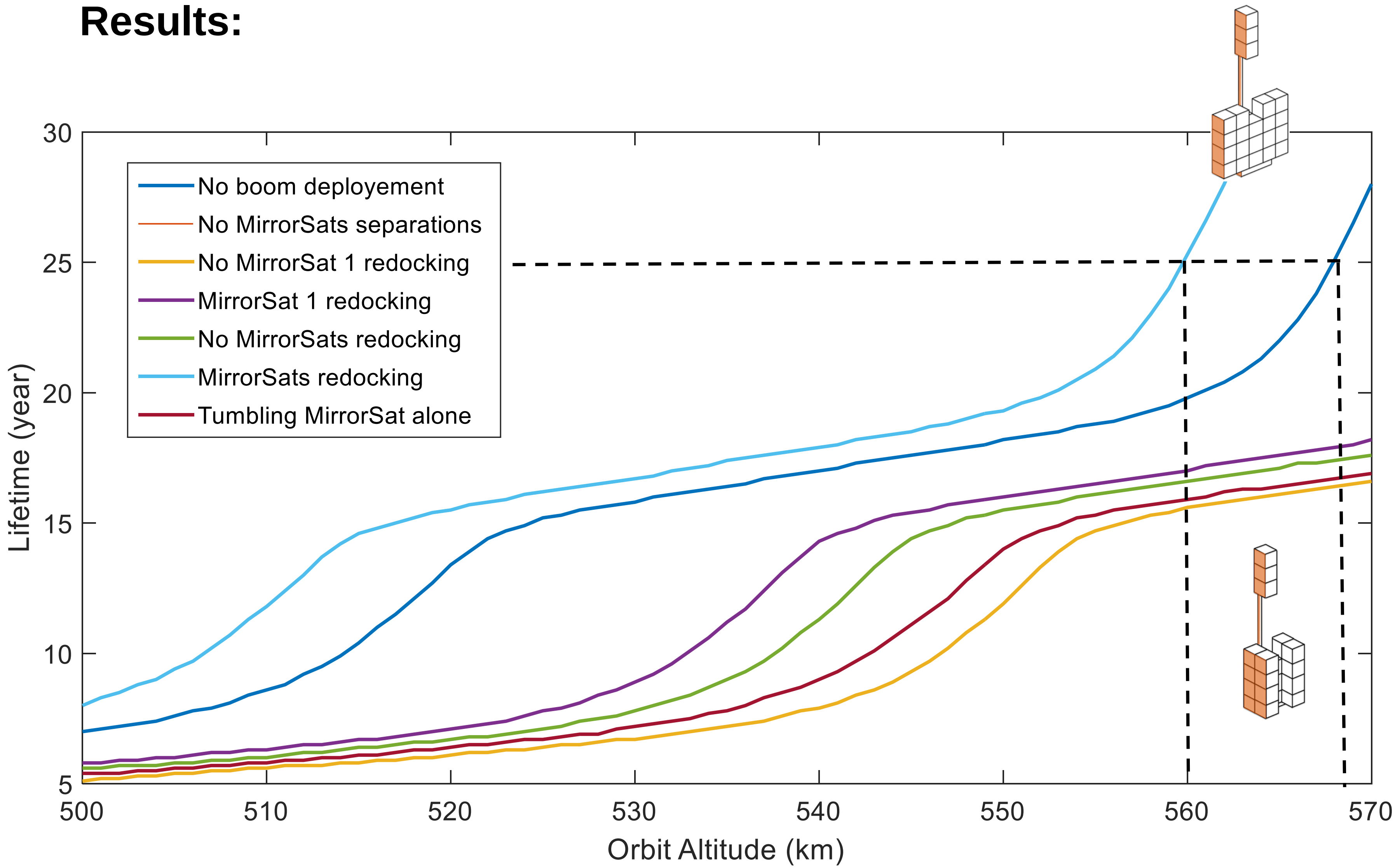
- AAReST mass: 24 kg
- Solar cycles and atmospheric density model: Jacchia 1970
- Solar pressure is negligeable
- Drag coefficient: 2.2
- Orbit considered: noon/midnight sun-synchronous orbit (worst case for power collection)

Framework:

- Software: AGI STK

Lifetime Analysis and Orbit Selection

Results:



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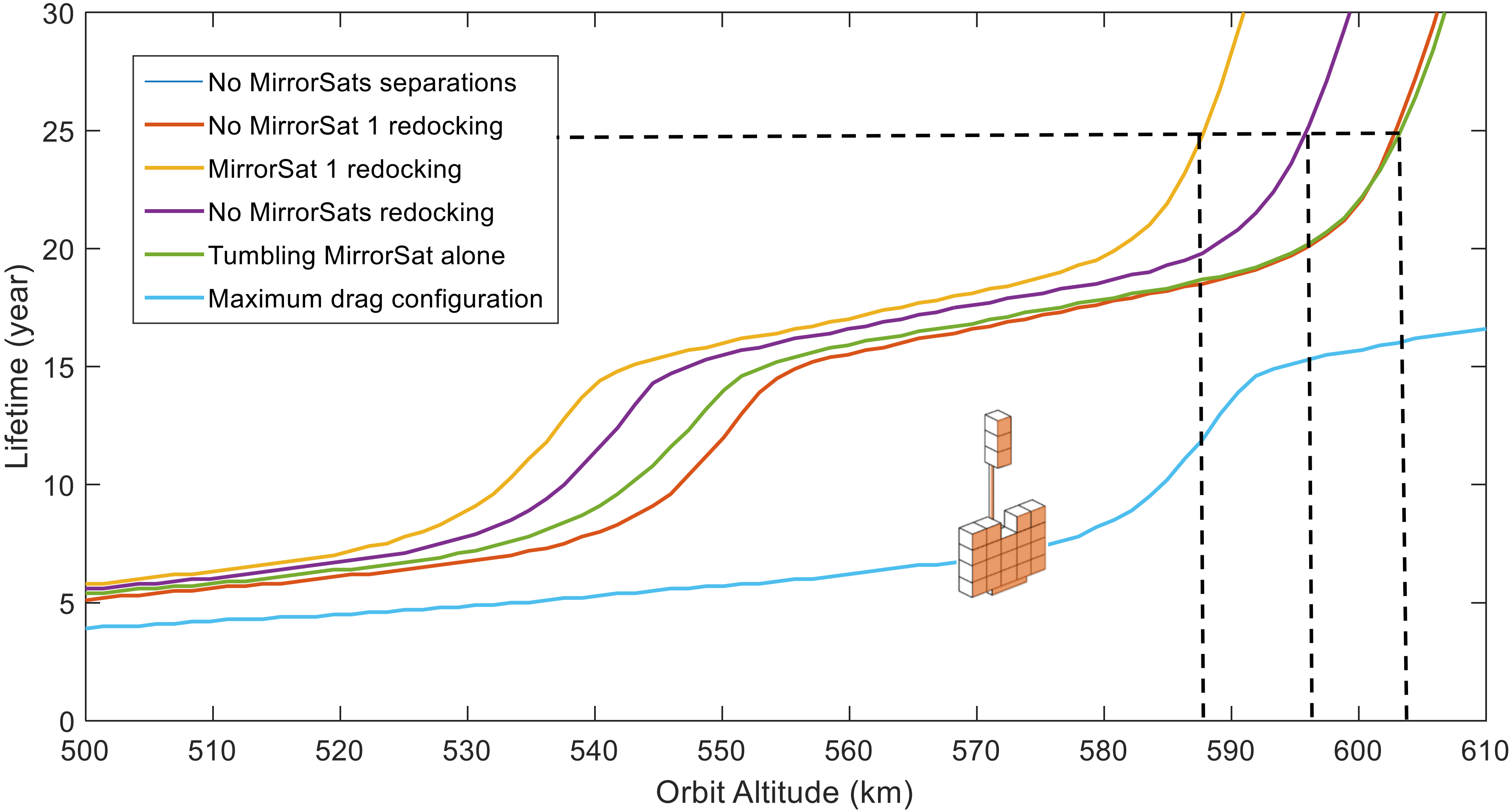
Lifetime Analysis and Orbit Selection

Results:



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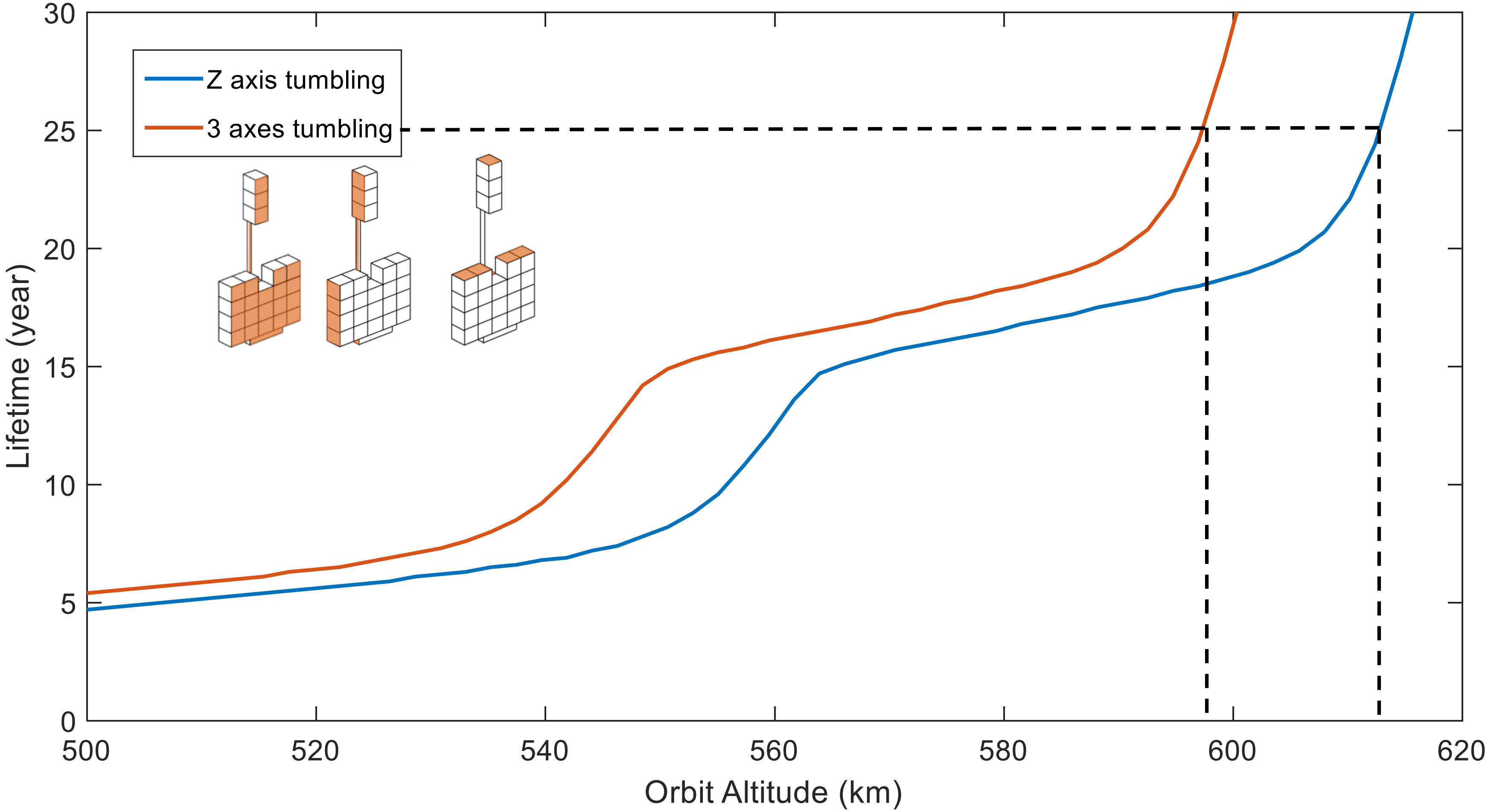
Lifetime Analysis and Orbit Selection

Results:



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Lifetime Analysis and Orbit Selection

Conclusion:

- Worst case lifetime scenario corresponds to nominal wide configuration:
  - ➢ Limit orbit: 560 km altitude
- Mitigation technique to decrease lifetime:
  - ➢ Make wide AAReST configuration tumbling at the end of the mission

    Limit orbit for Z axis tumbling: 614 km altitude

    Limit orbit for 3 axes tumbling: 598 km altitude

- Ideal PSLV scenario:
  - ➢ Direct launch to 550 km altitude (or less) sun-synchronous orbit (separation before primary payload)

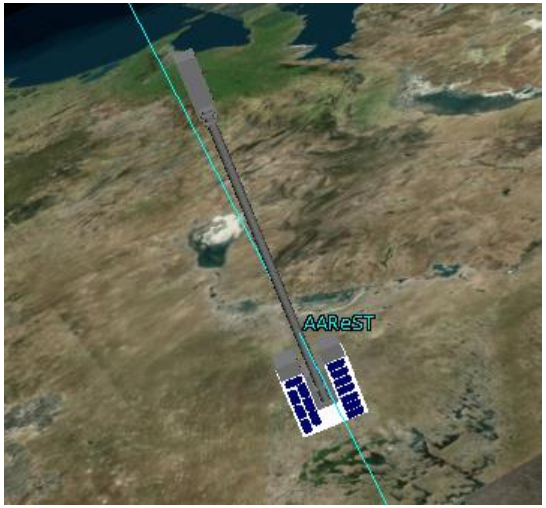
or

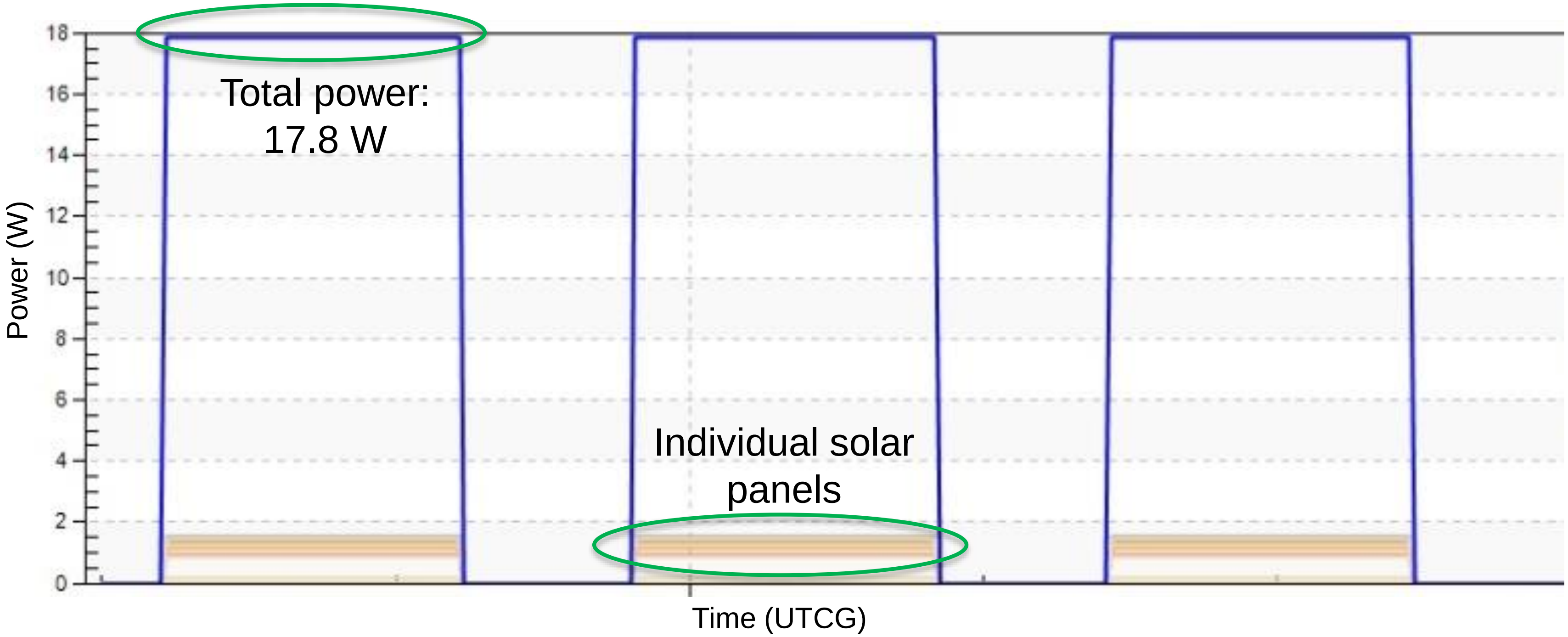
  - ➢ Upper stage goes down to 550 km altitude sun-synchronous orbit after launching primary payload

On-orbit Power Collection

Optimal charging phase:

- Altitude: 600 km
- Noon / midnight SSO
- Attitude: Sun pointing (-X)
- Solar panel efficiency: 0.30





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Mass Budget

Subsystem	Component	Max Mass (g)	Contingency (%)	Max Mass + contingency (g)
ADCS	Docking Units	1700	20	2040
ADCS	ADCS Stack + Reaction wheels	1106	10	1216.6
ADCS	Star Camera	166	20	199.2
ADCS	Payload Interface Board	200		200
Avionics/Comms	Transceiver	78	10	85.8
Avionics/Comms	Antenna	100		
Power	Solar Panels	520	30	676
Power	EPS + Batteries	675	10	742.5
Power	Mounting board	270	20	324
Structures	Chassis	1350	20	1620
Structures	Surface Structural Panels	140	10	154
Structures	Launch Interface	600	10	660
Structures	Launch Interface plate	860	15	989
Structures	HDRM - Frangibolts (2 for antennas and 2 for MirrorSats)	400	10	440
Structures	Circuit Boards (c.6-8)	560	30	728
Core Sat Total		**8725**		**8907.1**
	Wiring	436	30	566.8
From January 2017	MirrorSat (incl. propulsion)	8000	15	9200
	Camera	2700	0	2700
	Rigid Mirror Box	1900	0	1900
	Deformable Mirror Box	1200	0	1200
	Boom + Camera Interface + CoreSat Interface	600	0	600
Total System Mass		**23561**		**24507.1**

<u>Contingency scale:</u>
- 0 = verified
- 10 = COTS
- 15 = COTS + fab
- 20 = fab only
- 30 = very rough

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Communication Link Budget

Data Budget:

- **Max data rates:**
  - UHF: 9.6 kbps
  - VHF: 1.2 kbps
- **Downlink over UHF required (435 – 438 MHz)**
- **Assume 8 min passes; max. time between passes is 10 hrs.**
- **Docking video taken and downlinked over several passes**

Mode	Health data [kbps]	Ops data [kbps]	Data rate required for single pass [kbps]	Notes
Nominal	0.31	0	0.31	
Debug	8.86	0	8.86	
Docking data	0.31	0.27	0.58	ADCS and health data
Star imaging	0.31	1.4*	1.71	2 windowed SHWS images, 1 windowed star image
Earth/Moon imaging	0.31	5.1*	5.41	PNG image (no windowing)

* Computed from image size from flight detectors

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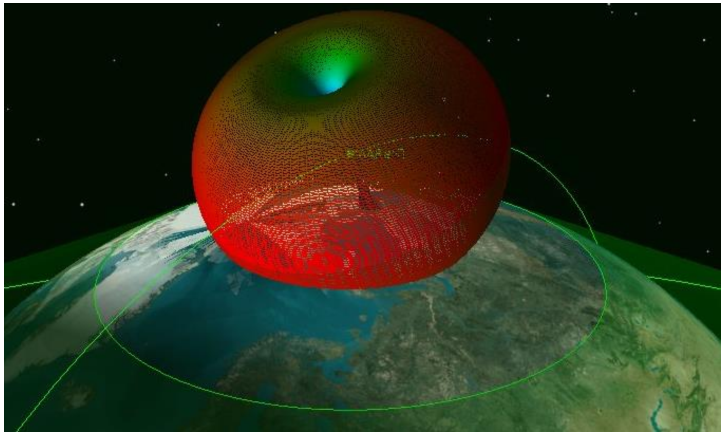
Communication Link Budget

Hypothesis:

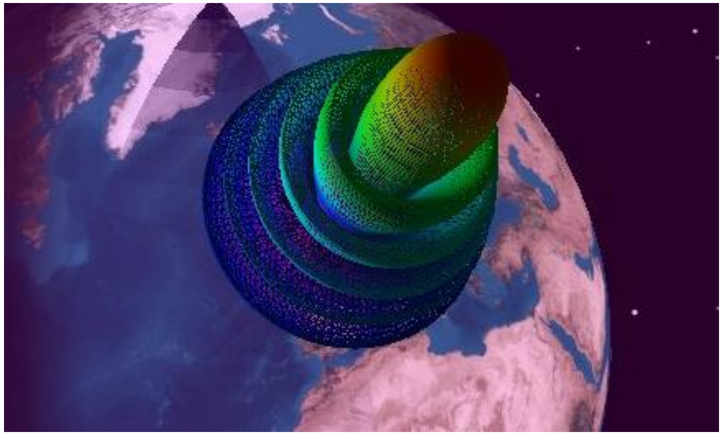
AAReST side

- Focus on UHF downlink: 438 MHz
- Data rate: 9.65 Kbps
- Antenna modeled as dipole: 0.17 m length
- Modulation scheme: FSK
- -X face pointing at the Sun
- Noon/midnight sunsynchronous orbit



Ground Station side

- Single ground station Guildford, UK
- 2.5 m diameter antenna
- Tracking AAReST
- System noise temperature: 135 K
- 85° cone visibility



Framework: AGI STK

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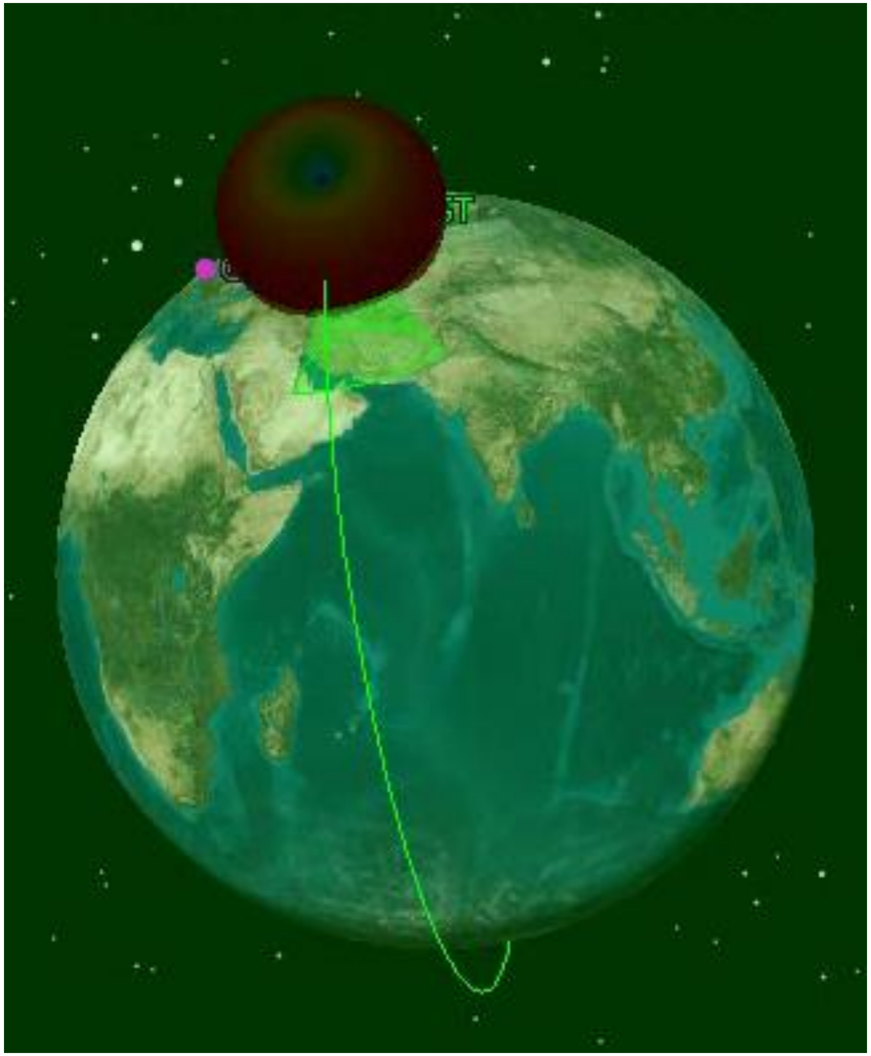
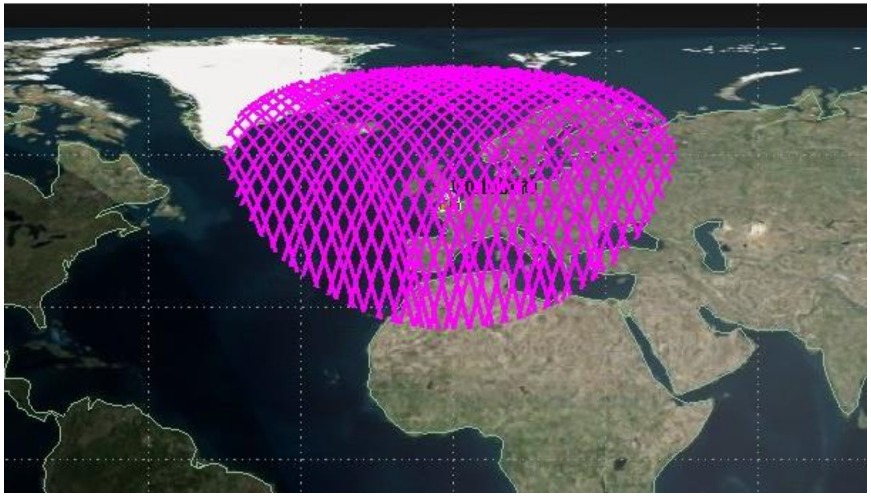
Communication Link Budget

Access intervals:





Statistics over 1 year

Max duration	14.1 min
Min duration (min)	0.15 min
Average duration (min)	10.8 min
Average passes per day	8

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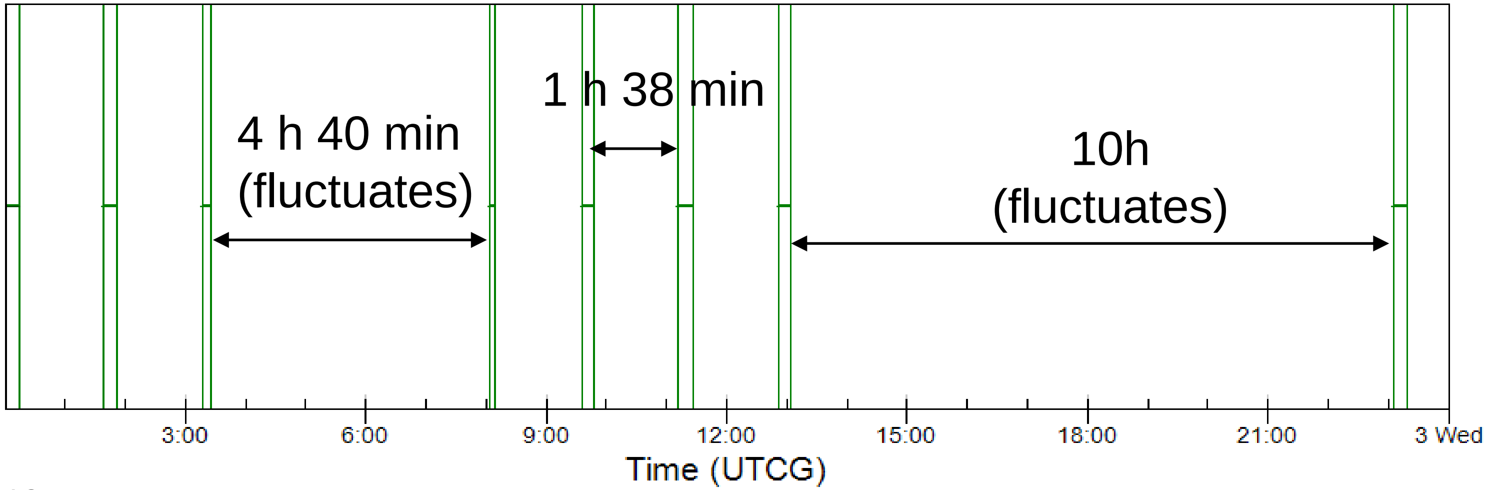
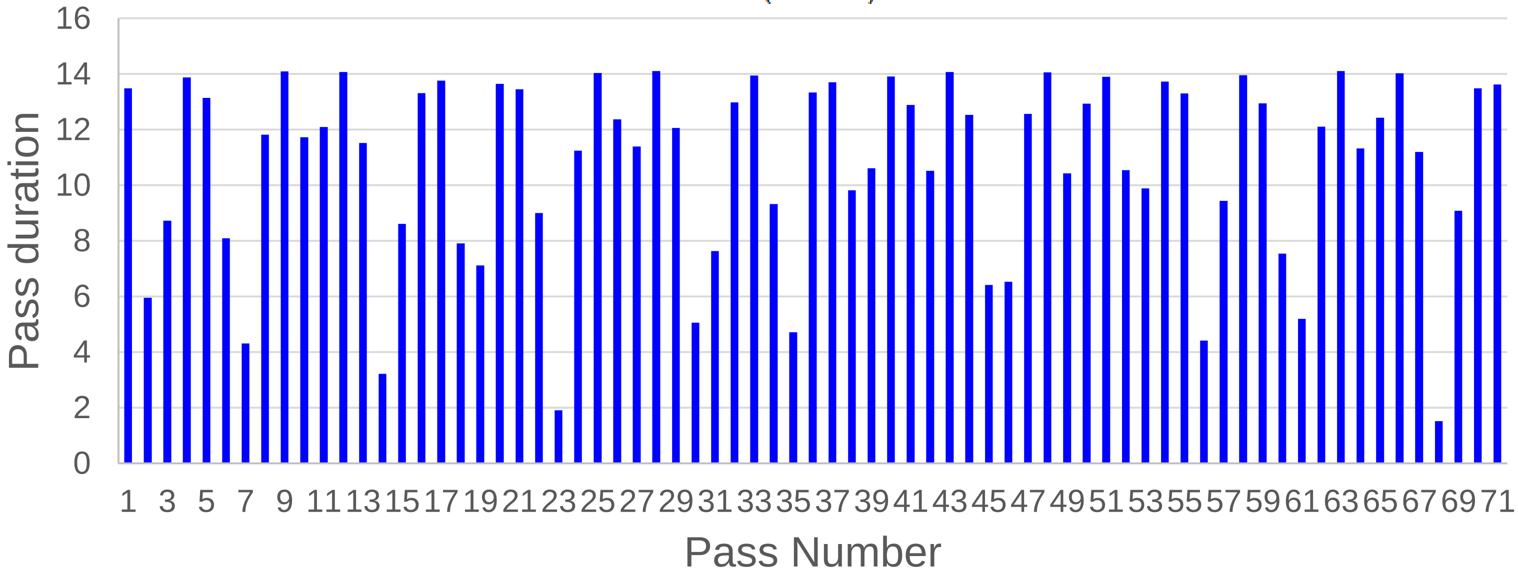
Communication Link Budget

Access intervals (one day):





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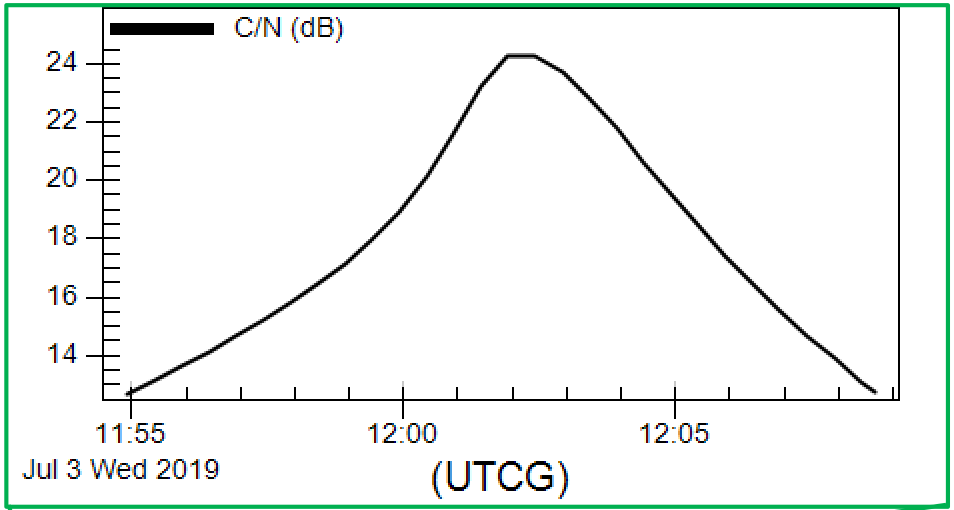
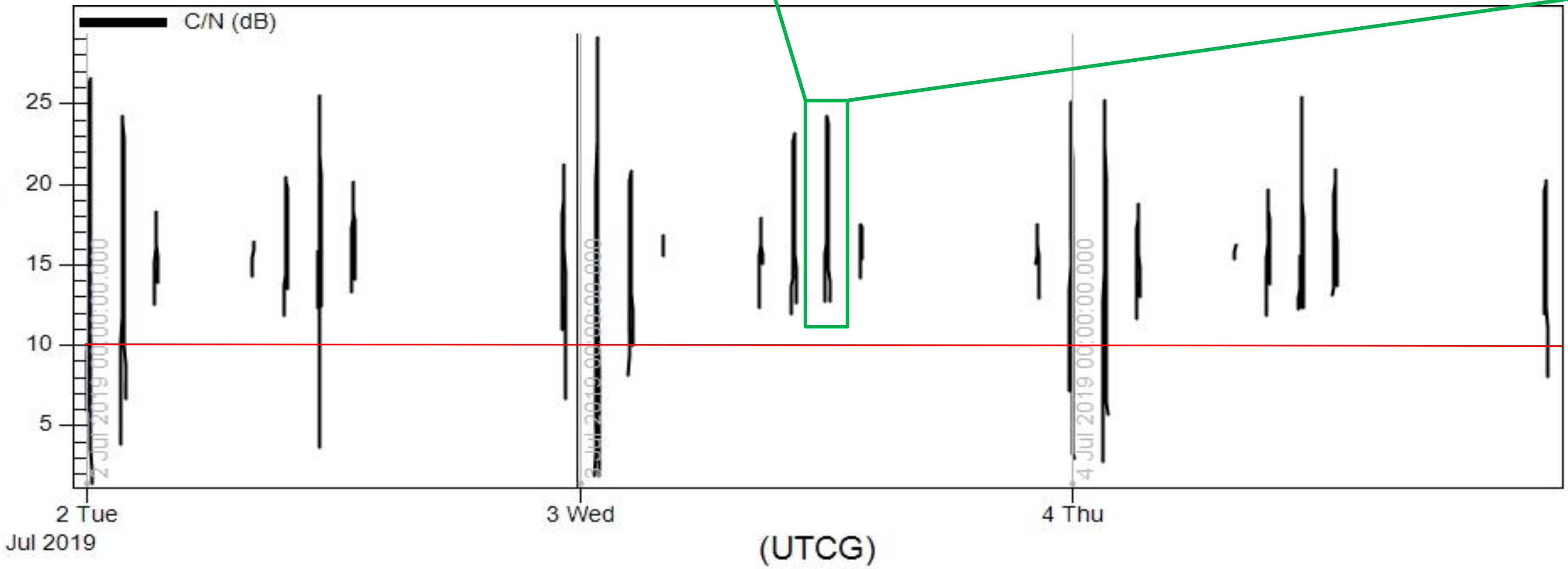
Communication Link Budget

Link Margin:

- Carrier to noise ratio desired: 10 dB
- Transceiver input power: 0.8 W
- Bit error rate less than 10^{-10}
- Average carrier to noise ratio: 15.4 dB





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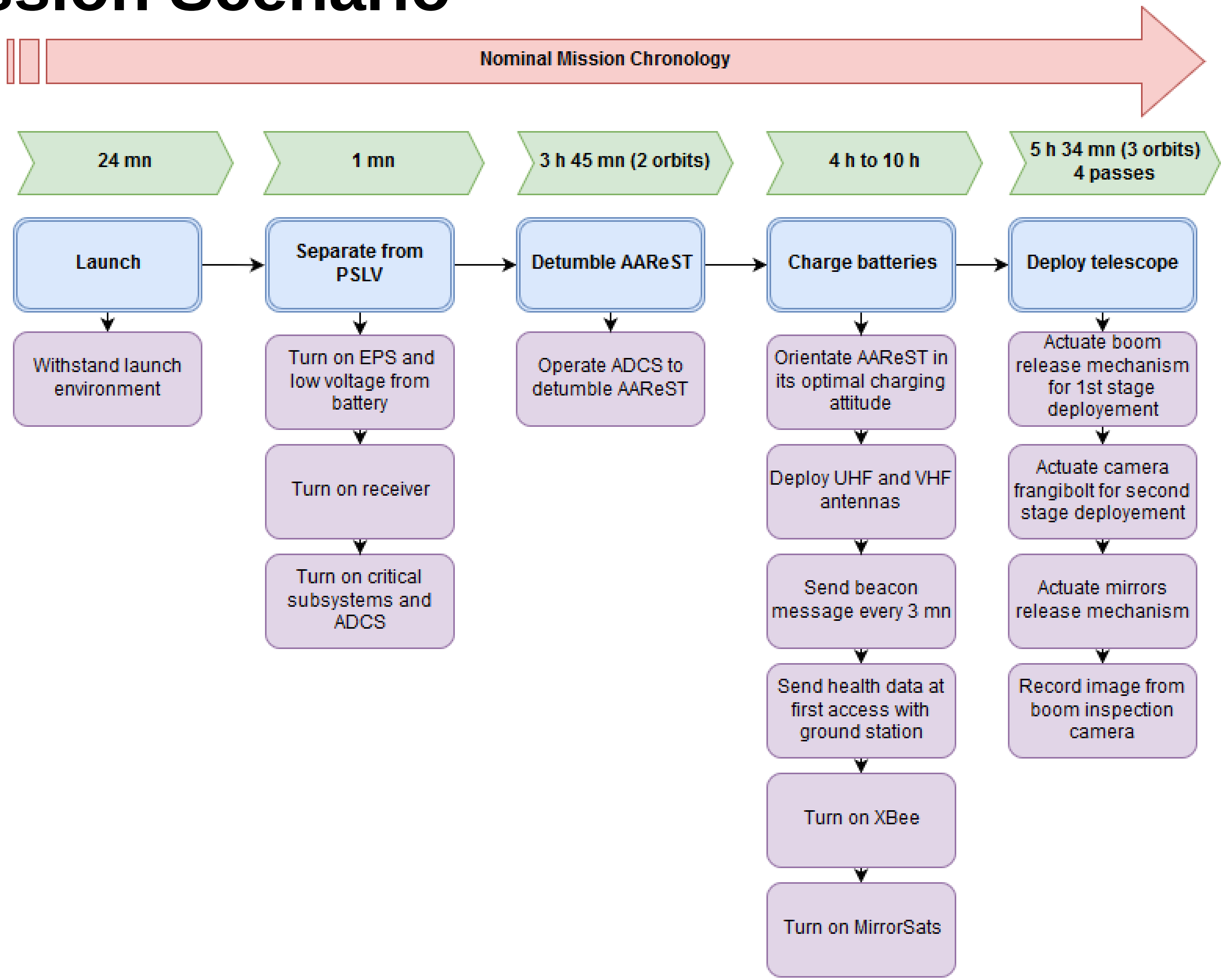
Mission Scenario



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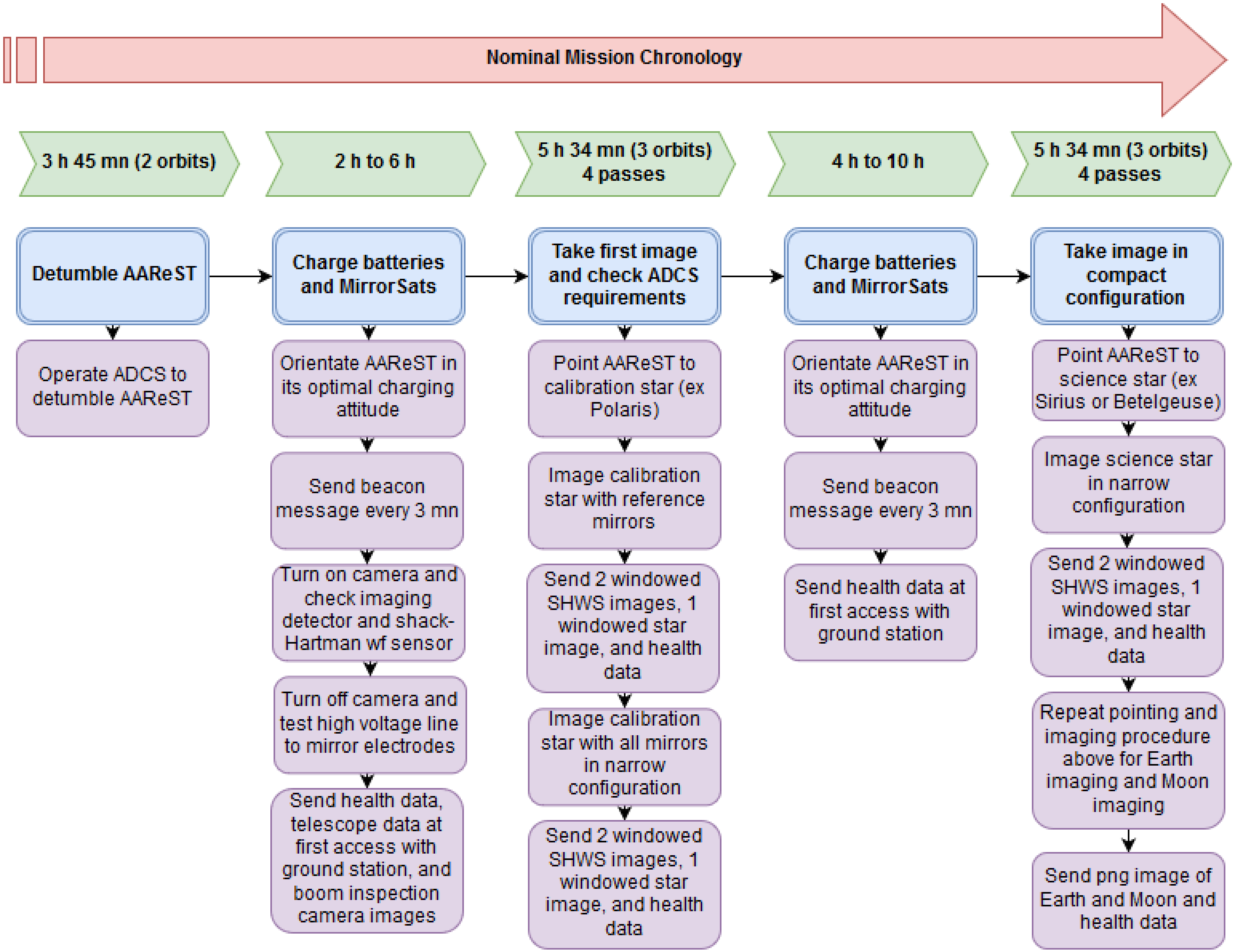

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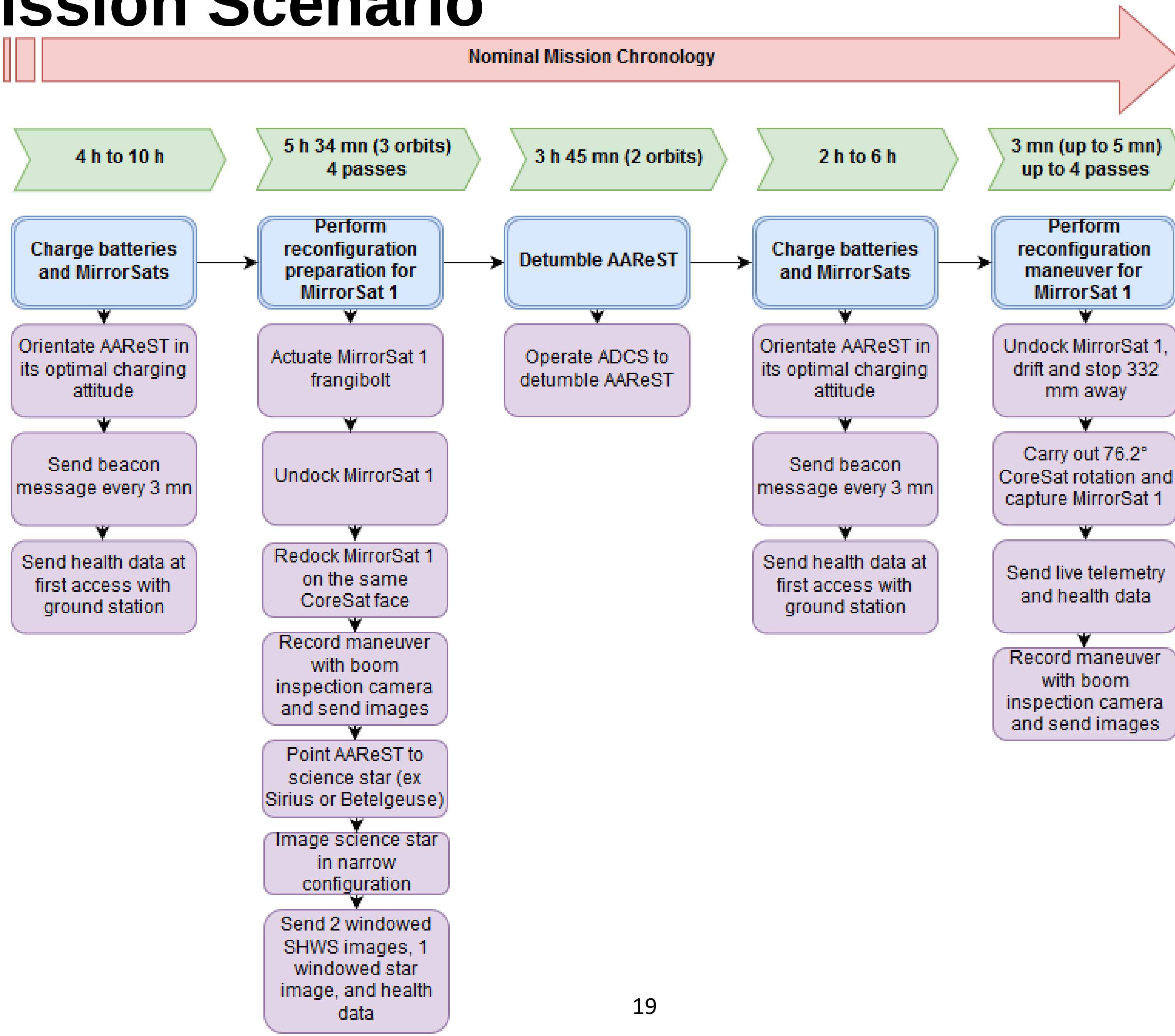
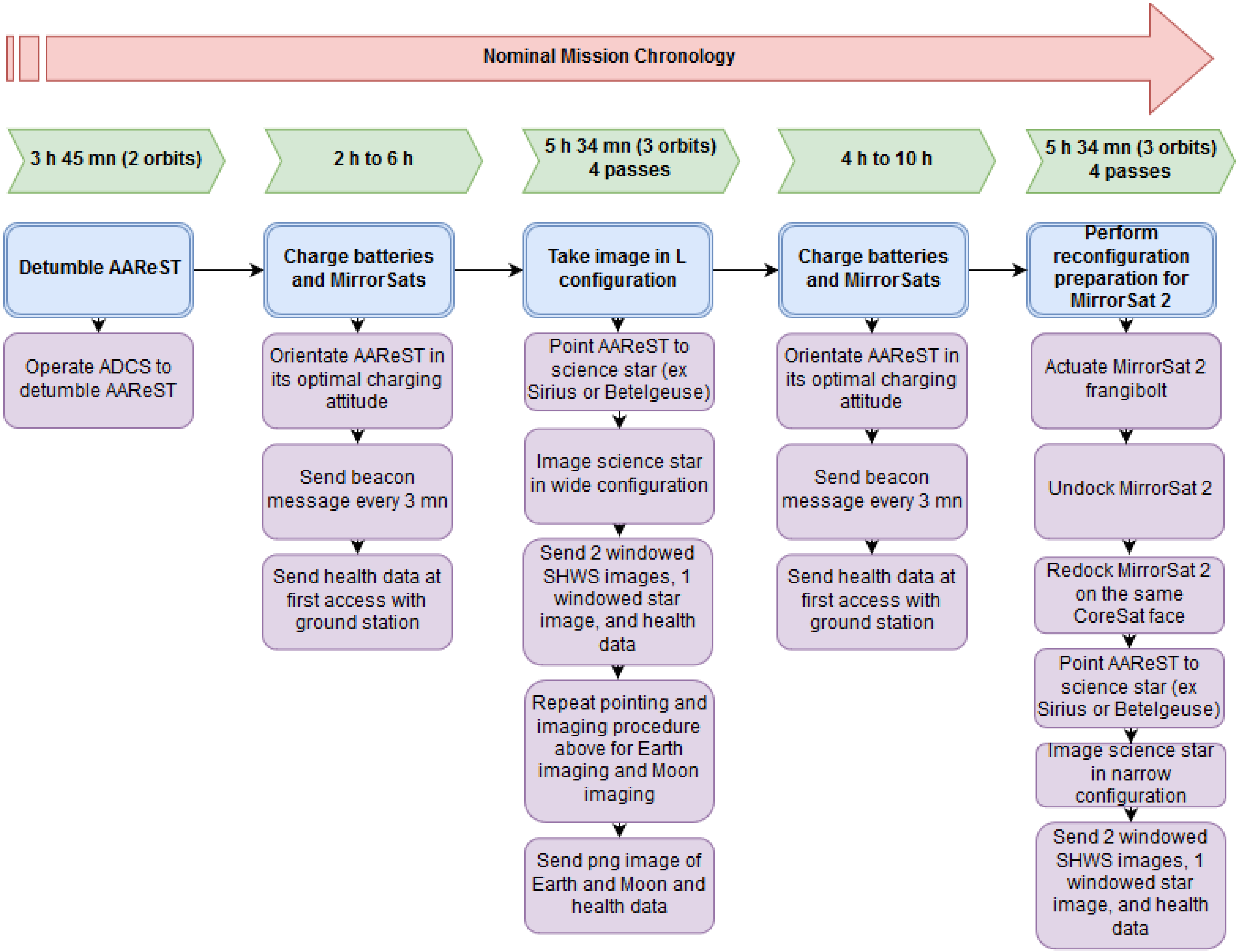


Mission Scenario



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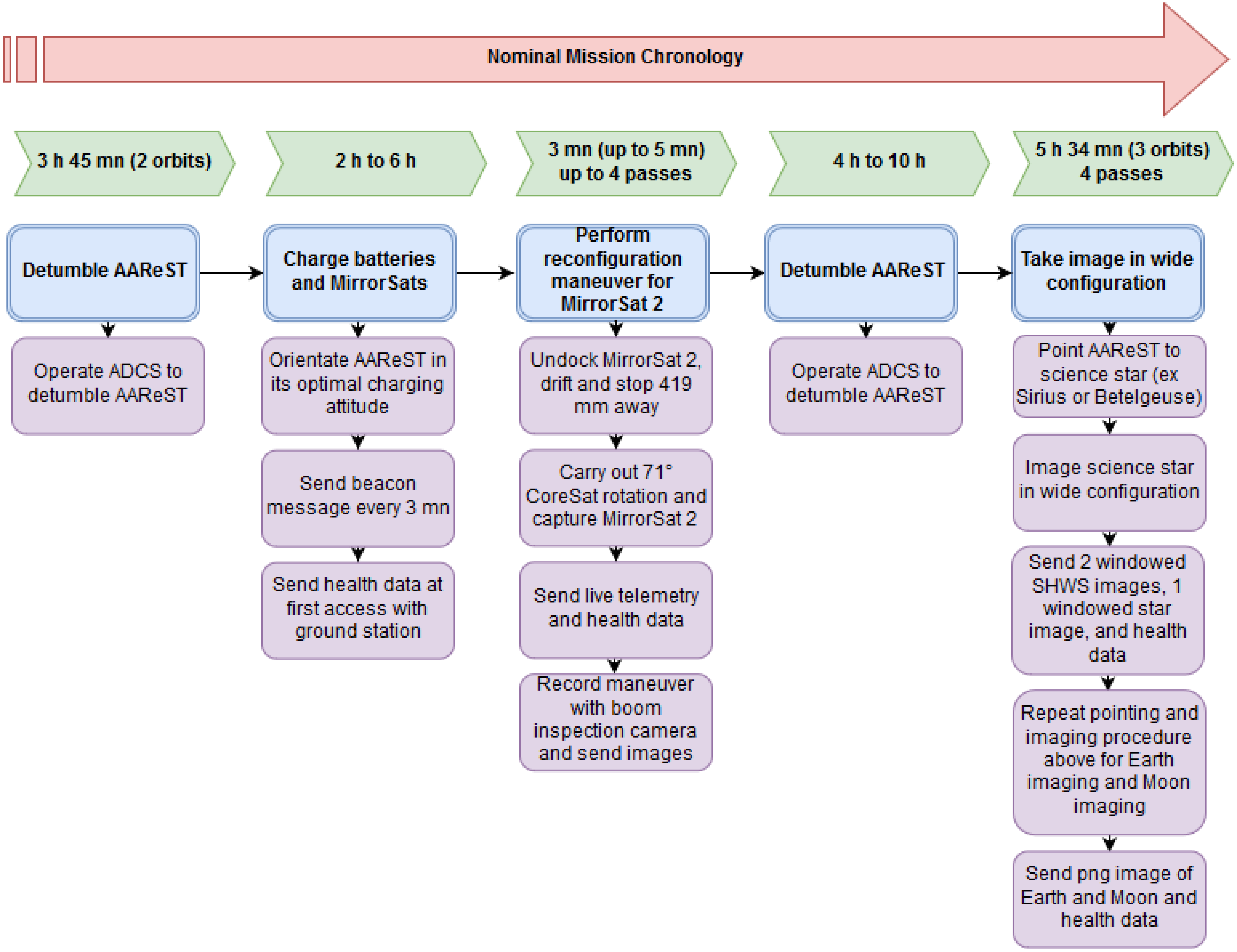
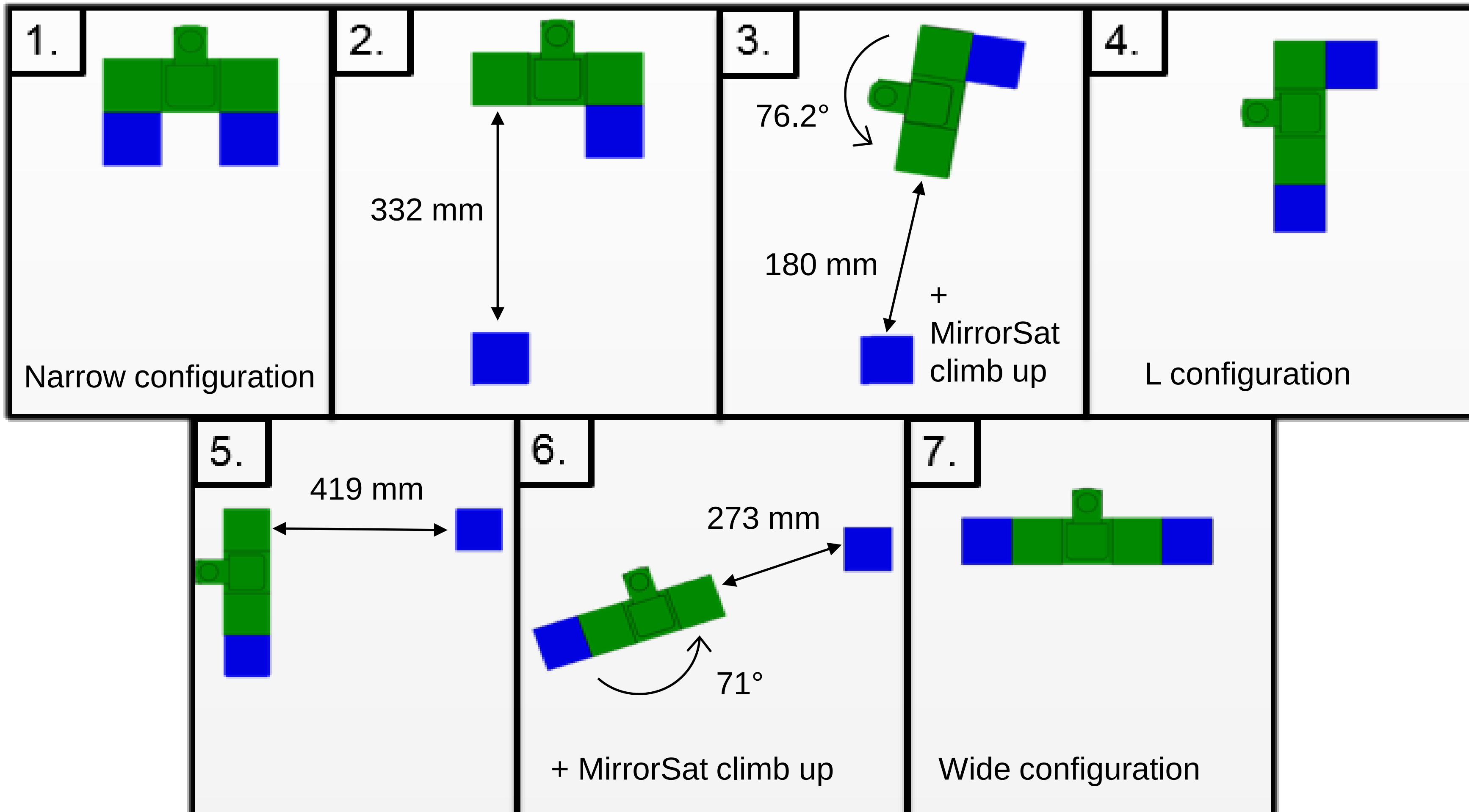
Mission Scenario



Mission Scenario

Docking Maneuver:



Open Issues and Planned Work

Open issues:

- Need to develop docking maneuver requirements
- Need to develop complete CONOPS documentation

Planned work

- Develop Integrated STK model for full mission scenario simulation
- Develop (and revisit) full AAReST integration and testing

space structures laboratory

AAReST Attitude Determination and Control (ADC) System Design

Michael Marshall

September 11th , 2017

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Outline

- **Design overview**
  - Driving requirements
  - Operational modes
  - Additional requirements
  - Primary design criteria
  - ADCS architecture block diagram
  - Overview of CubeSpace ADCS
  - Requirements Verification
- **ADCS Integration and Interfaces**
- **Future Work**

Driving Requirements

Detumble:

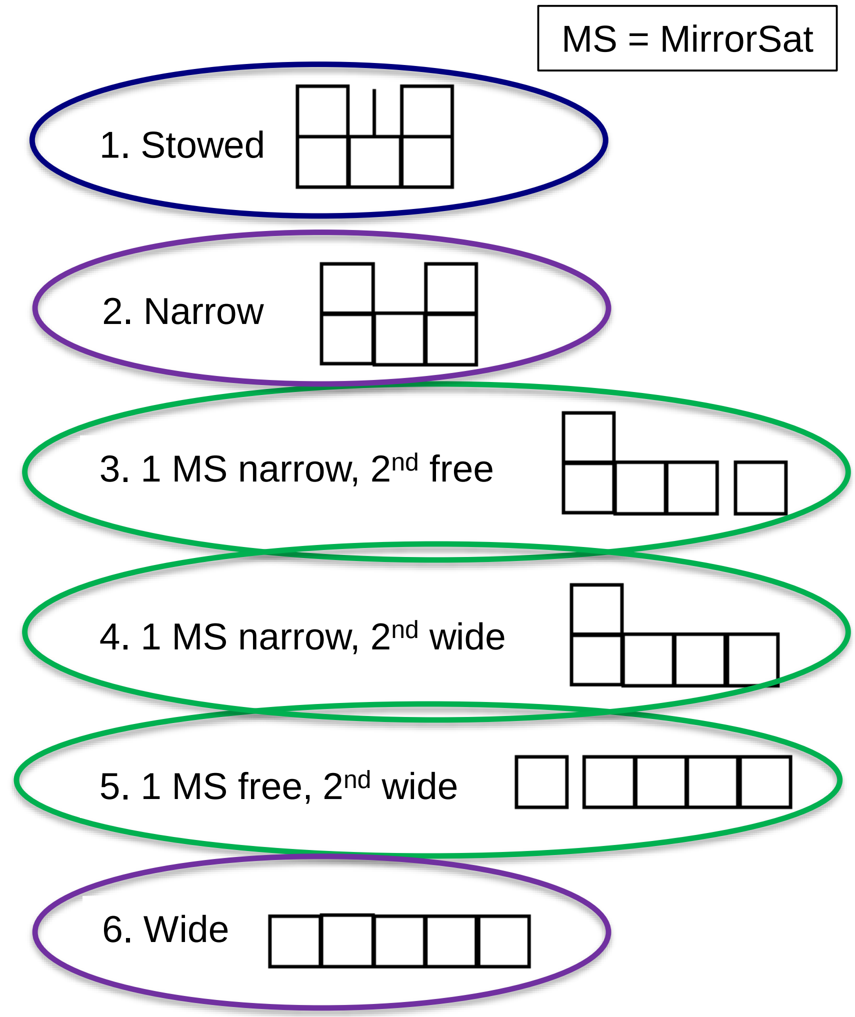
- Reduce body angular rates < 0.3°/s in 4 orbits or less

Science:

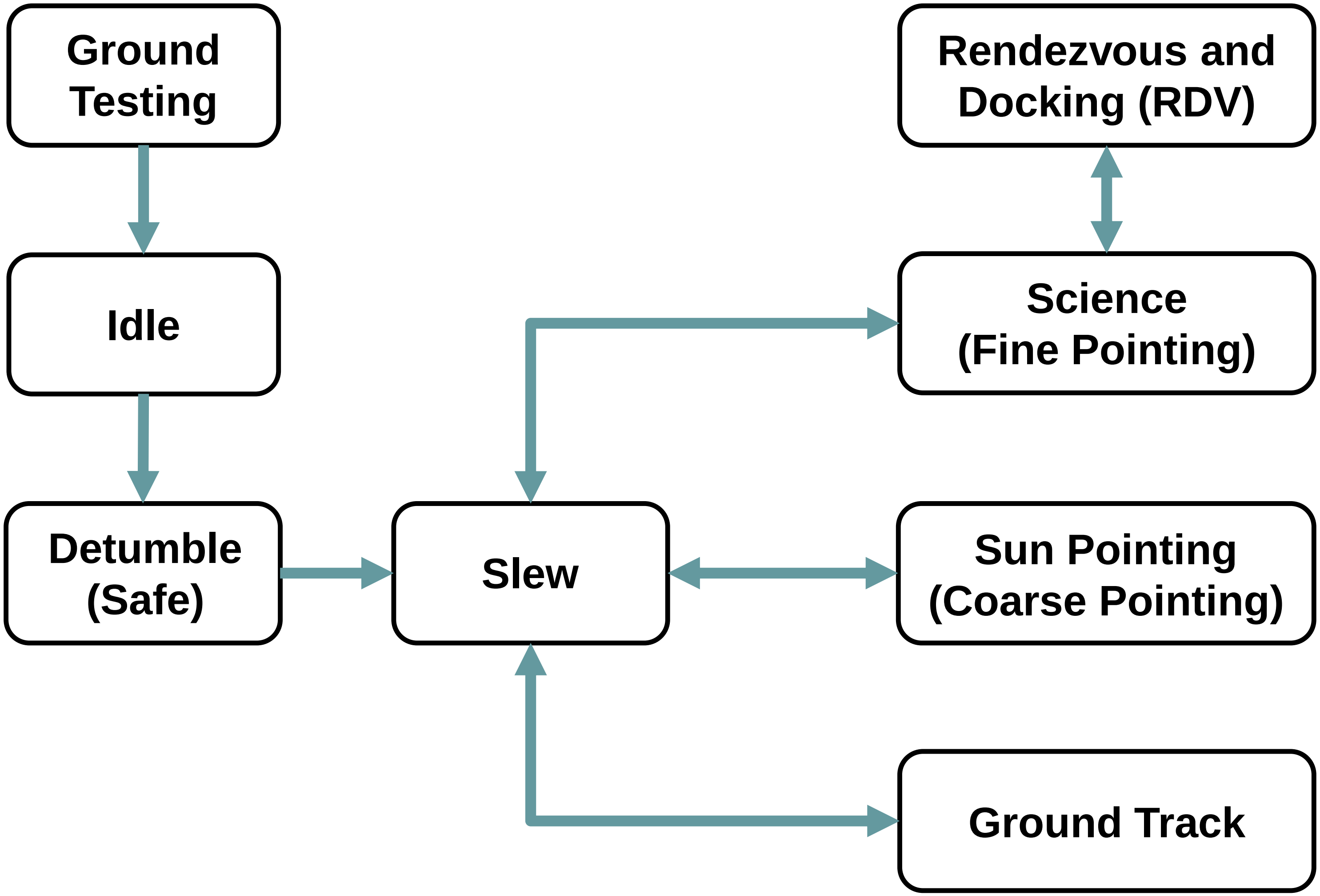
- Pointing accuracy – error < 0.1° 3σ per axis
- Attitude stability – jitter < 0.02°/s 3σ for 600s during science operations

Rendezvous and Docking (RDV):

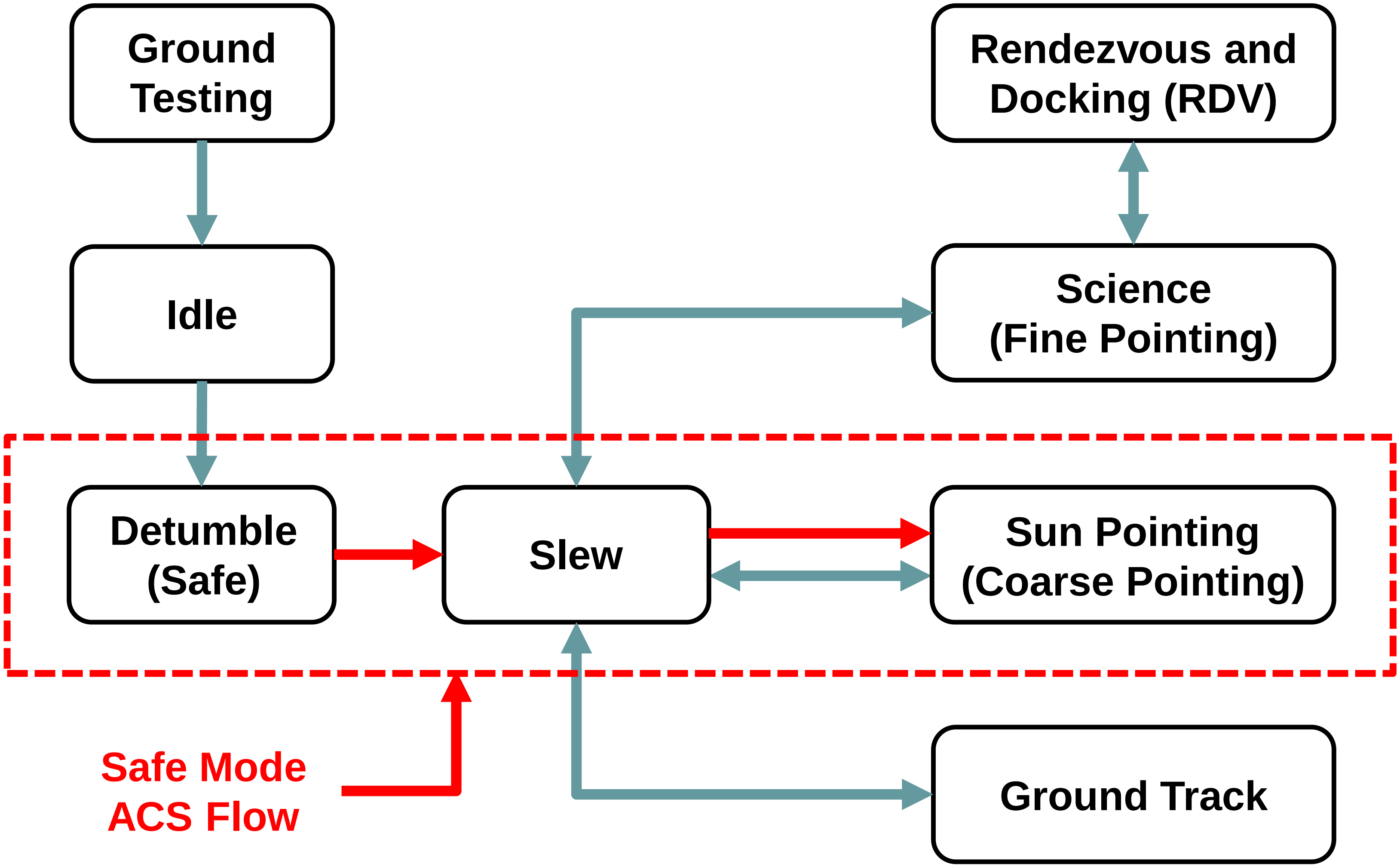
- Rotate 90° in 60s about boom axis



Operational Modes

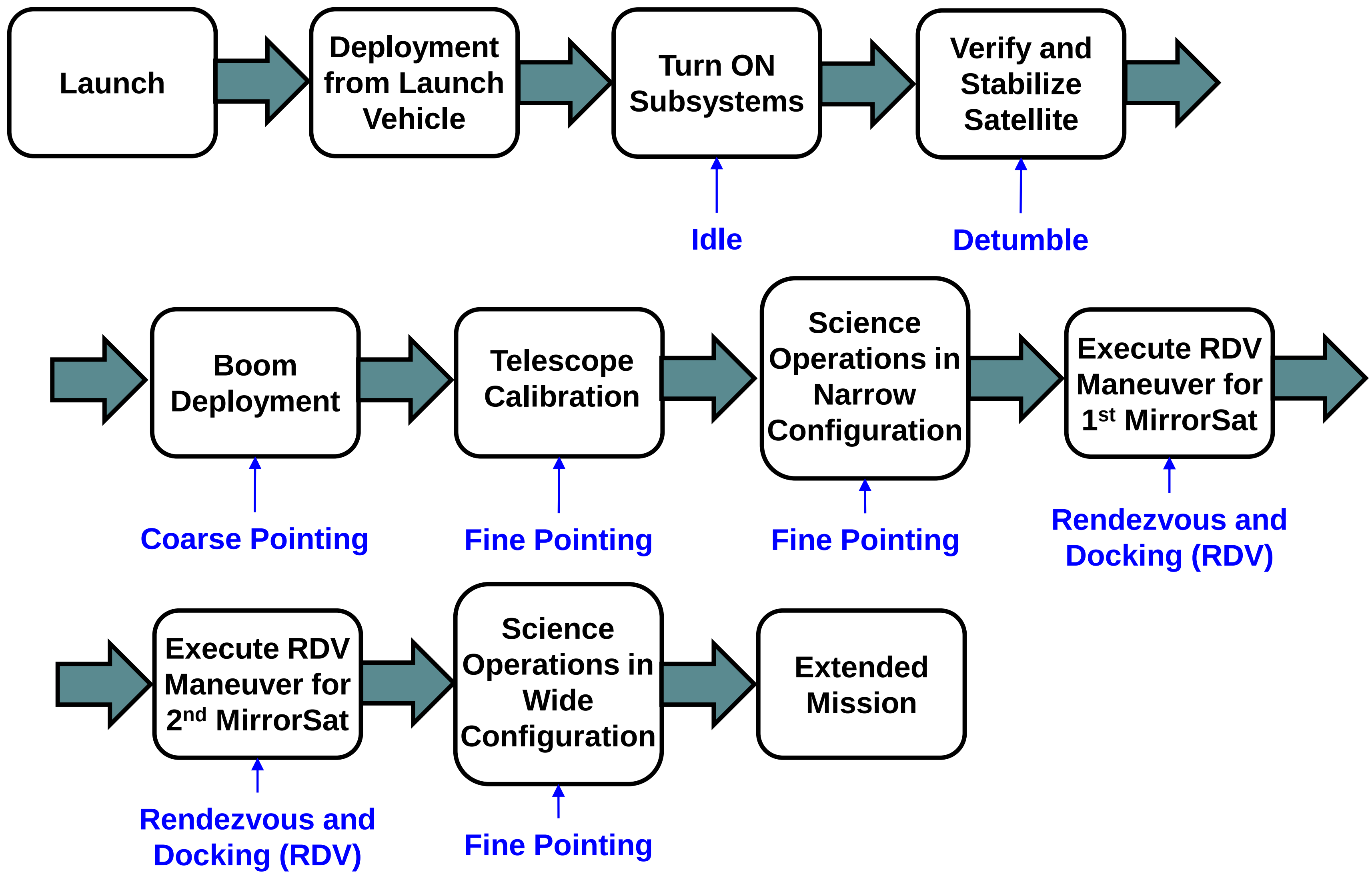


Operational Modes – Safe Mode ACS Flow



Overlap with Mission Chronology

ADCS Operational Modes



ADCS Generated Requirements

Operational Mode	Additional Requirements	Rationale
Ground Testing	• n/a	• n/a
Idle	• n/a	• n/a
Detumble (Safe)	• n/a	• n/a
Slew	• Reorient spacecraft to within 1° of desired attitude	• Required to change operational mode
Rendezvous and Docking (RDV)	• n/a	• n/a
Science (Fine Pointing)	• n/a	• n/a
Sun Pointing (Course Pointing)	• Maintain attitude within ± 10° of optimal charging angle	• Maximize power generation
Ground Track	• Maintain commanded antenna orientation with TBD degrees	• Maintain proper antenna orientation during pass
All	• Have capability to desaturate reaction wheels	• Required to maintain control of spacecraft

Primary Design Criteria

- Meets system and ADCS requirements
- Integrated solution that includes all sensors, actuators, and software
- Reaction wheels with sufficient torque and angular momentum storage to:
  - Execute z-axis slew maneuver for RDV
  - Reject worst-case disturbance torques during science operations (with continuous momentum dumping from torque rods)
- Low cost, (relatively) short lead time
- Solution: CubeSpace 3-Axis ADCS w/Star Tracker

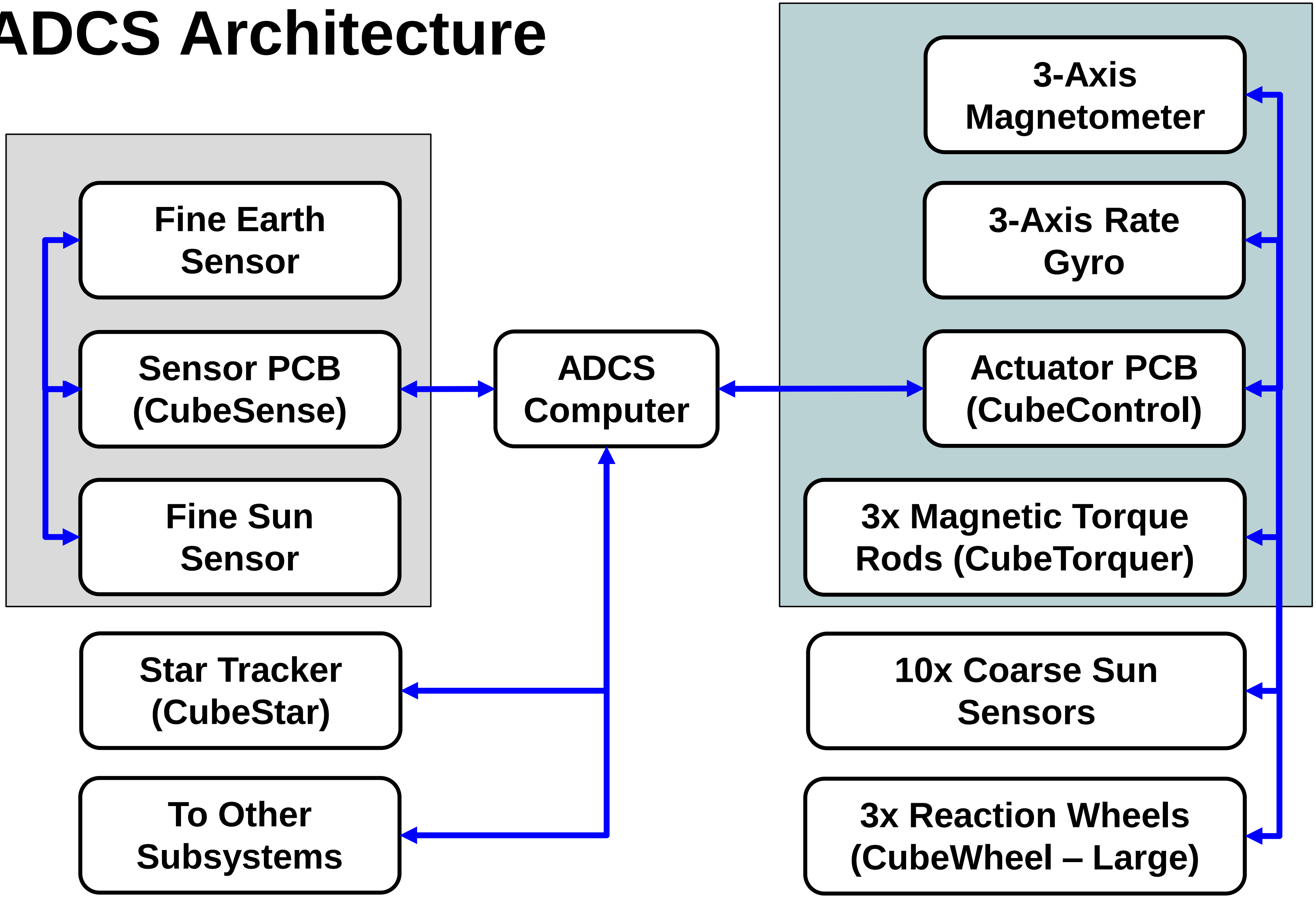
Overview of CubeSpace 3-Axis ADCS

- Integrated 3-axis ADCS capable of providing accurate and precise pointing for CubeSats
- Advertises pointing and estimation accuracies in excess of 0.1° 3σ per axis (during eclipse with star tracker)
  - Lower performance in sun
- Includes ADCS software and CubeComputer OBC
- Flight heritage for most components (via QB50)
- 5 month lead time

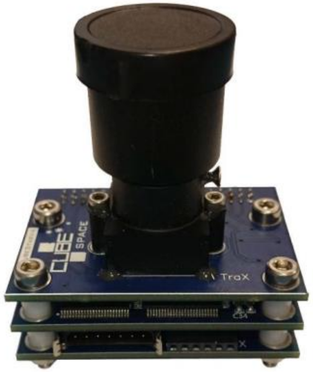
CubeSpace 3-Axis ADCS Components

- **Includes:**
  - CubeComputer – radiation tolerant on-board computer (OBC) that doubles as AAReST OBC
  - CubeControl – sensor and actuator interface board w/3-axis rate gyros
  - CubeSense – fine earth and sun sensors
  - 3x Large CubeWheels – mounted separately from stack on orthogonal body axes
  - 10x coarse sun sensors – for coarse attitude determination (e.g. during detumbling)
  - 2x CubeTorquer Rods + 1x CubeTorquer Coil – magnetic torque rods for detumbling and momentum desaturation
  - CubeStar – star tracker for quaternion and angular rate estimation during fine pointing/science operations

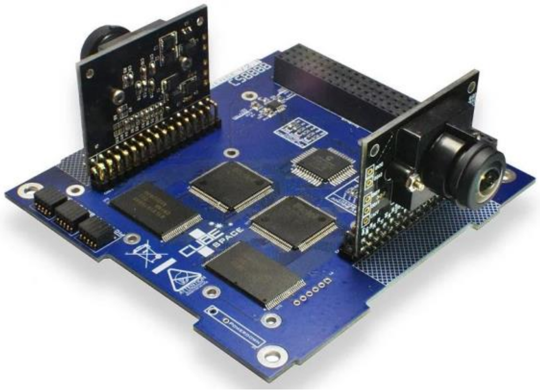
ADCS Architecture



ADCS Sensors



- CubeStar – star tracker
  - 3σ estimation accuracy - 0.03° 3σ yaw/pitch, 0.09° roll (about boresight)
  - Typically averages 3-10 star vector measurements per second using Extended Kalman Filter (EKF)
- CubeSense – fine Earth and sun sensors
  - Earth sensor 1σ estimation accuracy – 0.1° (with full earth in FOV)
  - Sun sensor 1σ estimation accuracy – 0.1°
- CubeControl – MEMs rate gyros
  - 10 milli-deg/s RMS noise
- Magnetometer
  - 0.5° RMS accuracy in roll, pitch, yaw



ADCS Actuators

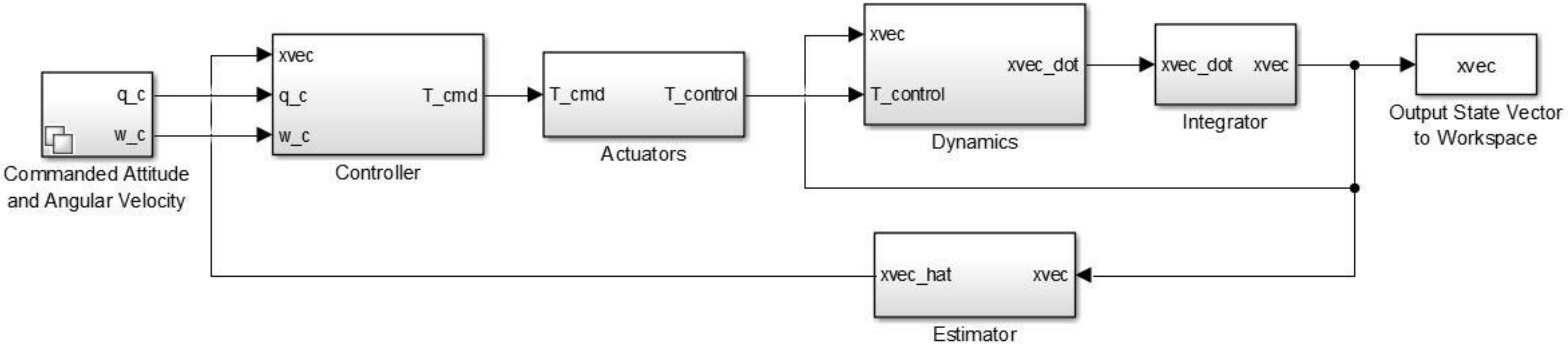
- Large CubeWheel – reaction wheels
  - Speed range ±6000 rpm
  - Maximum torque – 2.3 mN-m
  - Maximum angular momentum storage – 30.7 mN-m-s
  - 220g/wheel
- CubeTorquer – magnetic torque rods
  - 0.4 A-m^2 saturation magnetic moment

Requirements Verification Overview

- Developed Simulink tool to analyze ADCS performance in each operational mode
- Conducted Monte Carlo analyses to assess ADCS performance over a wide range of attitudes
  - Typically consider 100 random attitudes in a nominal 550 km sun-synchronous orbit
  - Consider all *relevant* spacecraft configurations (but will only present representative results from a single configuration)
  - Analyses conducted to asses pointing accuracy and stability and system's capability to desaturate reaction wheels, all during science operations
- Separate analysis to show feasibility of z-axis slew maneuver for RDV

Requirements Verification Tool

- Dynamics
  - 2 body orbit dynamics
  - Full 3D nonlinear Euler equations for rotational motion
  - Quaternions for attitude propagation
  - Reaction wheel model with static and dynamic imbalances
  - Simple magnetorquer model
  - Models for gravity gradient, magnetic and drag disturbance torques



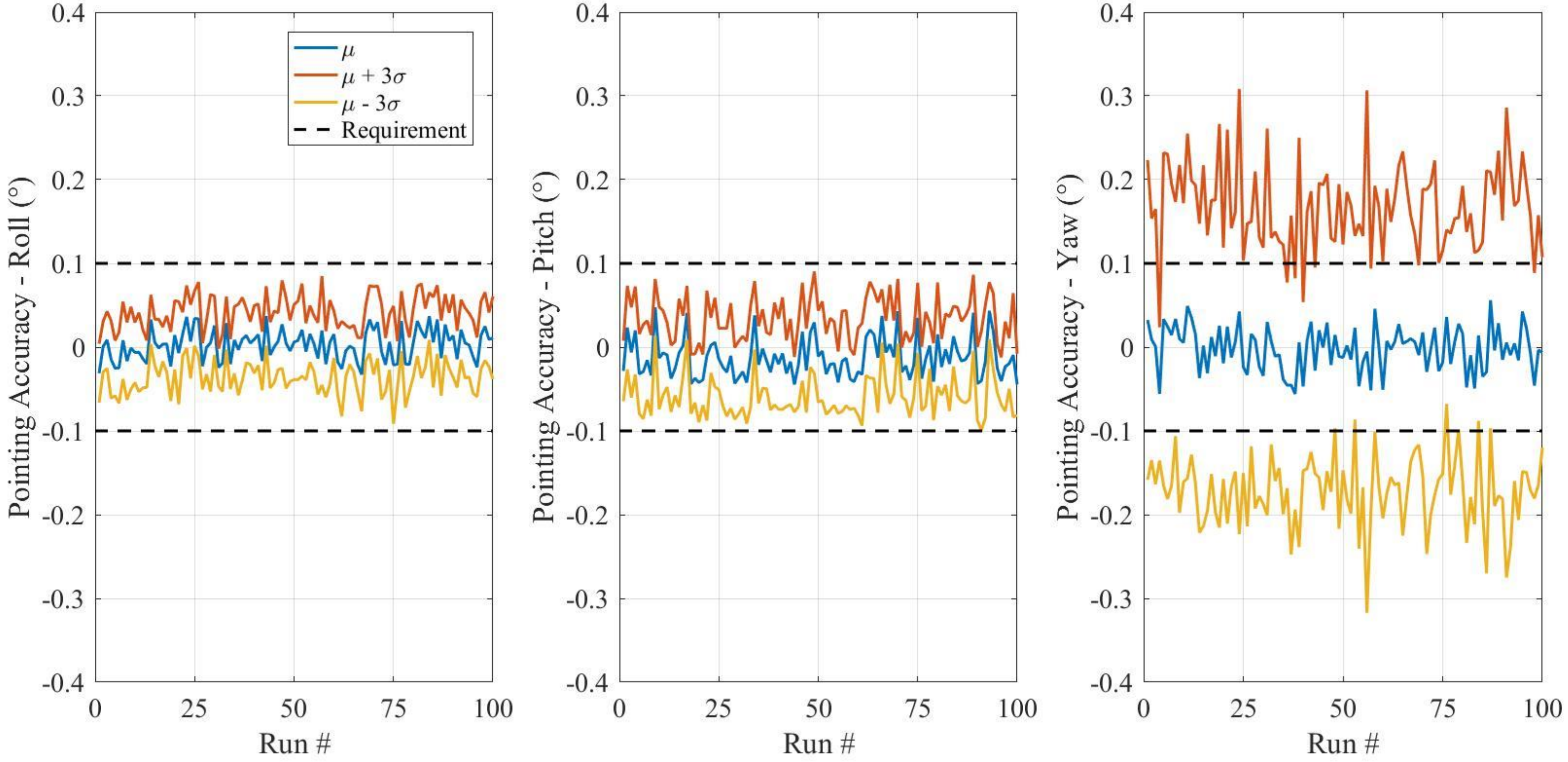
Requirements Verification Tool (cont.)

- Control
  - B-dot detumble controller
  - Momentum dumping controller
  - Nonlinear PD controller (slew, trajectory tracking, pointing)
- Estimation
  - Rate gyro model
  - Star tracker model
  - Kalman filter (fine pointing)
  - Extended Kalman filter (EKF)

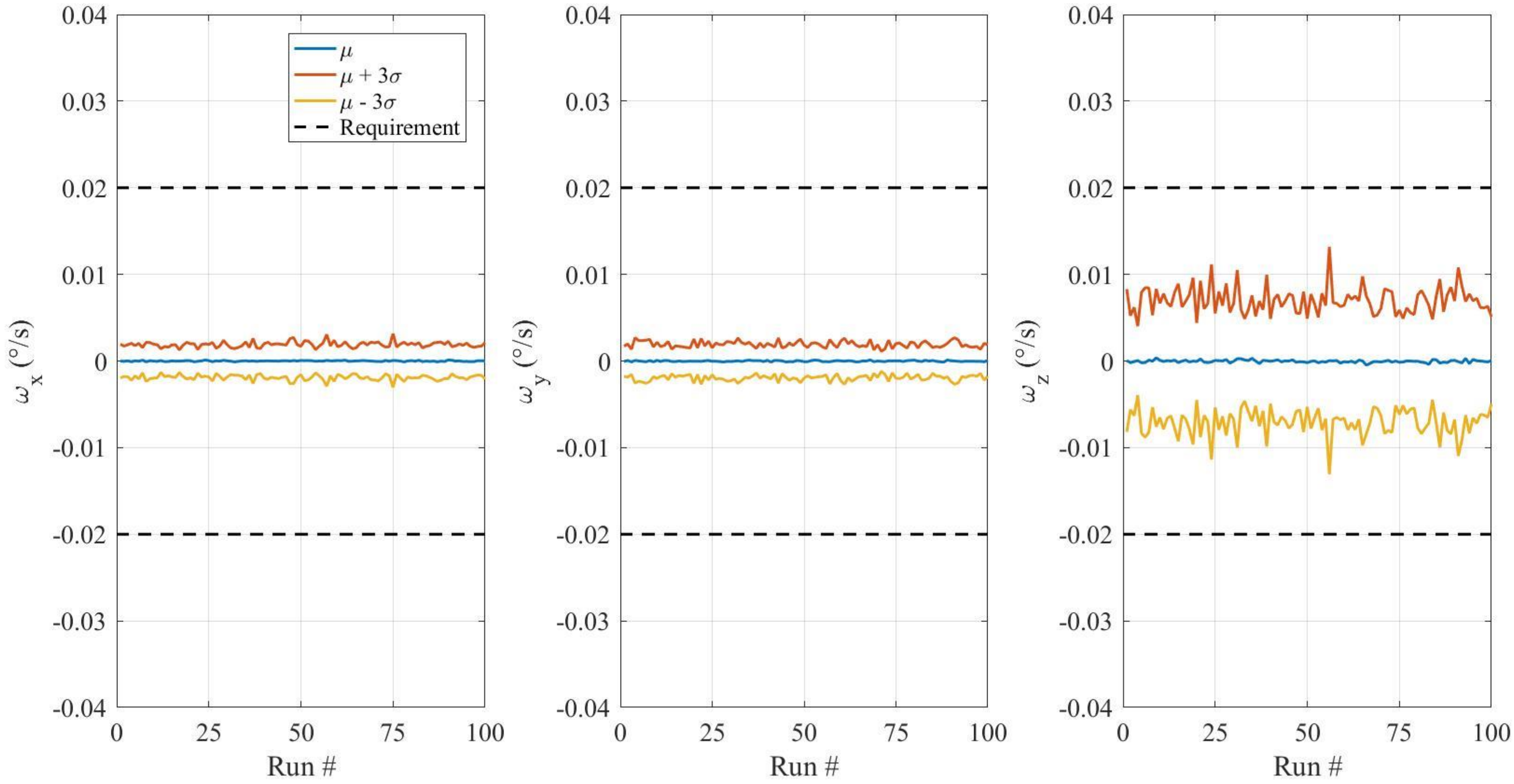
Pointing Accuracy and Stability Analysis

- Applicable requirements:
  - Pointing accuracy – error < 0.1° 3σ per axis
  - Attitude stability – jitter < 0.02°/s 3σ for 600s (10 min) during science operations
- Assumptions:
  - Inertially-fixed attitude (to simulate science operations)
  - Modeling dominant environmental disturbance torque (gravity gradients), reaction wheel disturbances, process noise
  - Estimated dynamics (from Kalman filter – estimate attitude and angular velocity from star tracker measurement)
- Results shown for *wide* configuration

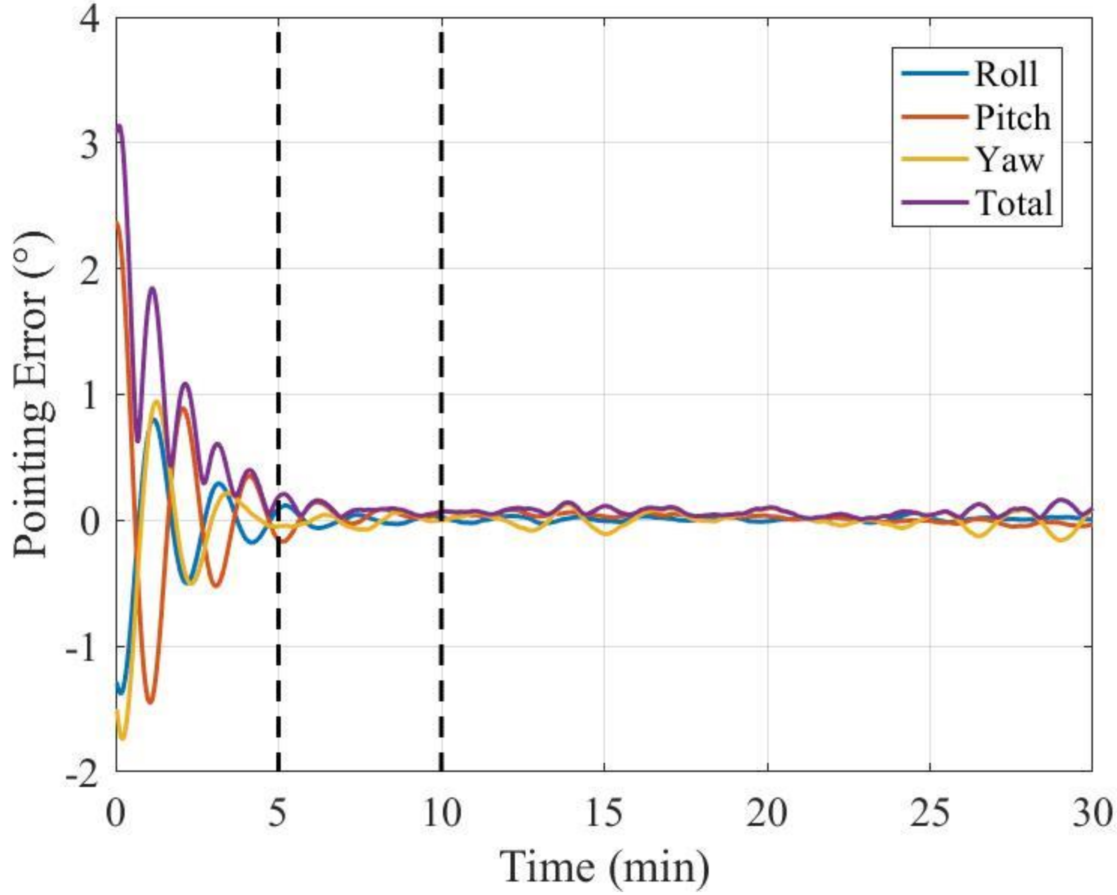
Pointing Accuracy – Wide, Wide



Pointing Stability – Wide, Wide



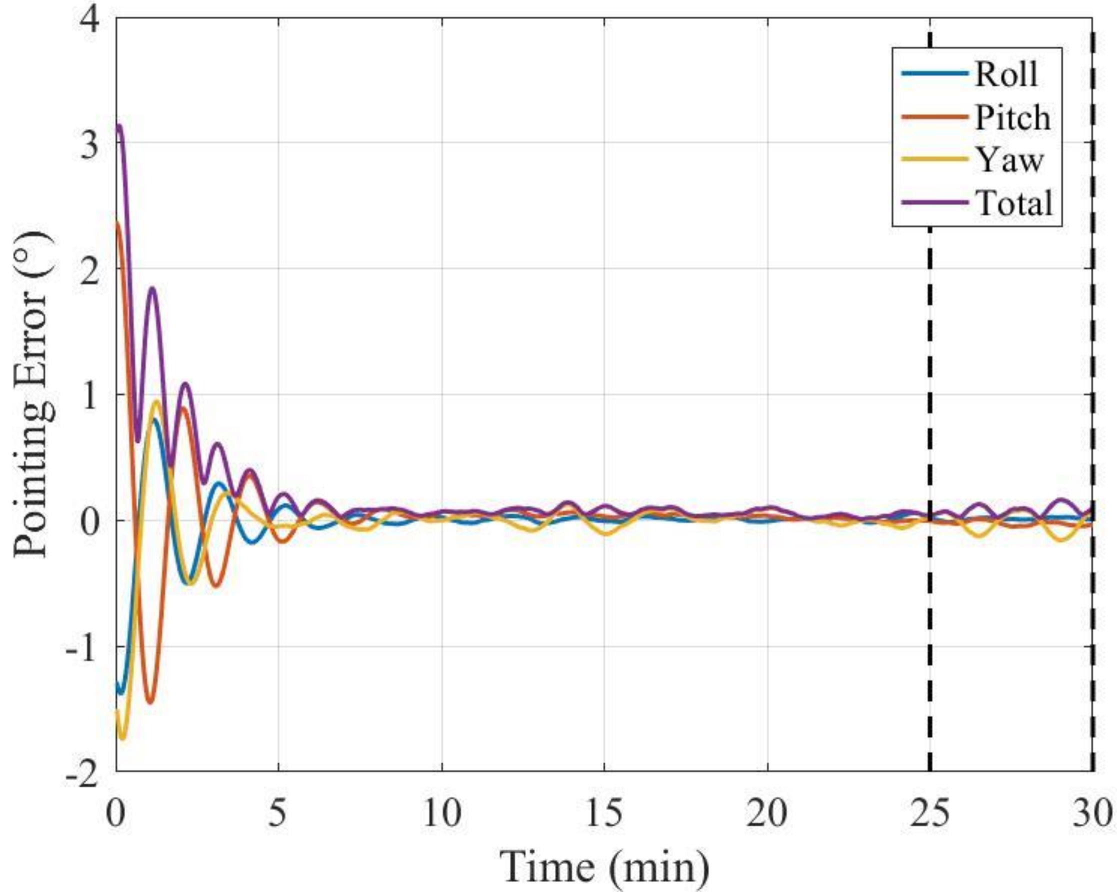
Camera Frame Visualization - Slewing



Camera Frame Visualization - Slewing □□□□□

video @ 10x actual

Camera Frame Visualization - Pointing □□□□□



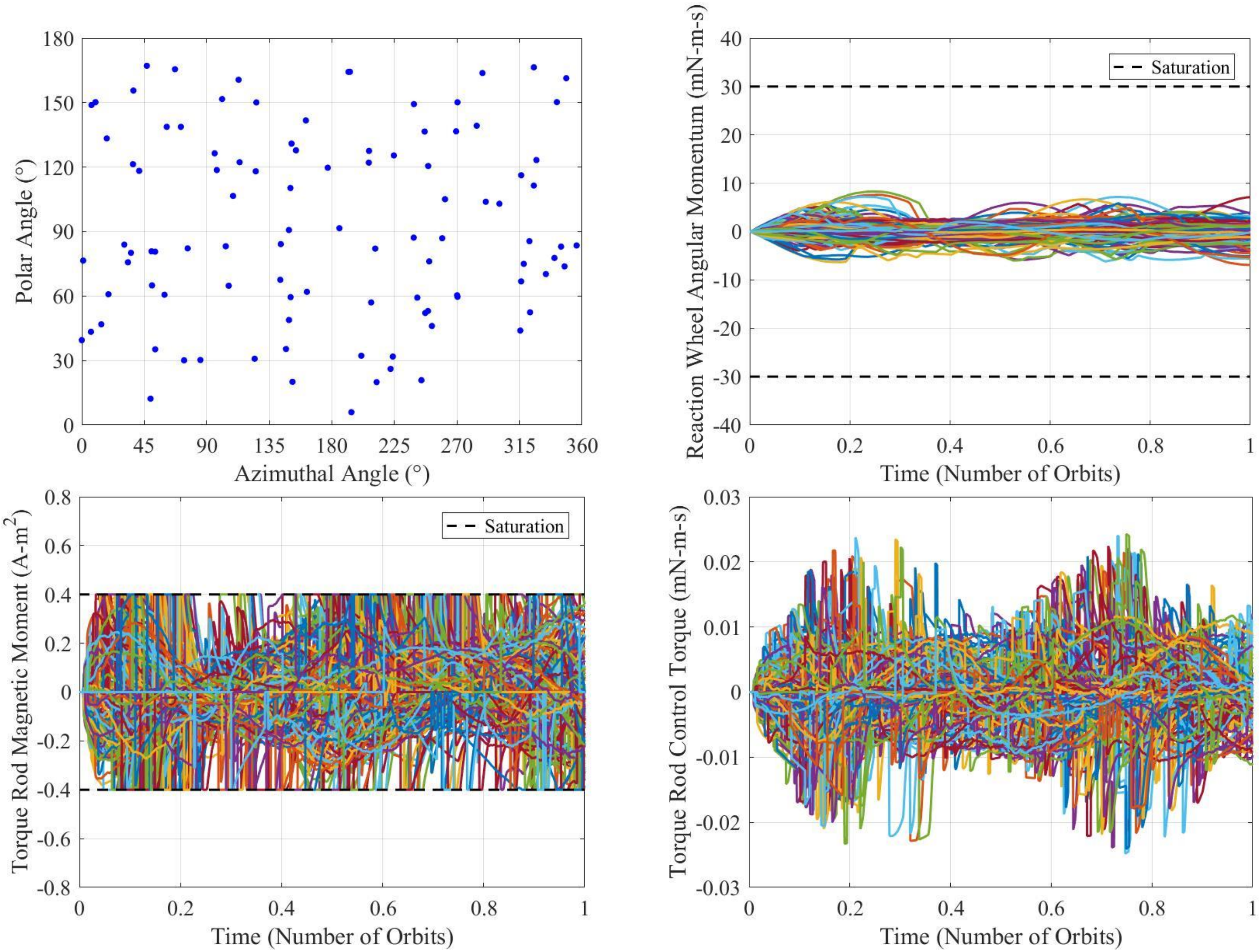
Camera Frame Visualization - Pointing □□□□□

video @ 10x actual

Desaturation Analysis

- Applicable requirement: ADCS shall have the capability to desaturate the reaction wheels
- Assumptions:
  - Continuous desaturation with magnetic torque rods (max magnetic moment 0.4 A-m^2)
  - Inertially-fixed attitude (to simulate science operations)
  - Modeling dominant environmental disturbance torque (gravity gradients), reaction wheel disturbances
  - Truth dynamics
- Results shown for *wide* configuration

Desaturation Analysis – Wide, Wide

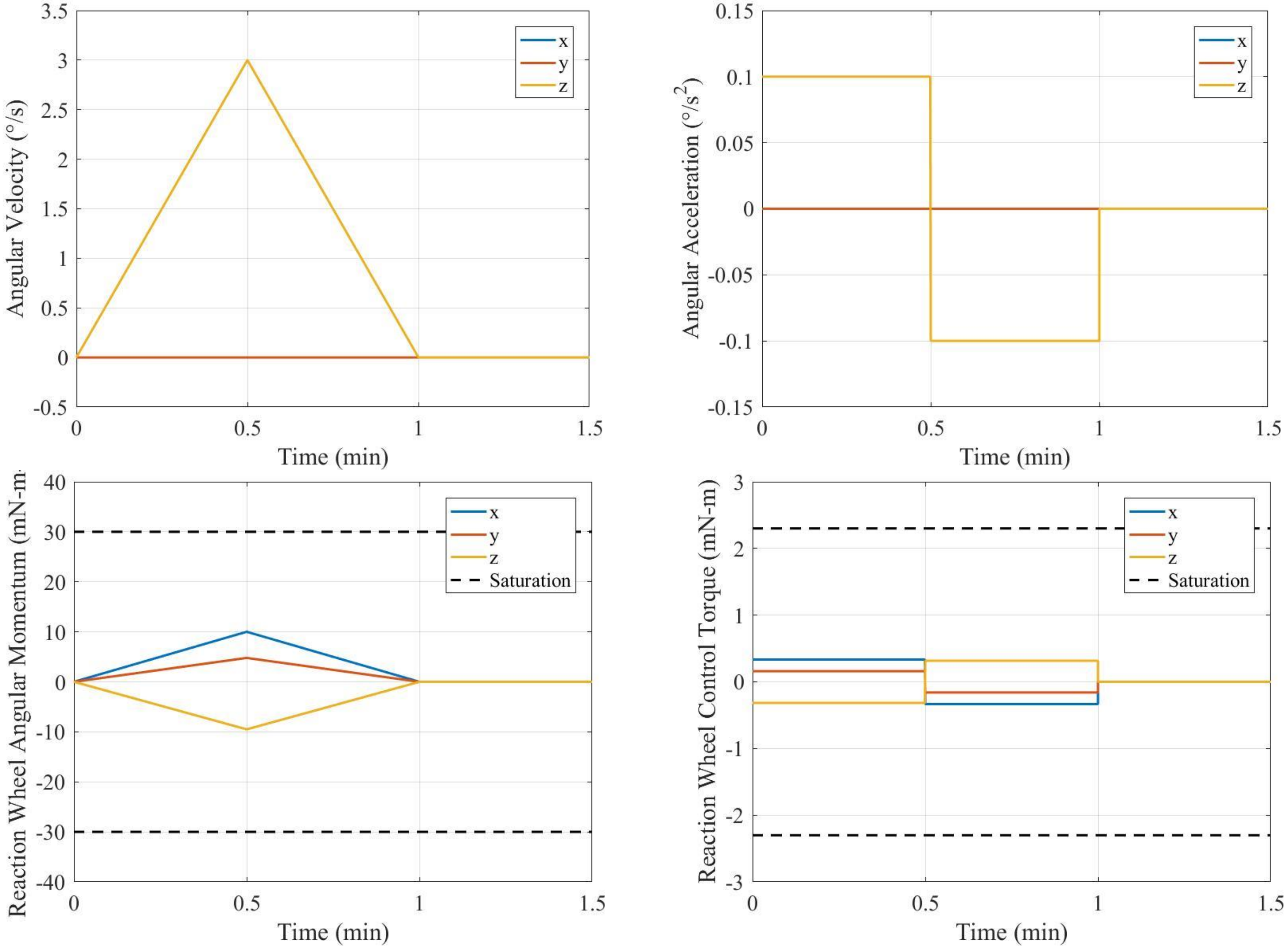


Z-Axis Slew Maneuver

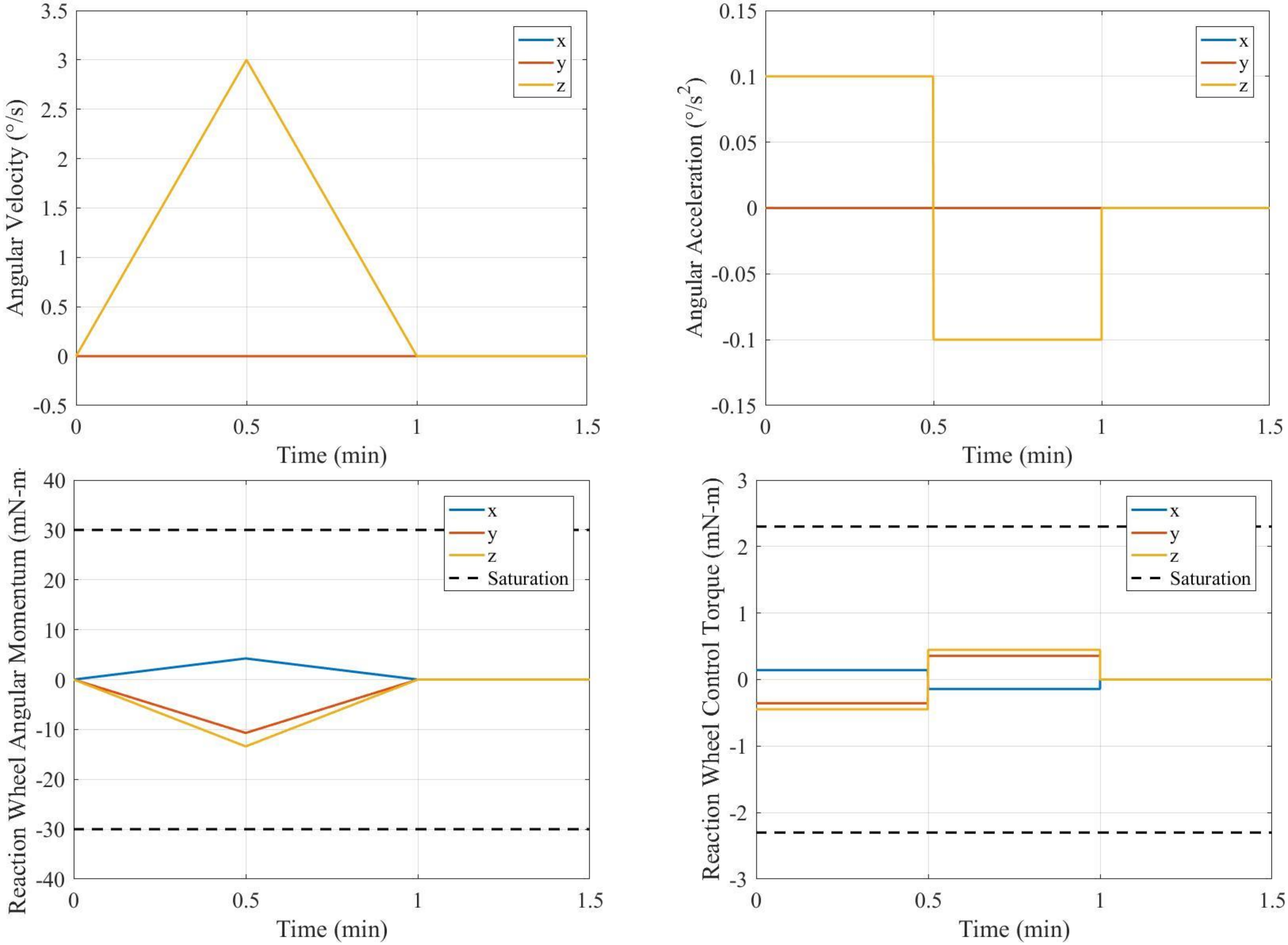
- Applicable requirement: rotation 90° in 60s about boom (z) axis
- Assumptions:
  - Idealized slew maneuver – no disturbances, noise, etc.
  - Truth dynamics
- Maneuver simulated open-loop via precomputed control trajectory

- **Takeaway:** z-axis slew maneuver completed in 60 seconds with large angular momentum margins

Z-Axis Slew Analysis – Empty, Narrow



Z-Axis Slew Analysis – Wide, Empty



Requirements Verification Matrix

Requirement	Requirement Met?
Detumble:	
• Reduce body angular rate < 0.3°/s in 4 orbits or less	**Yes***
Science:	
• Pointing accuracy – error < 0.1° 3σ per axis	**Yes****
• Attitude stability – jitter < 0.02°/s 3σ for 600s during science operations	**Yes**
Rendezvous and Docking (RDV):	
• Rotate 90° in 60s about boom axis	**Yes**
All	
• Have capability to desaturate reaction wheels	**Yes**

*Preliminary results
**Some caveats

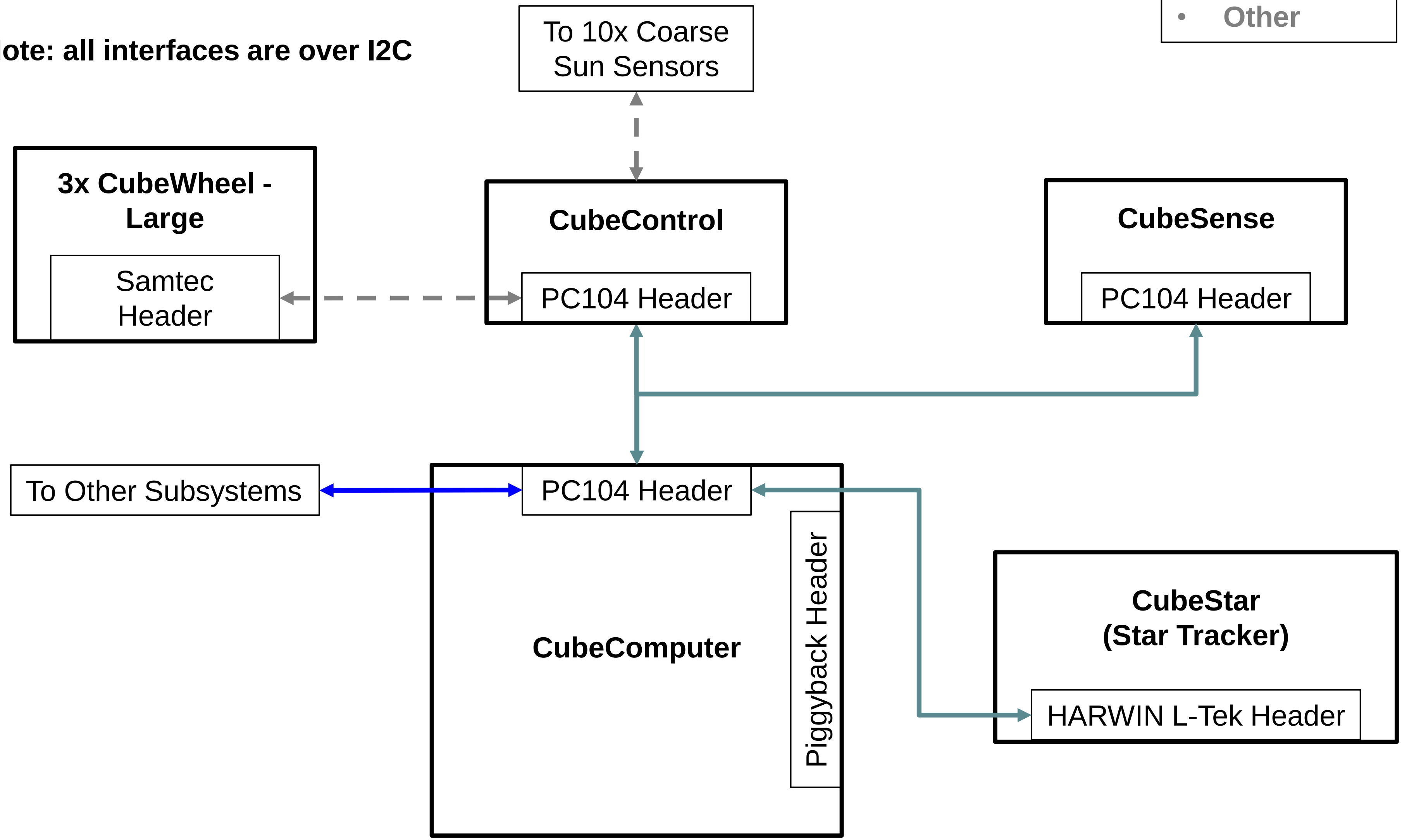
ADCS Integration into CoreSat

- CubeComputer, CubeSense, and CubeControl in central PC104 stack
  - Fine earth and sun sensors mounted separately from CubeSense board
- 3x Large CubeWheels (reaction wheels) located near center of mass in central stack, mounted on orthogonal body axes
  - Mechanical interfaces TBD
- Star tracker mounted to maximize field of view (FOV) given other constraints (e.g. optical system)
- Interfaces over I2C

(Notional) ADCS Interfaces Diagram

Legend:
- Primary
- Secondary
- Other

Note: all interfaces are over I2C



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Future Work

- Detailed (Monte Carlo) detumble analysis
- Higher fidelity z-axis slew maneuver simulation
- Quantification of pointing constraints (e.g. star tracker cannot be pointed at the sun)
- Algorithm for real-time execution of z-axis slew maneuver?
- Hardware acquisition
- Component testing
- Subsystem integration, assembly, and testing

Open Issues/Discussion Topics

- ConOps during rendezvous and docking (RDV) maneuver (including z-axis slew maneuver)
- Docking system magnetic modeling
  - Updates/models for remnant magnetic moments, torques on spacecraft during RDV, etc.

Questions?

Backup Slides

Notes on Gravity Gradient Torques

- Largest disturbance torque acting on AAReST by 1+ orders of magnitude
- For a given orbit, maximum gravity gradient torque is proportional to maximum difference between principal inertias
  - $T_{gg,max} = \frac{3\mu}{2r^3} |J_{xx} - J_{zz}| \cong 15\ \mu N - m$
- Function of attitude relative to *orbit* and inertias
- Independent of roll

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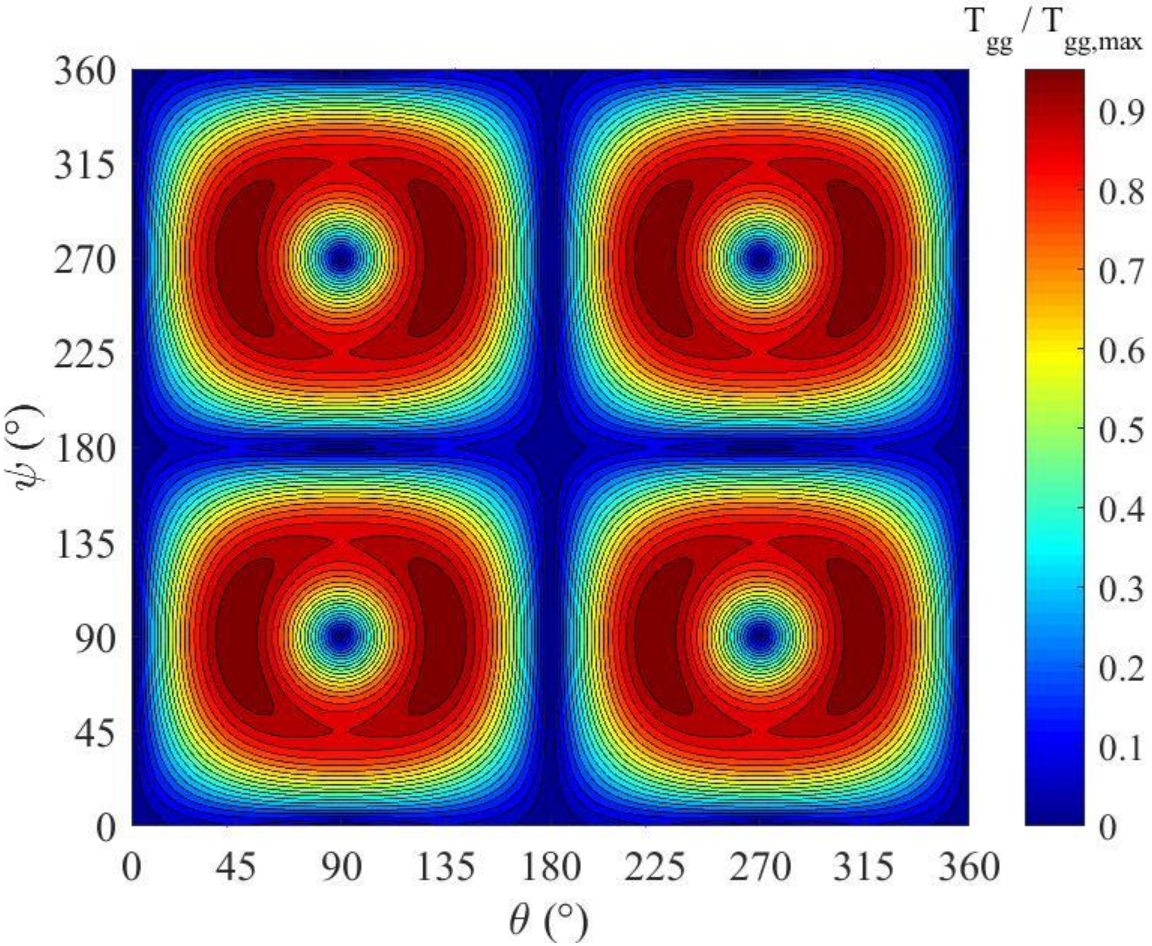
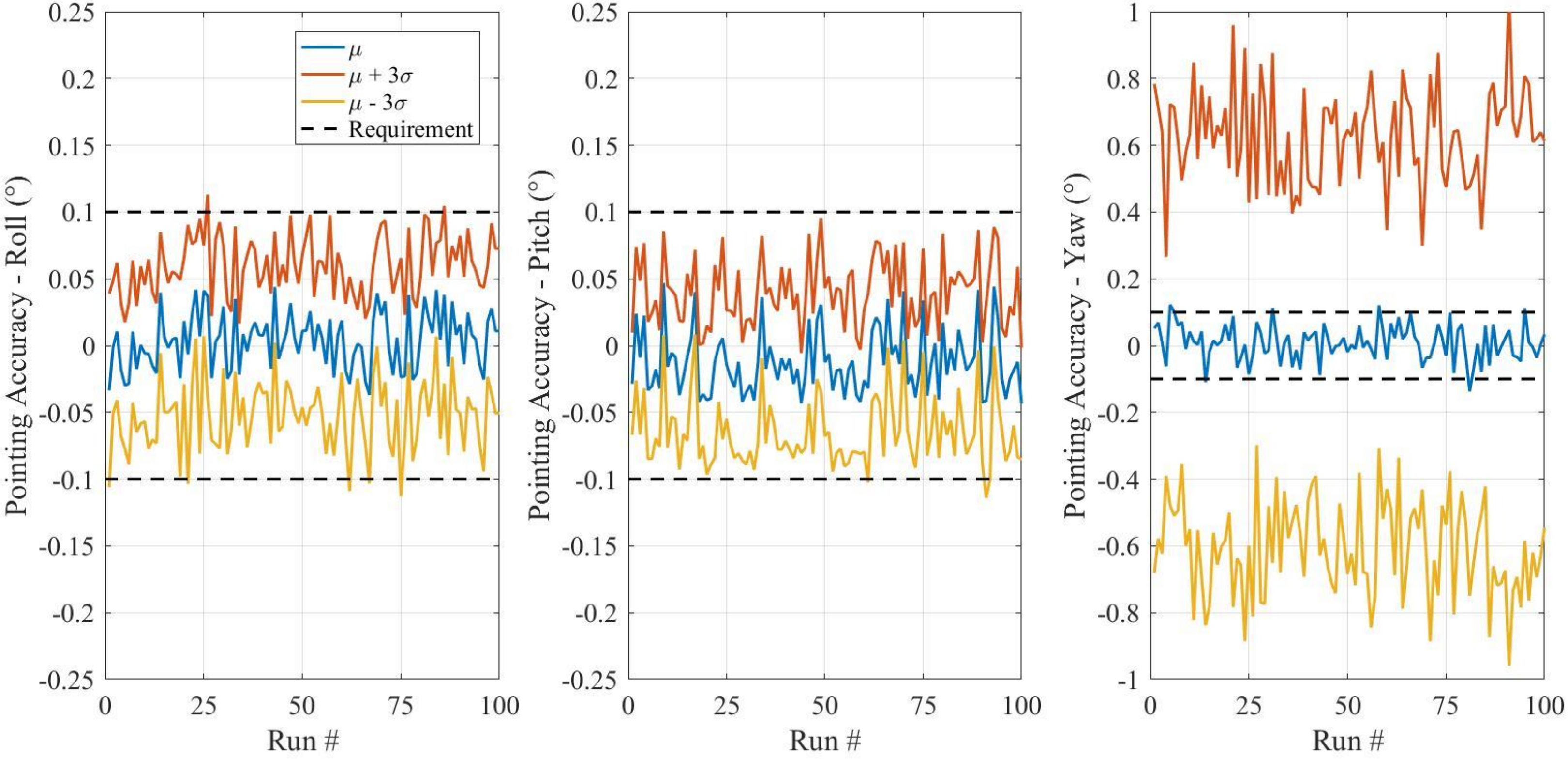
Note on Gravity Gradient Torques (cont.)

- Approximately 1/3 of sky with $T_{gg} > 0.75\, T_{gg,max}$

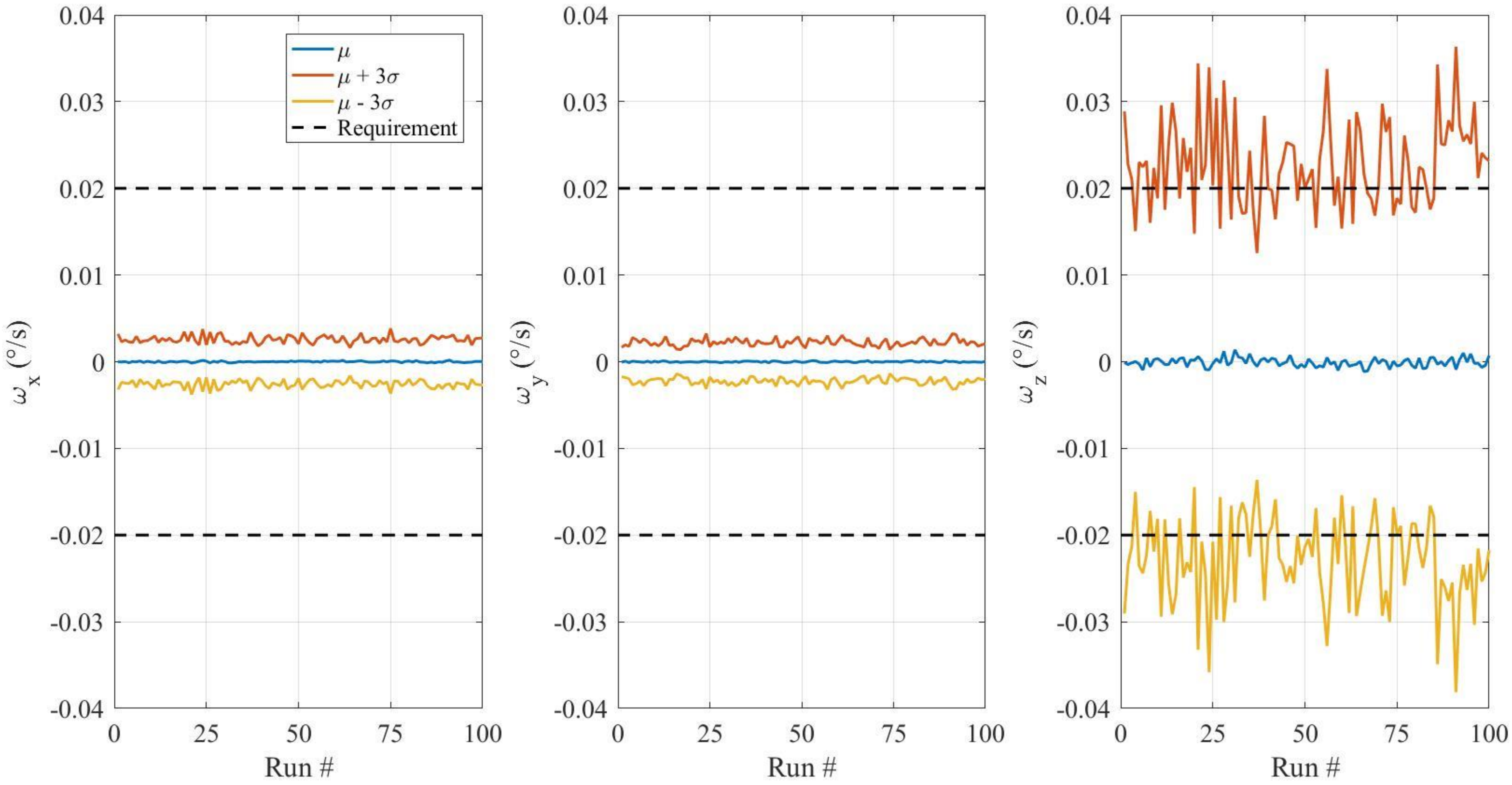


Pointing Accuracy and Stability Analysis – Additional Results

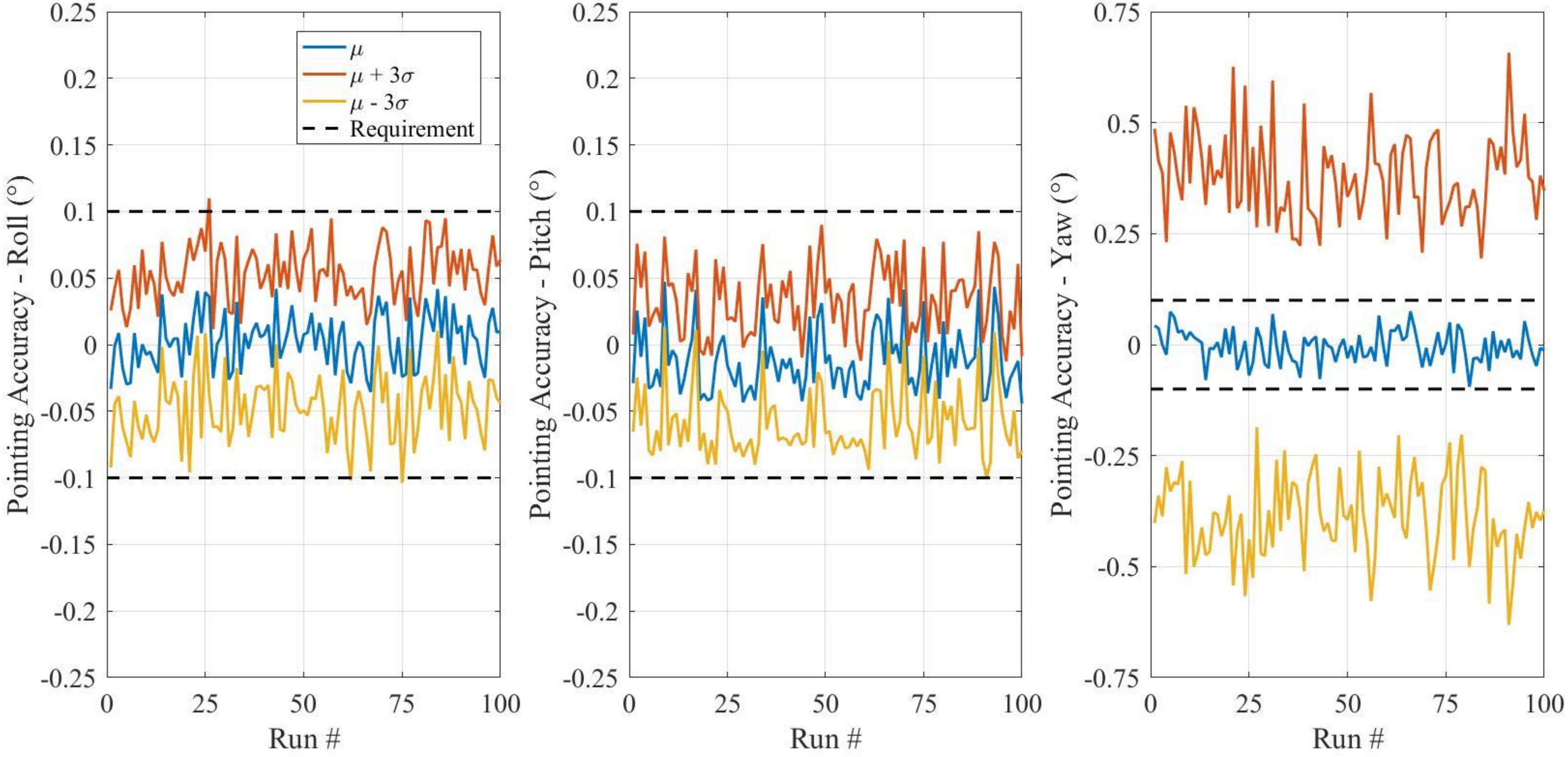
Pointing Accuracy – Empty, Narrow



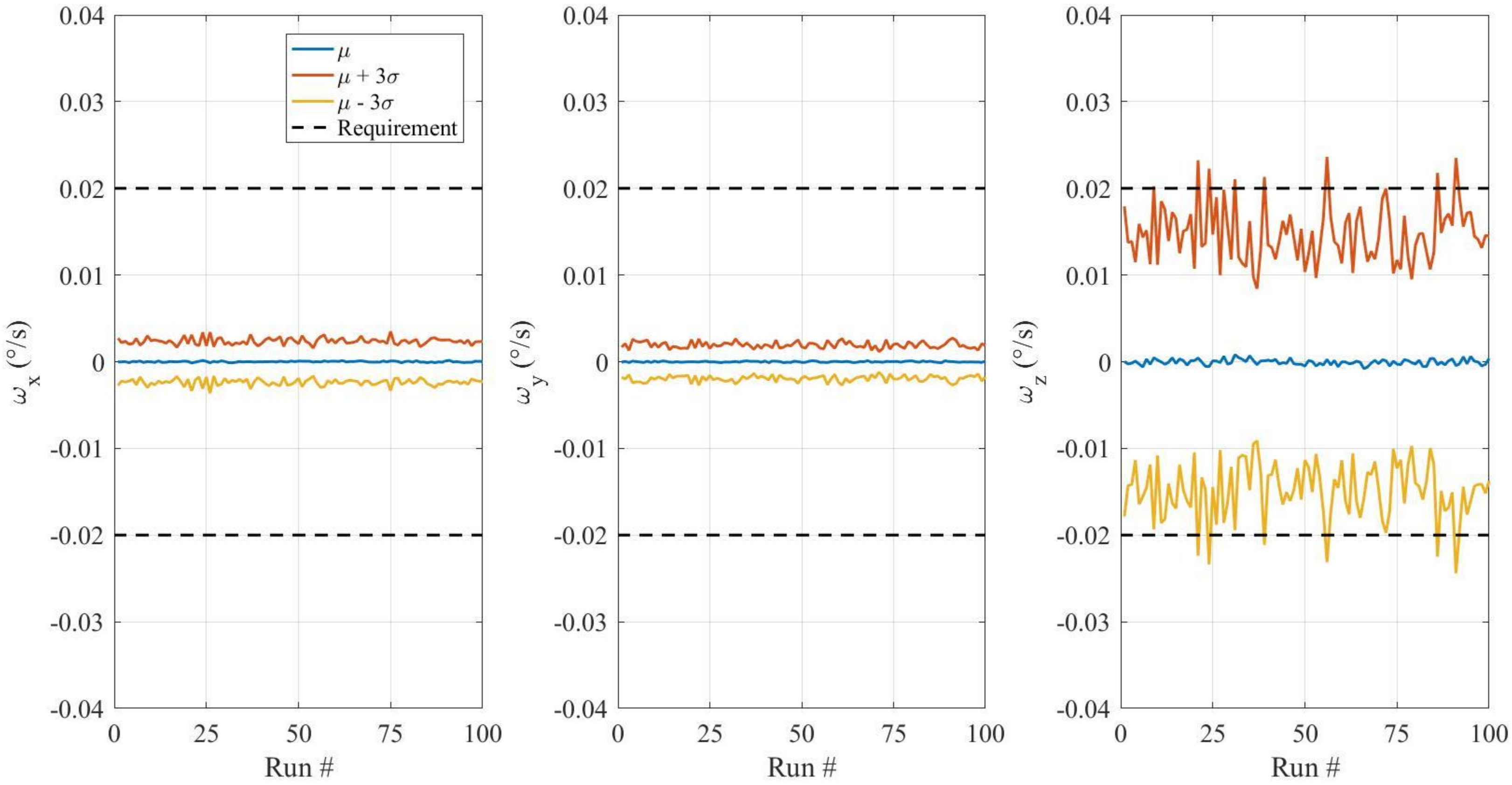
Pointing Stability – Empty, Narrow



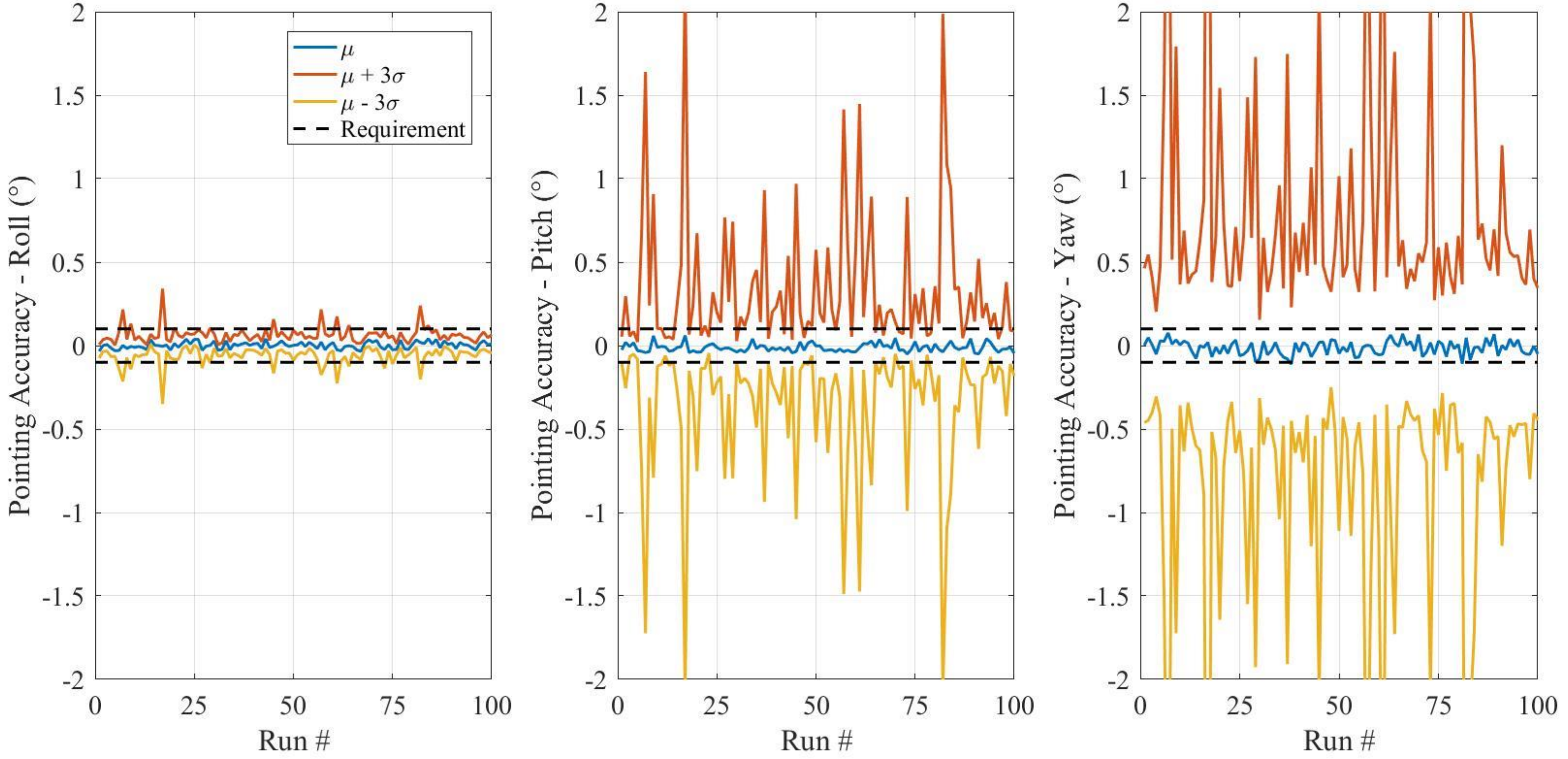
Pointing Accuracy – Narrow, Narrow



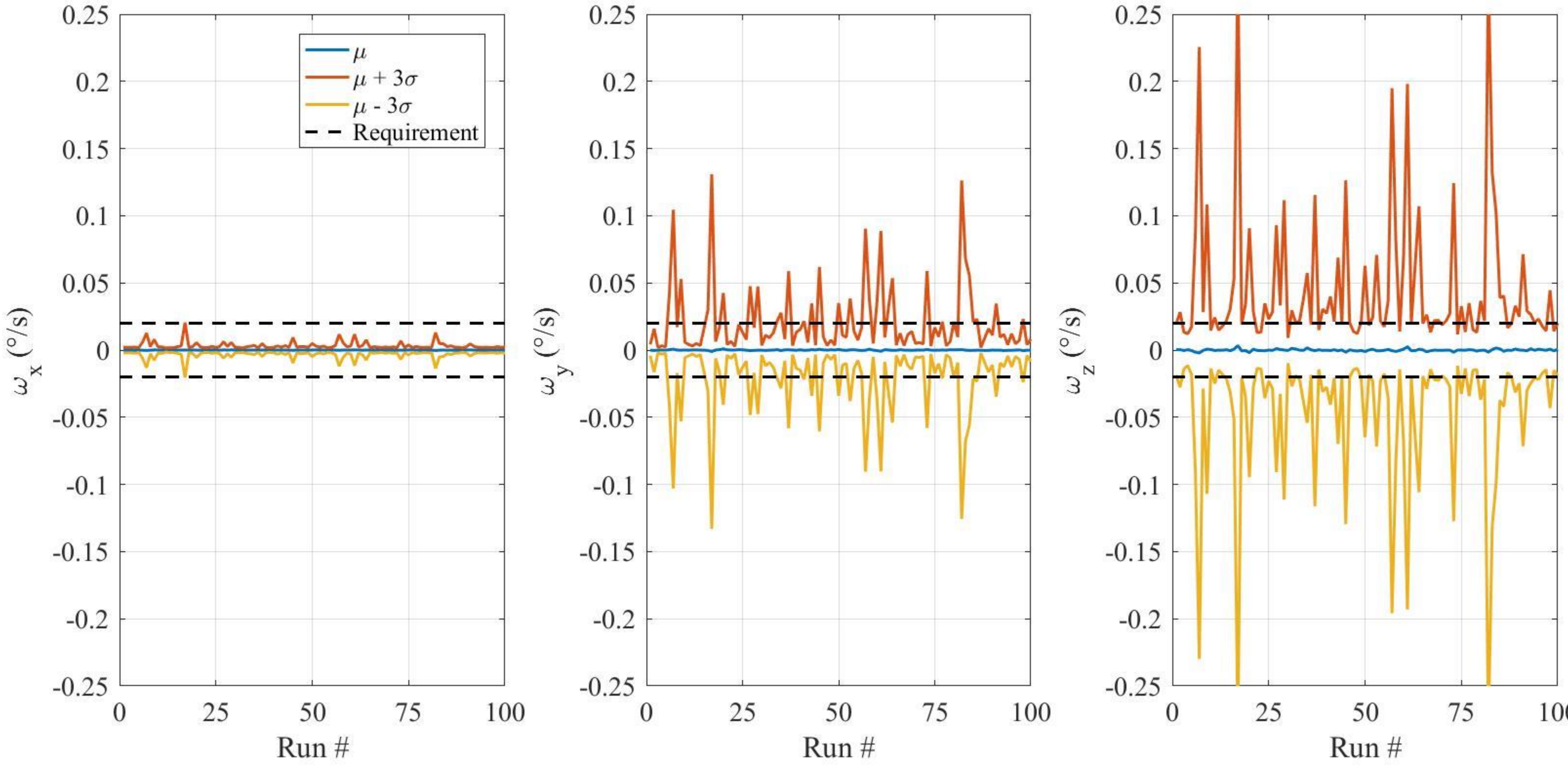
Pointing Stability – Narrow, Narrow



Pointing Accuracy – Wide, Empty

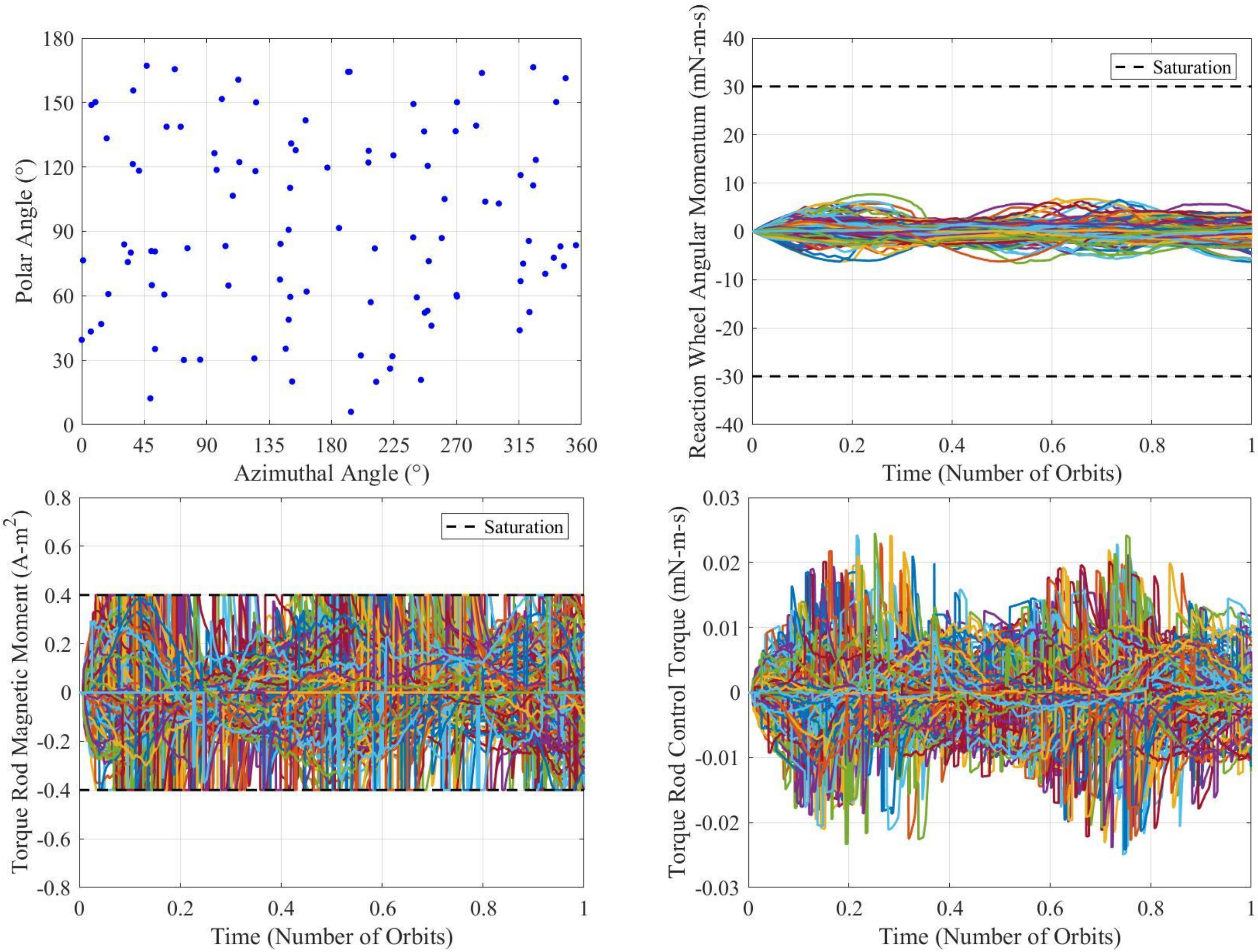


Pointing Stability – Wide, Empty

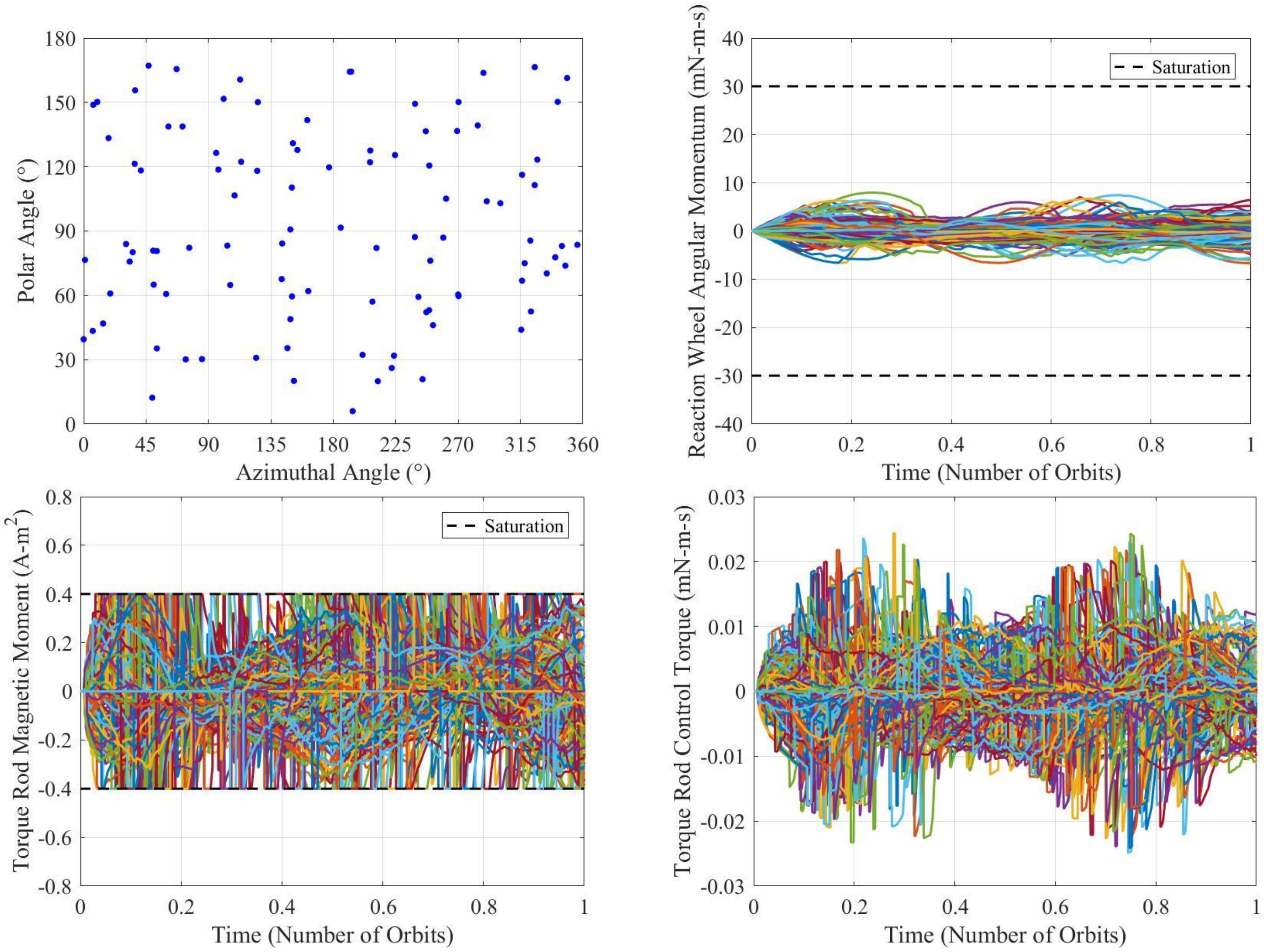


Desaturation Analysis – Additional Results

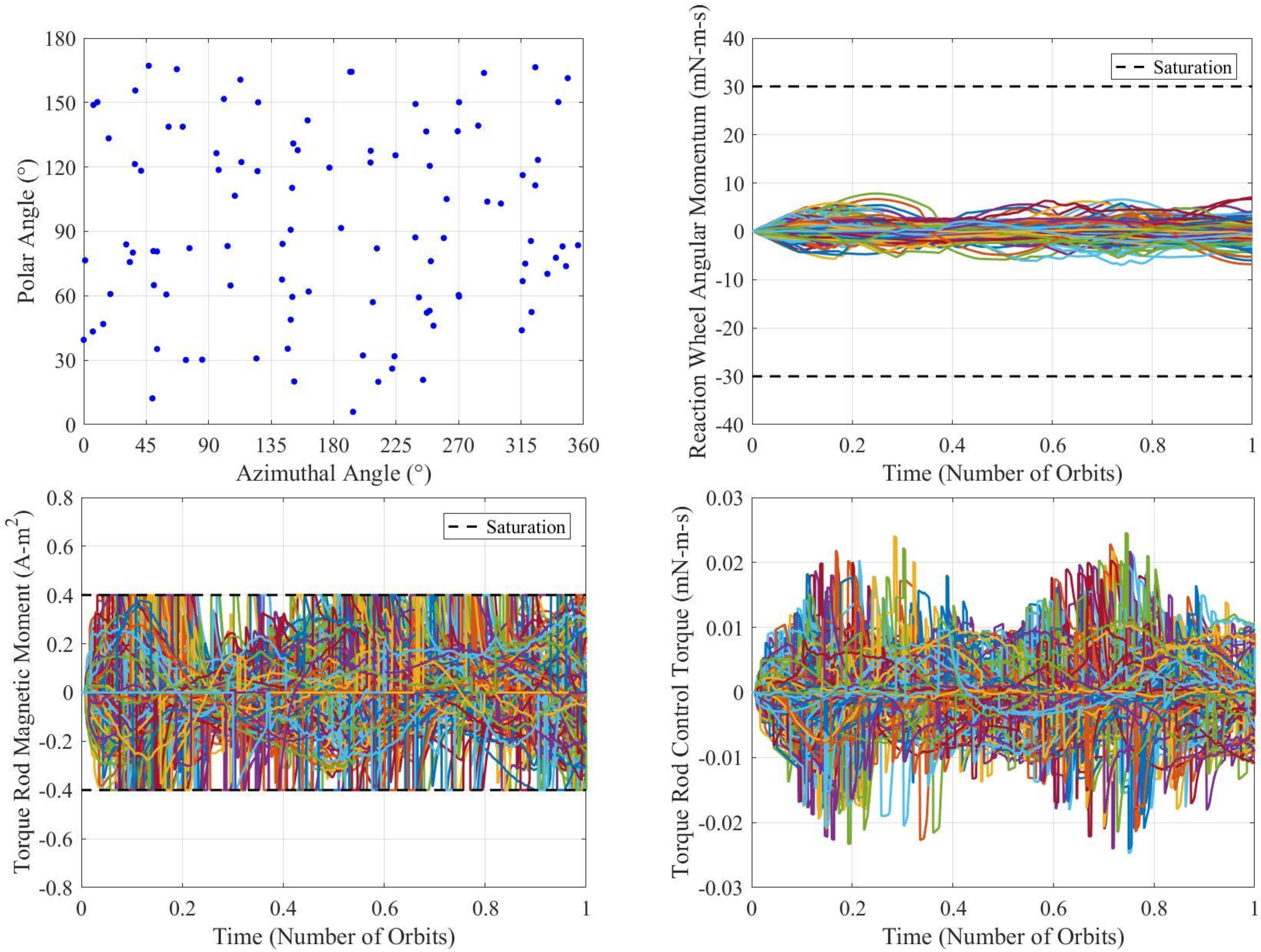
Desaturation Analysis – Empty, Narrow



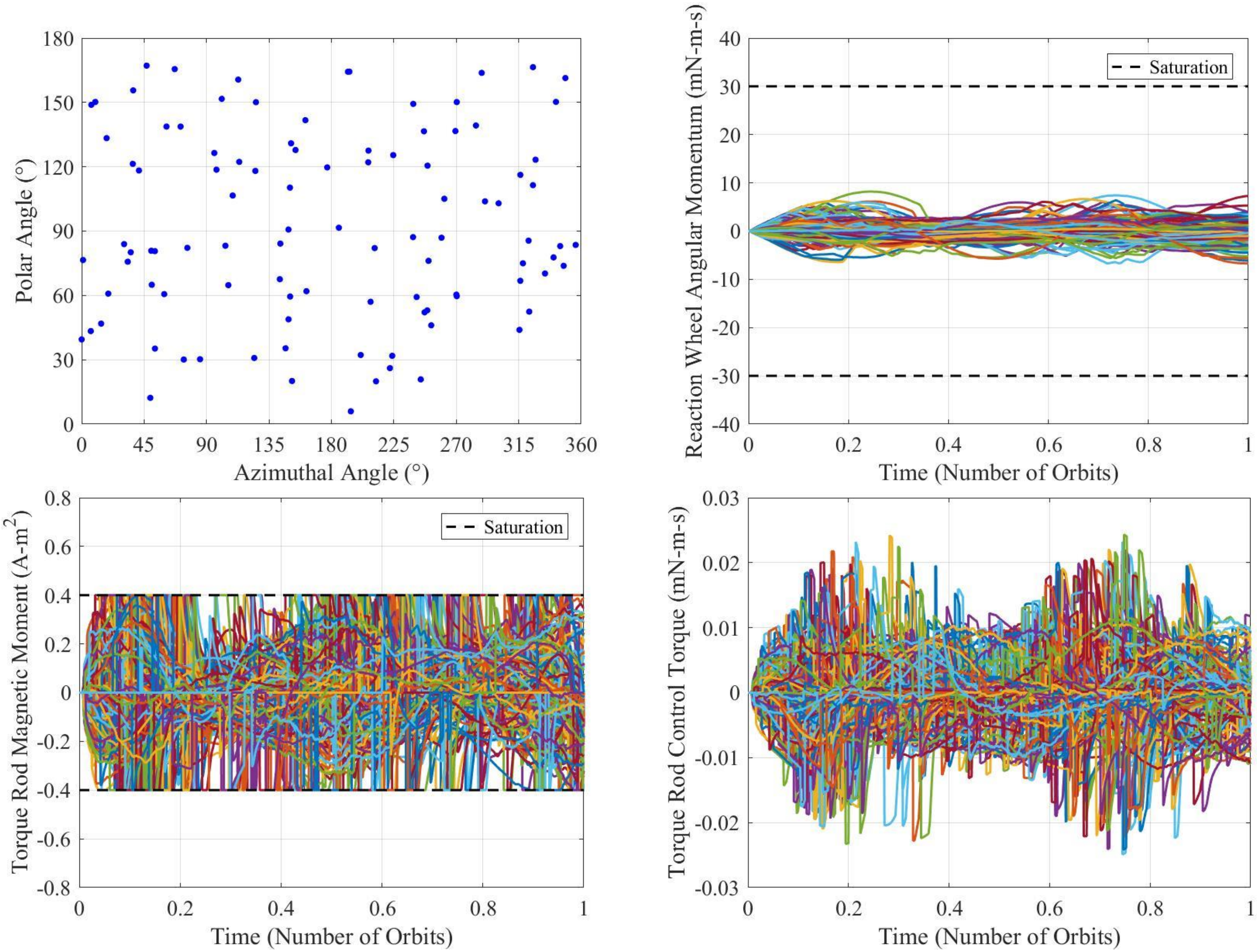
Desaturation Analysis – Narrow, Narrow



Desaturation Analysis – Wide, Empty



Desaturation Analysis – Wide, Narrow



space structures laboratory

AAReST CoreSat Power System

Ashish Goel

Chris Bradley

Charlie Dorn

Juliane Preimesberger

Caltech

Outline

- **Power sub-system requirements**
- **Power budget**
- **Proposed solution**
  - Solar cells
  - EPS and batteries
  - Solar panel mounting and fabrication
  - Power generation and depth of discharge analysis
  - System diagram with voltages and currents
- **Interfaces**
- **Outstanding issues/concerns**

Power Sub-System Requirements

- **Provide sufficient power to all subsystems in all operating modes for proposed mission lifetime of 6 months**
- **Meet nominal, peak and inrush current requirements of all components**
- **Provide up to 5 W of power to MirrorSats (5V, 1A)**
- **Provide sufficient power for frangibolt (28 V, 0.9 A) and burn wire (~2 V, 2.5 A) actuation**
- **Solar panels must accommodate coarse sun sensors, thermistors and not interfere with the docking process**
- **Solar cell arrangement must deal with likelihood of shadowing from the boom and other deployables**
- **Batteries must carry sufficient capacity to power the satellite during detumbling phase**
- **Batteries must incorporate heaters to keep them within operating temperature range (0-40 C)**
- **EPS must incorporate safety inhibits (RBF), kill switch and separation detection switches**

Power Budget

	Operating mode	Burn wire	Detumble	Actuator release	Nominal	Ground comm	Science	Docking	Mirrorsat Charging	Battery heating
	Configuration	Narrow	Narrow	Narrow	Both	Both	Both	Both	Both	Both
Power	Battery Heater									6
	EPS	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
ADCS	CubeComputer	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	CubeSense	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
	CubeControl	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
	CubeWheel - Large	1.5	6.6	1.5	1.5	1.5	1.5	3.2	1.5	1.5
	Star Camera						0.9	0.9		
Avionics	UHF Transceiver					2				
	Payload Interface Computers						5	5		
Docking	WiFi						1	1		
	Electromagnets							13		
	LEDs							1		
Other	Boom Deployment	4								
	Rigid Mirror Payload						6			
	Mirrorsat Charging								10	
	Camera						5			
	Release Actuators			25						
	Misc (health monitoring sensors)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	Total Power (W)	9.51	10.61	30.51	5.51	7.51	23.38	28.08	15.51	11.51
	Total Power with 30% Margin (W)	**12.36**	**13.79**	**39.66**	**7.16**	**9.76**	**30.40**	**36.51**	**20.16**	**14.96**
	3.3 V bus peak current (A)	0.56	0.56	0.56	0.56	0.56	0.83	0.83	0.56	0.56
	5 V bus peak current (A)	1.23	0.43	0.43	0.43	0.43	2.63	4.43	2.43	0.43
	16 V bus peak current (A)	0.34	0.41	1.66	0.09	0.22	0.47	0.20	0.09	0.47
	Max Mode Duration	< 2 min	< 2 orbits	seconds	N/A	< 8 min	< 10 min	2 min	< 4 hours	5 min

Good estimate
Subject to change

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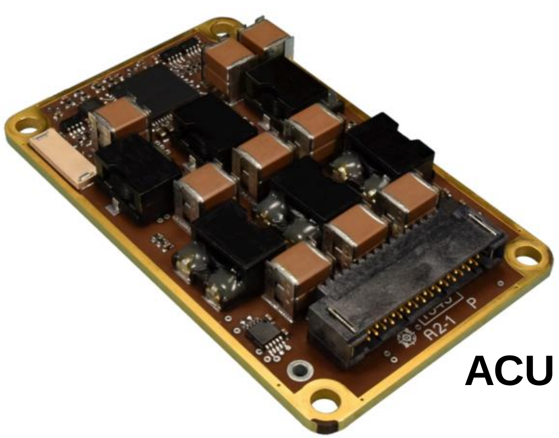
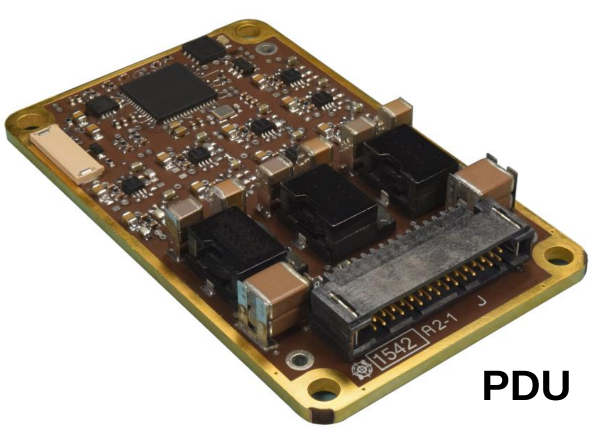
EPS – GomSpace NanoPower P60

- **P60 dock**
- **Array conditioning unit (ACU)**
  - 6 PV input channels
  - 16 V, 2A max per input
  - Individual MPPT on each input
  - Current and voltage measurements on each input
- **Power distribution unit (PDU)**
  - 9 switchable, overcurrent protected outputs
  - All outputs through PC 104 header, 6 outputs also through discrete connector
  - 1-2 A programmable current limits (not PC104)
  - Current, voltage and overcurrent diagnostics on each output



ACU



PDU

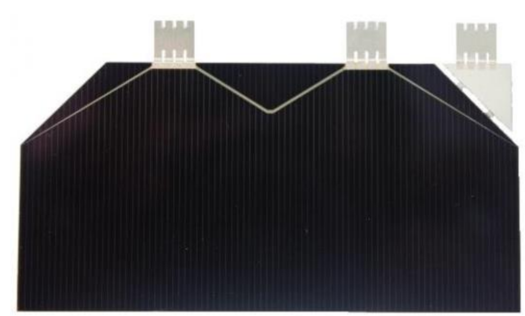
Solar Cell Selection

- **Commercial panels vs in-house**
- **Coverglass Interconnected Cell options (includes tabs, bypass diode)**

	Efficiency	**Surface area (cm^2)**	**Lead time (weeks)**
Spectrolab XTJ Prime	30.7%	27.2	3-4
Spectrolab UTJ	28.3%	26.6	5-6
Azurspace 3G30A	29.3%	30.2	8-12

Spectrolab XTJ Prime

Spectrolab UTJ



Azurspace 3G30A

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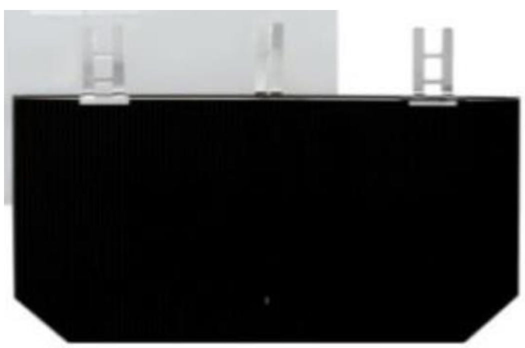
Solar Cell Selection

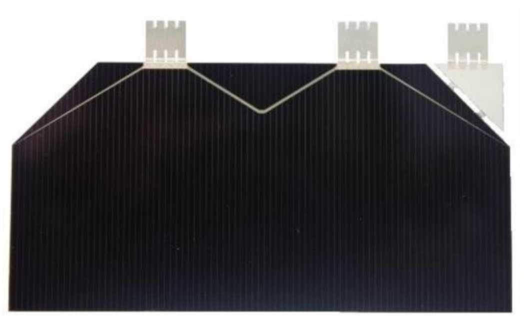
- **Commercial panels vs in-house**
- **Coverglass Interconnected Cell (CIC) options**

	Efficiency	**Surface area (cm^2)**	**Lead time (weeks)**
Spectrolab XTJ Prime	30.7%	27.2	3-4
Spectrolab UTJ	28.3%	26.6	5-6
Azurspace 3G30A	29.3%	30.2	8-12

Spectrolab XTJ Prime



Spectrolab UTJ



Azurspace 3G30A

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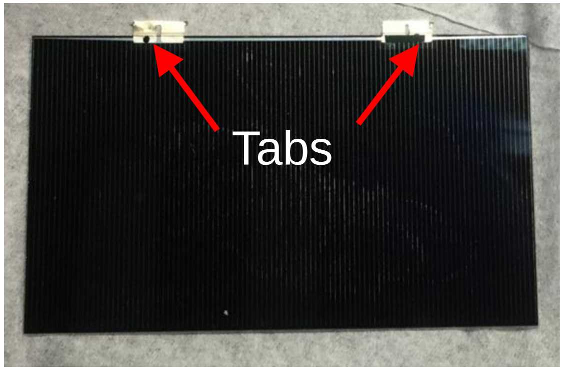
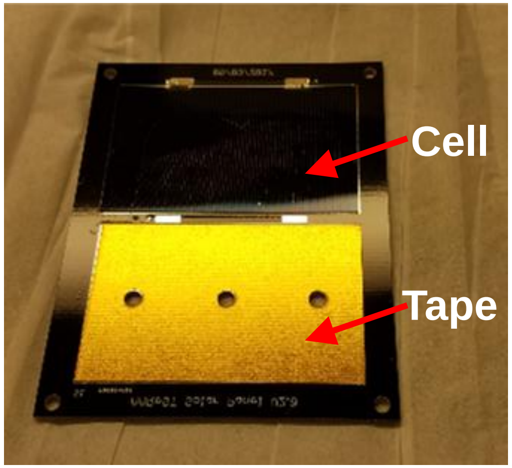
Panel Assembly Procedure

- **Modified CU Boulder procedure**
- **Fabricated and tested three functioning panels**
- **Finalized procedure steps:**
  - Cut tabs
  - Laser cut double-sided Kapton tape
  - Vacuum bagging
  - Solder and add conductive epoxy

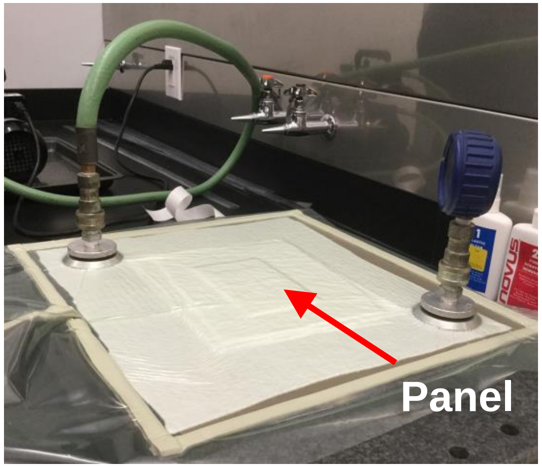
Cut tabs



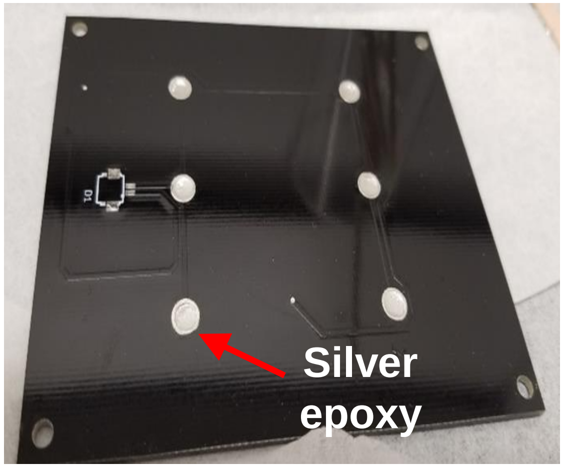
Align tape



Vacuum bagging



Add epoxy



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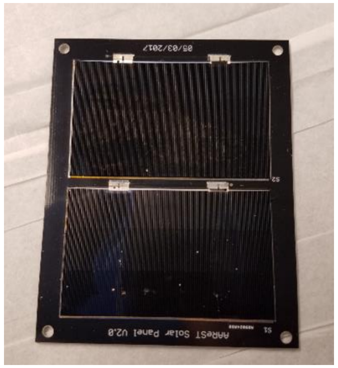
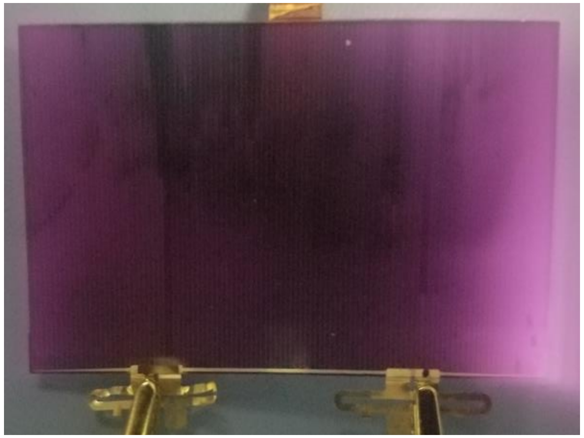
Panel Testing

Illumination

	Pre-assembly	Post-assembly
Cell A	6.7 mA, 0.51 V	9.7 mA, 0.63 V
Cell B	5.3 mA, 0.79 V	10.6 mA, 0.78 V
Solar panel	-	11.37 mA, 1.46 V

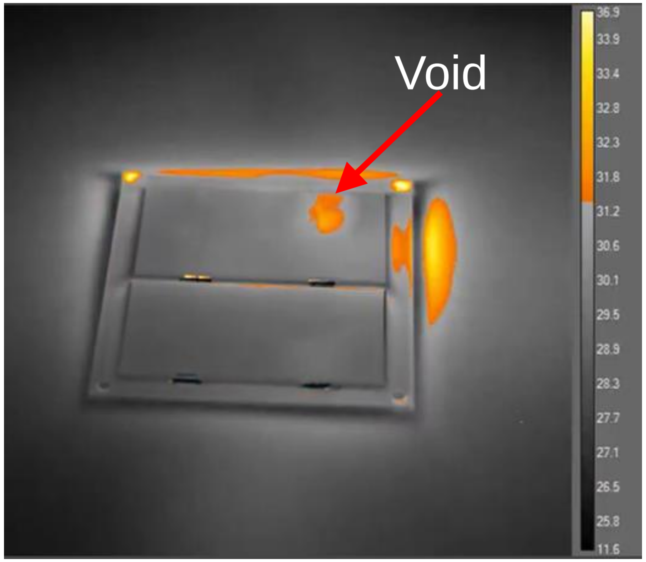


Electroluminescence

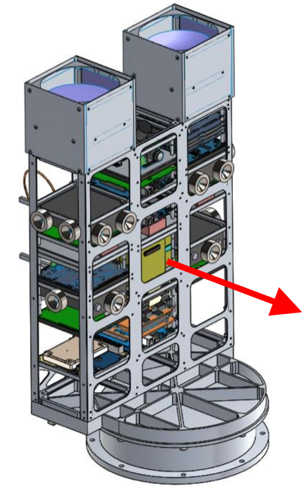


Vacuum

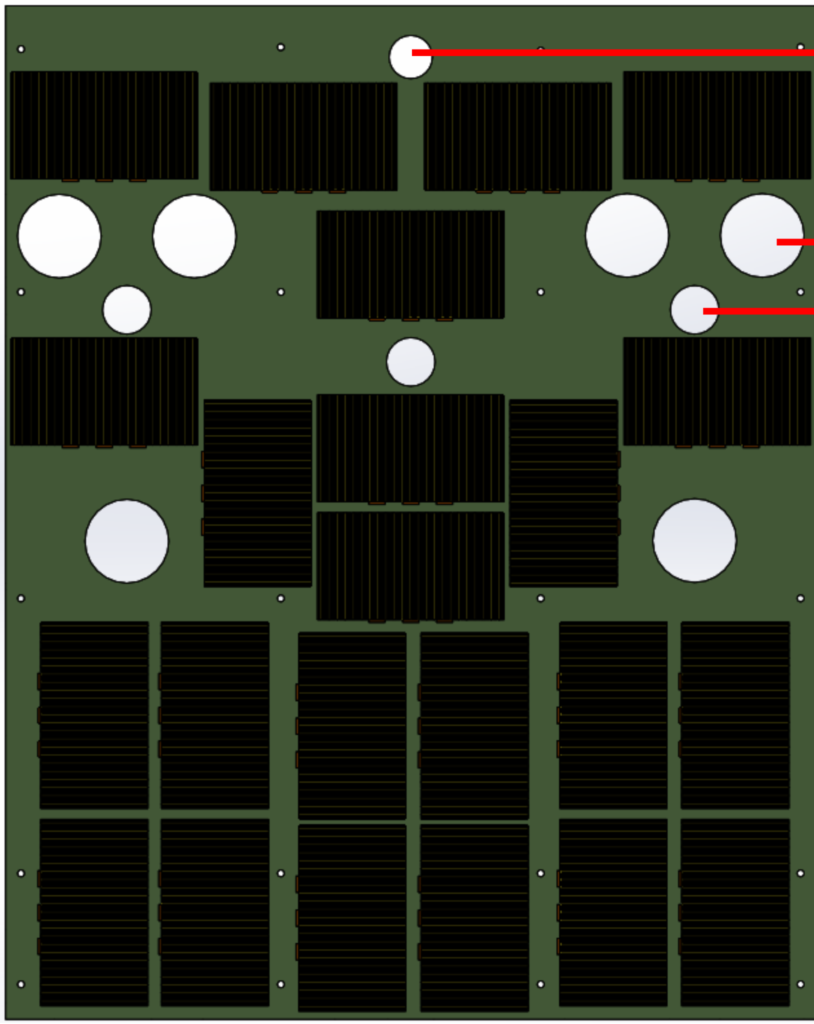
IR imaging



Solar Cell Placement: +X Face



General approach: Place cells wherever possible, even undesired orientations



Fine sun sensor/nadir sensor

Docking port

Frangibolt

Not shown

- **Coarse sun sensors**
- **Thermistors**

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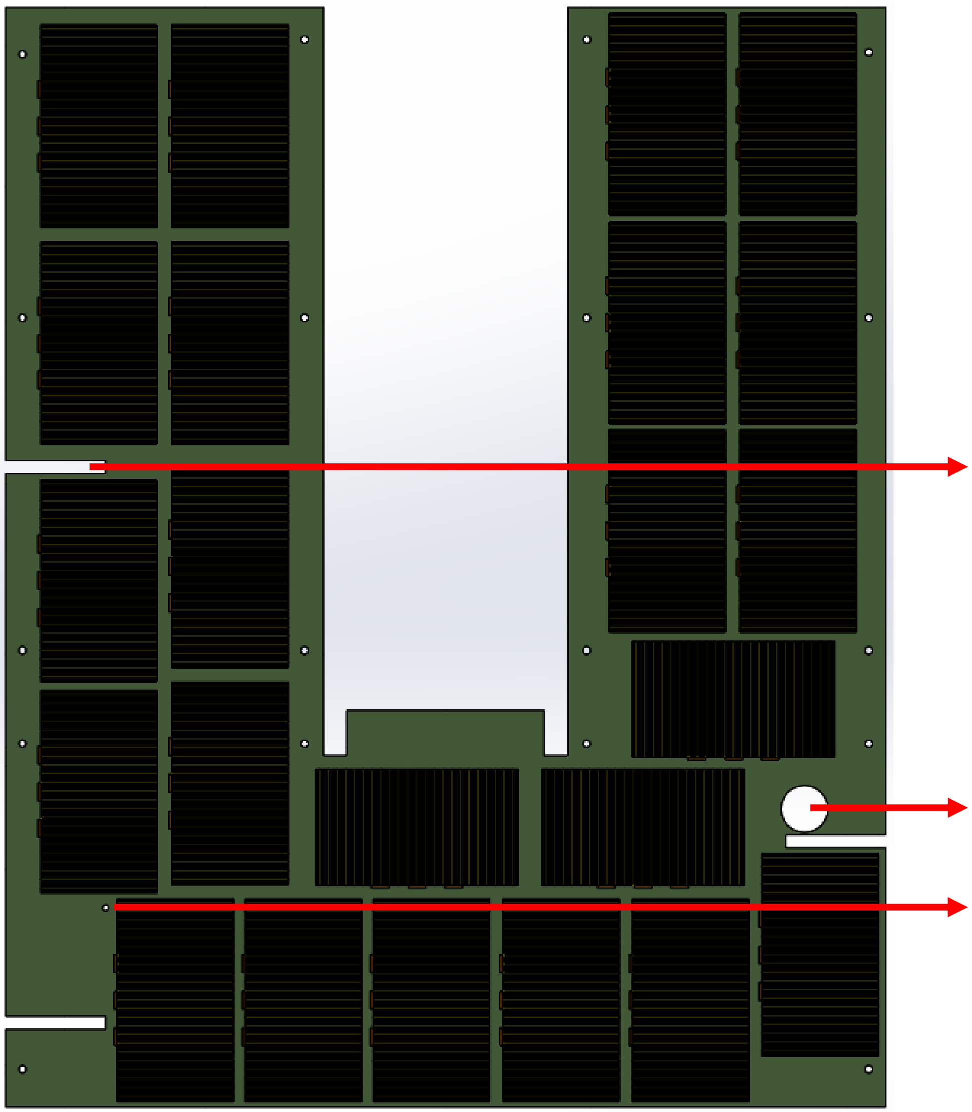
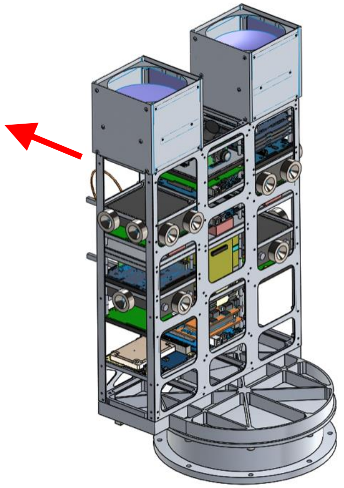
Solar Cell Placement: -X Face





Assumption: -X panel will be removed for tensioning the frangibolts during integration in India

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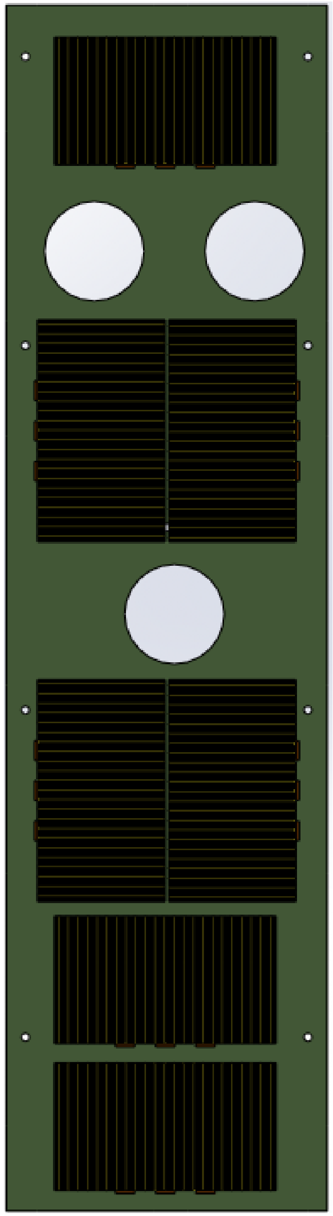
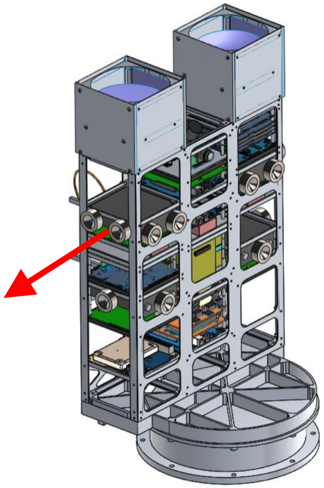
Solar Cell Placement: +/-Y Face



Not shown/unknown

- **LIDAR/LEDs/Optical camera for docking**
- **Access panel**



-X	+X	-Y	+Y	RMB	Total
23	23	7	7	12	**72**

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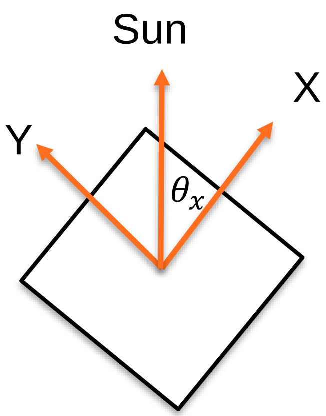
Total Power Available

	Spectrolab XTJ Cells	
Orientation	CoreSat OAP (W)	Total OAP (W)
Narrow optimal (θ_x=27.4°)	25.7	29.5
Wide optimal (θ_x=0°)	24.6	33.8
Detumble	7.9	12.3

[1]Noon-midnight sun synchronous orbit, 600 km
[2]Temperature, design and assembly-related losses: 20%
[3]BOL numbers due to short mission duration



Optimum angle $\boldsymbol{\theta_x = atan\left(\frac{A_y}{A_x}\right)}$

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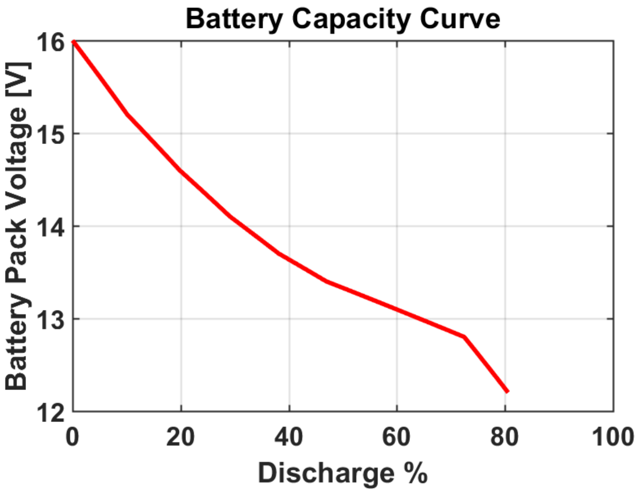
Battery Selection

- **GomSpace NanoPower BPX**
  - 77 Whr
  - 500 g
  - Integrated heater
  - 8 weeks lead time



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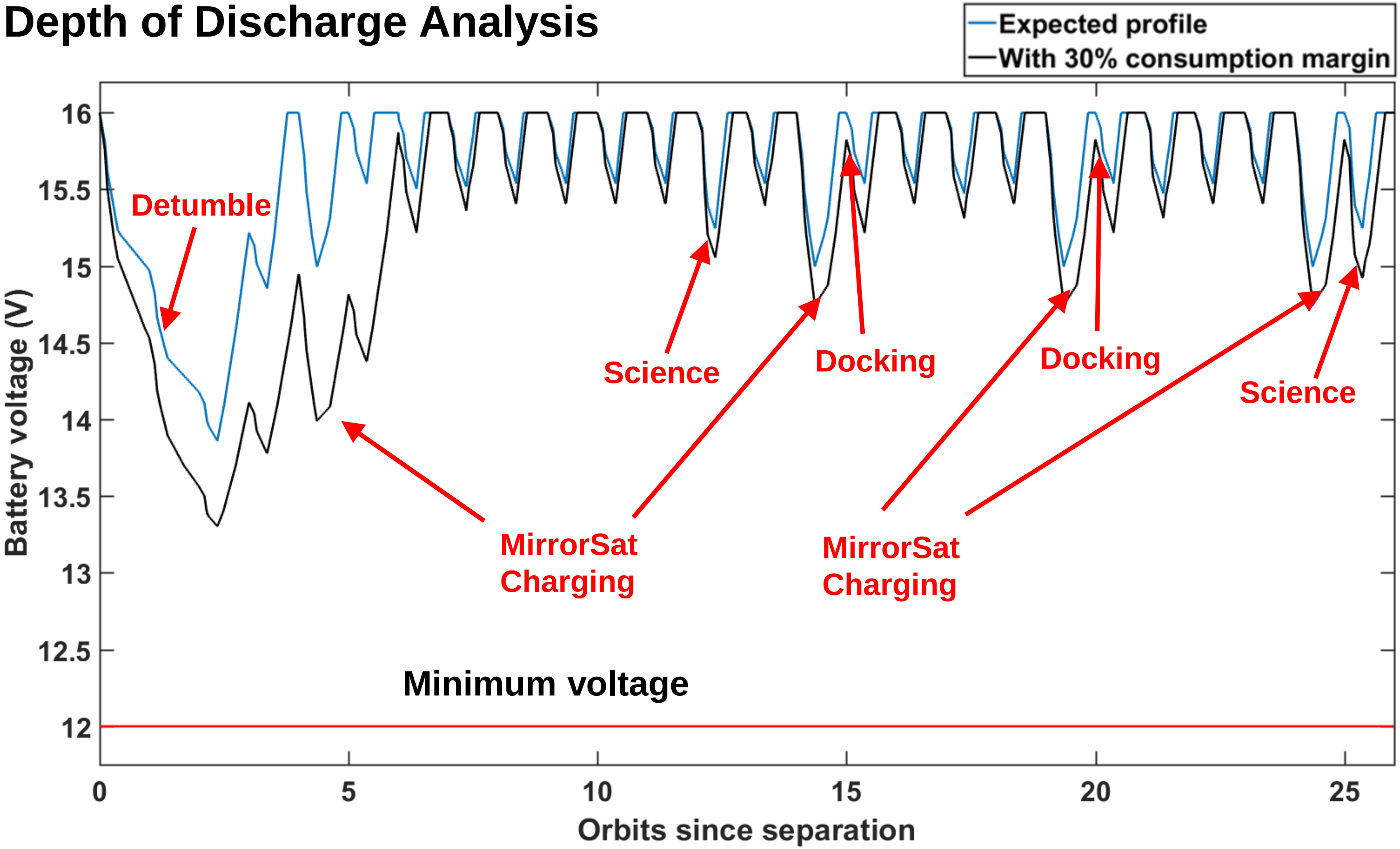
Depth of Discharge Analysis



- GomSpace BPX battery (77 Whr) provides sufficient storage
- Detumbling mode is the largest strain on the battery

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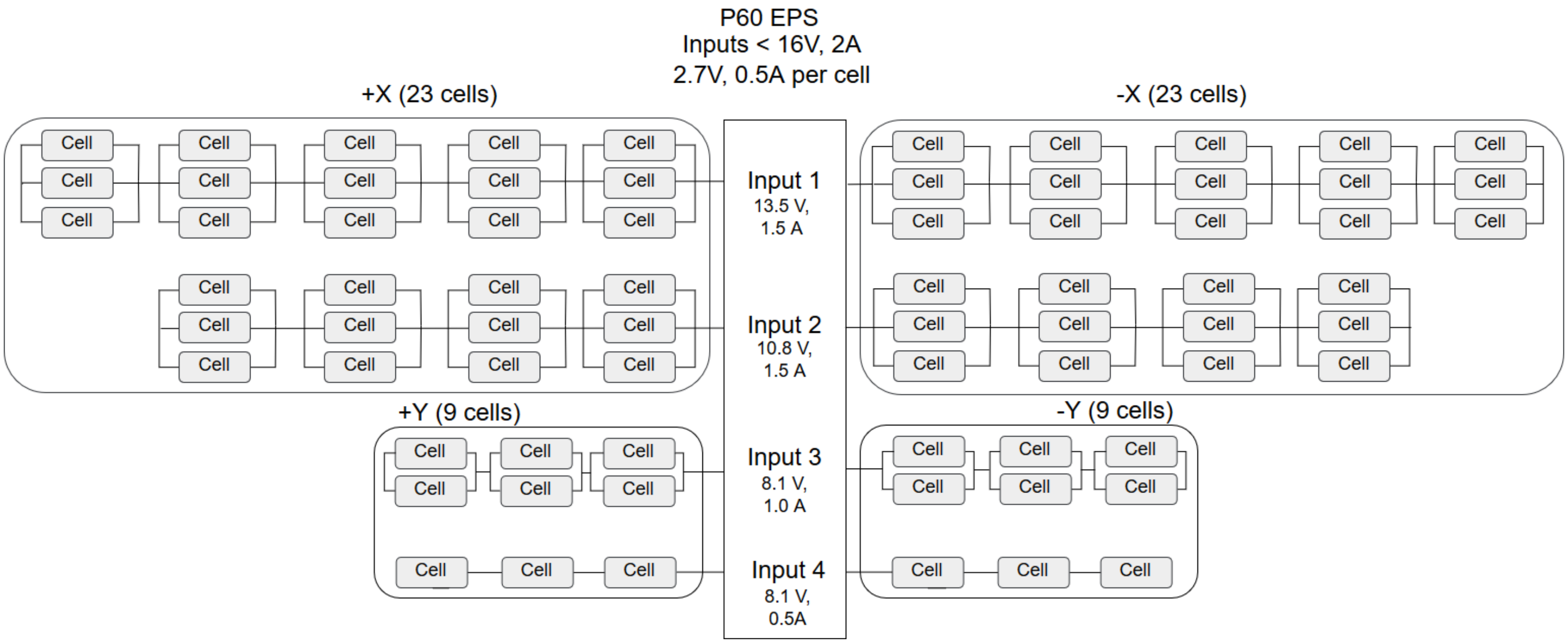
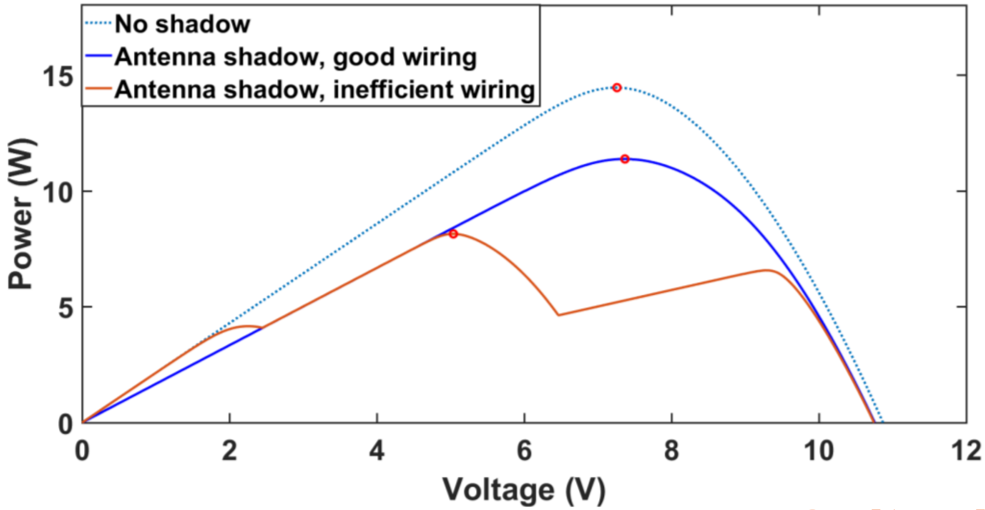
Solar Cell Wiring Schematic



- **Possible shadowing due to folded antennas, boom**
- **Inefficient wiring of shadowed cells leads to large power losses**



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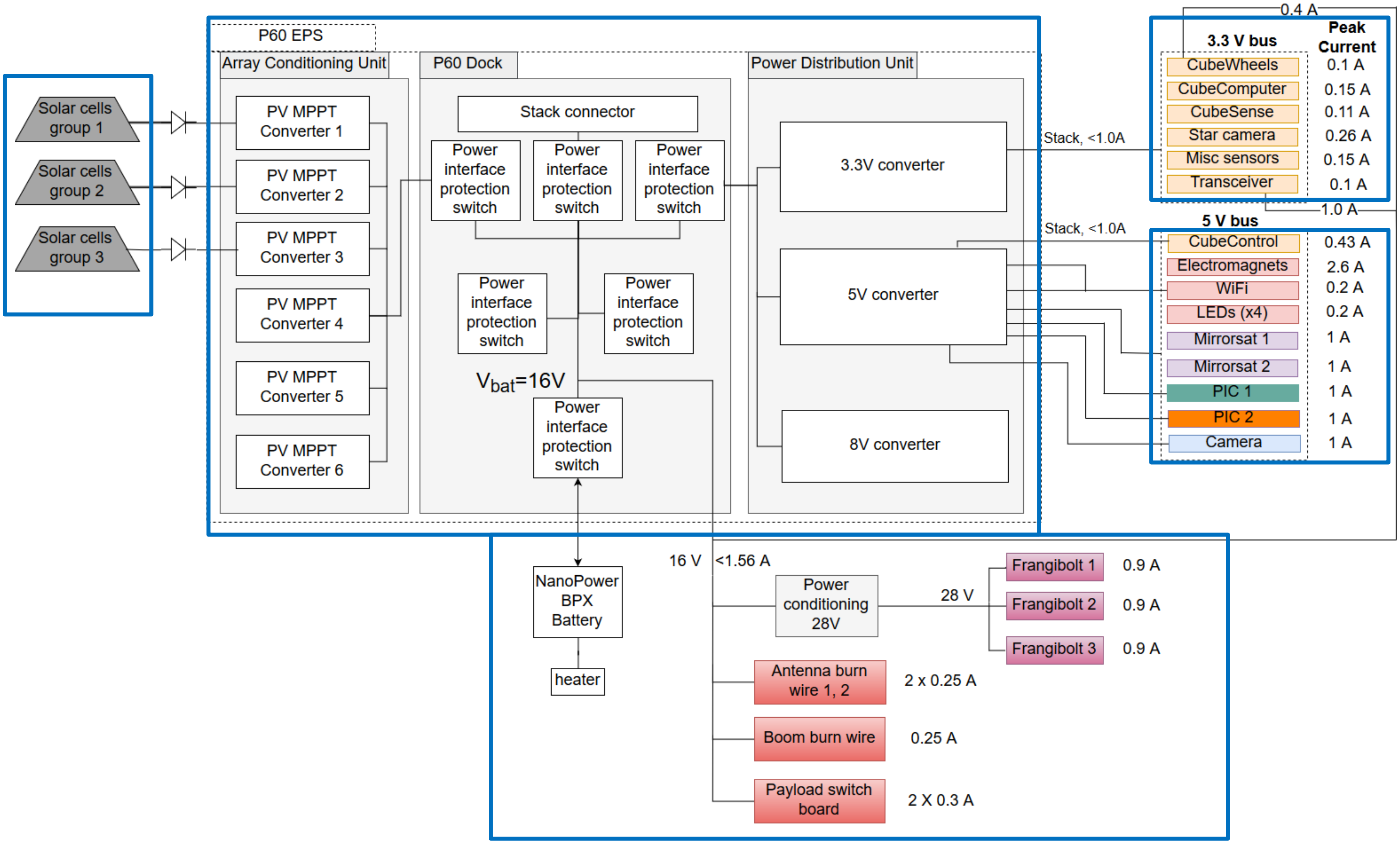
System Diagram



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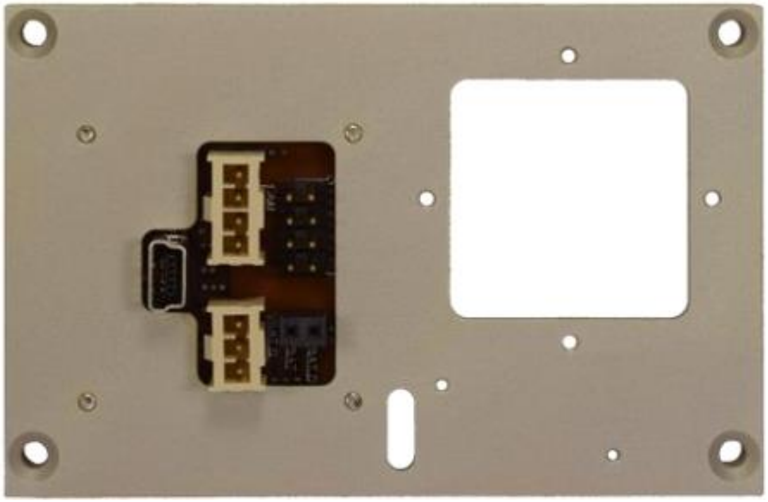
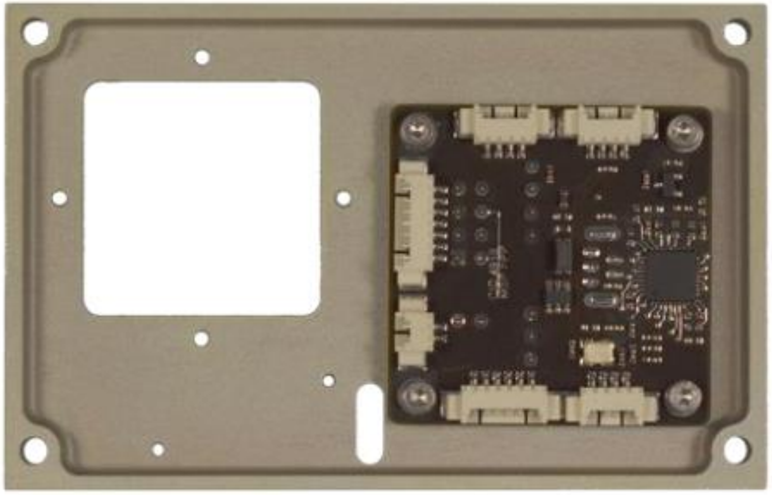
Pre-Launch Interface from Gomspace

- **USB charging**
- **CAN Interface to communicate with**
  - EPS
  - BPX battery
- **Battery voltage sensing pins**
- **RBF pins, kill switch**
- **Board dimensions: 32 mm X 32 mm**





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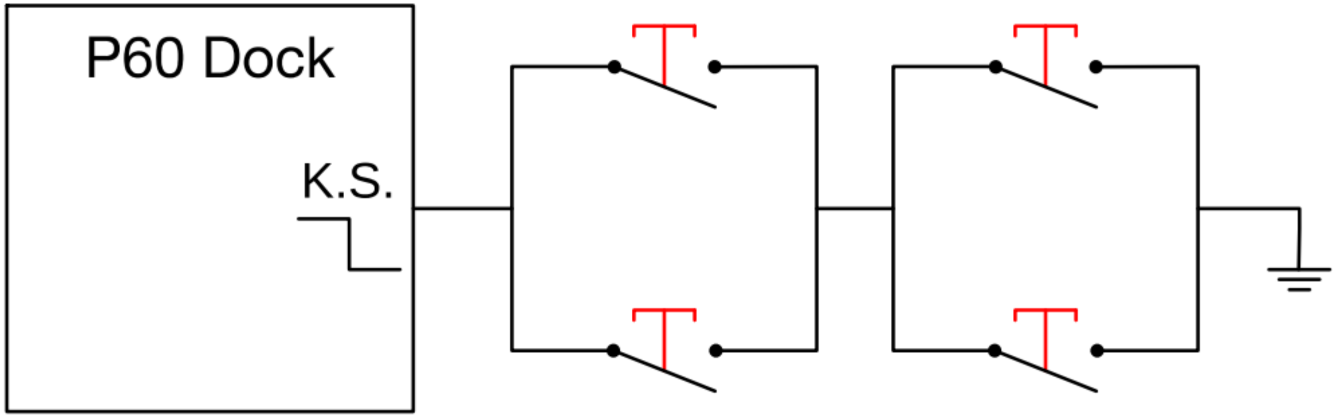
Inhibit Scheme (Separation Detection)



2 DPDT switches in series

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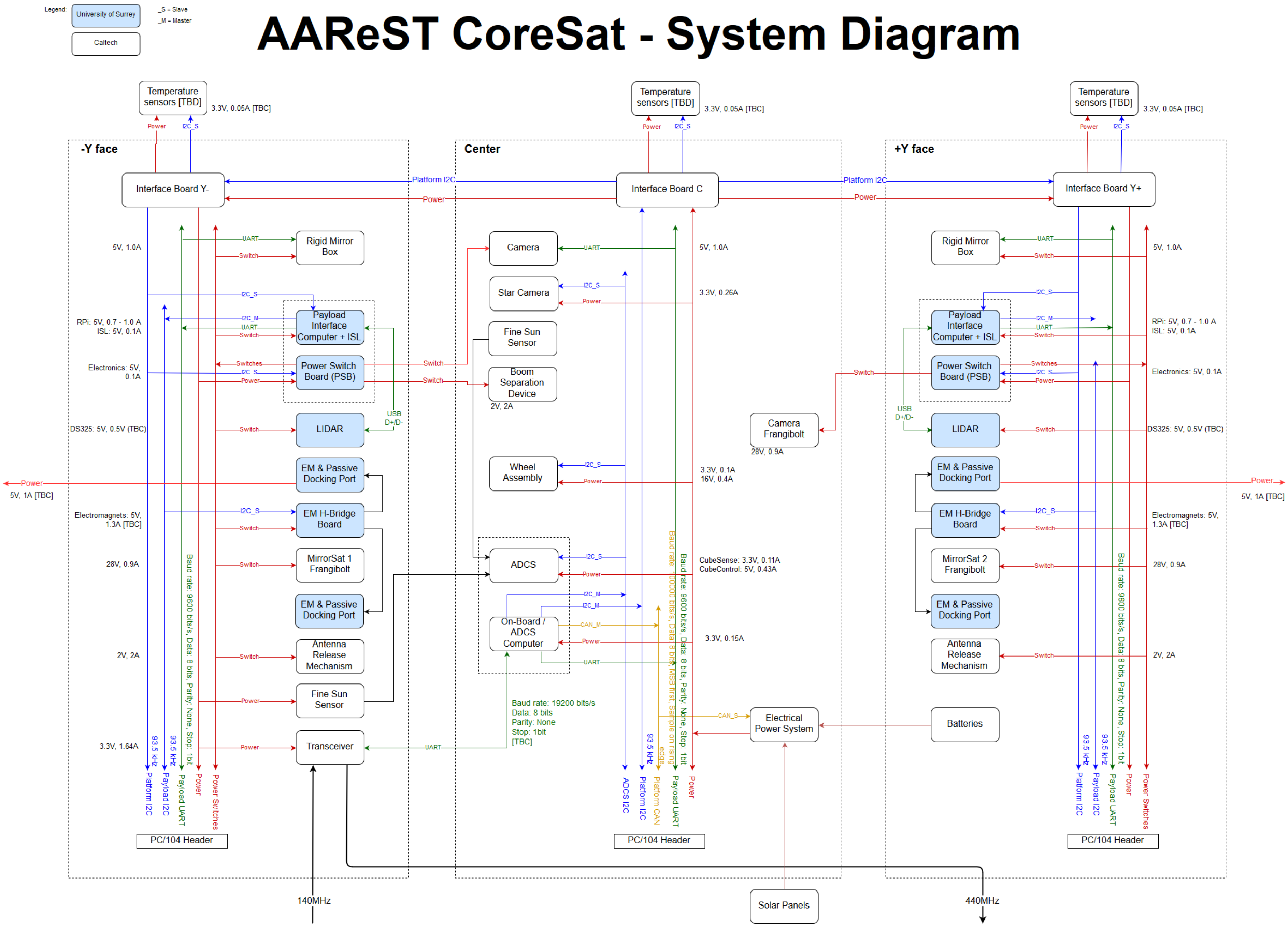
AAReST CoreSat - System Diagram



Unresolved Issues/Future Work

- **MirrorSat charging interface**
- **Dimensions and locations of docking-related sensors**
- **Number and location of separation switches**
- **Functionality of payload switchboard**
- **Location of access port**
- **Finalizing cabling scheme**
- **PC104 header compatibility checks**

space structures laboratory

Thank you

Questions?

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CoreSat Structures

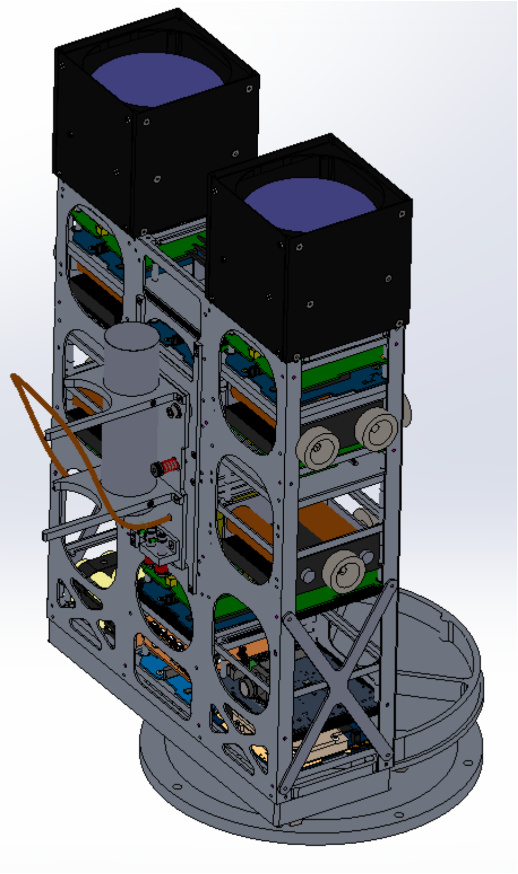
Christophe Leclerc
Mélanie Delapierre
Federico Bosi

September 11 2017

Outline

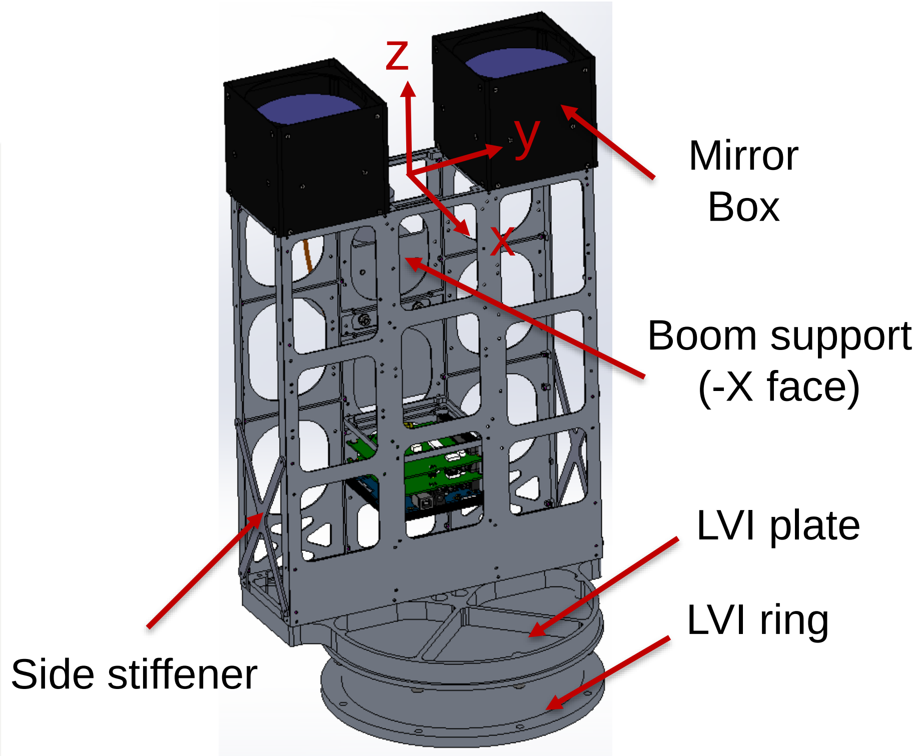
1. CoreSat Design
   - Requirements
   - Structural Design
   - Internal Configuration
   - Interfaces
2. FEM: Launch Survivability
   - Model Description
   - Results
3. Future Work

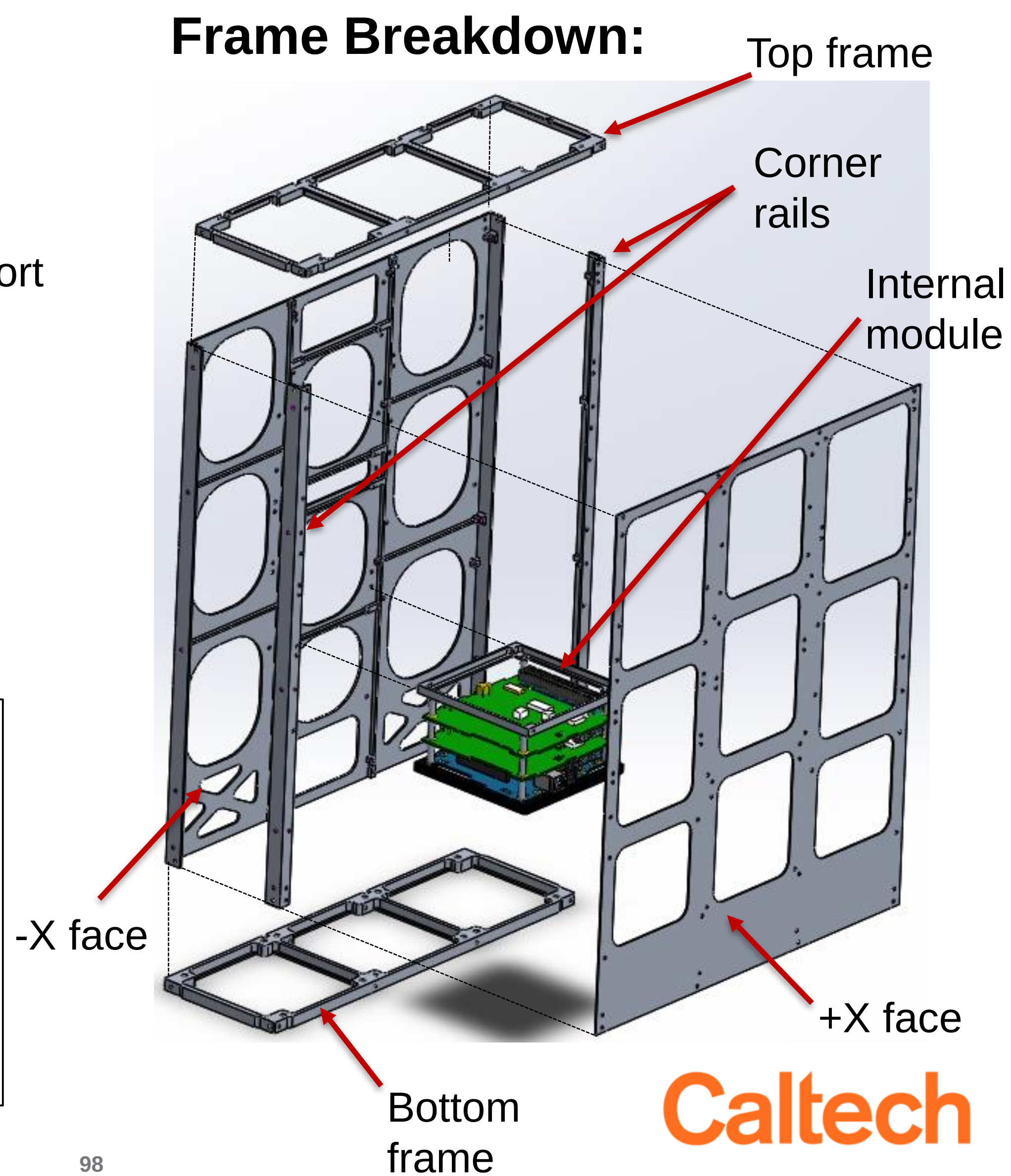
Main Structural Requirements



- Withstand launch environment, with critical acceleration of 11 g
- Natural frequencies must be higher than (TBC):
  - 90 Hz (longitudinal mode)
  - 45 Hz (lateral mode)
- Provide accurate positioning of optical systems:
  - Mirror boxes
  - Boom support
  - Docking ports
- Provide mechanical support for all subsystems
- Use CubeSat standards for subsystem components (96 mm x 96 mm PCBs)
- Provide vertical clearance of 50 mm for MirrorSat docking maneuvers

CoreSat Structural Design

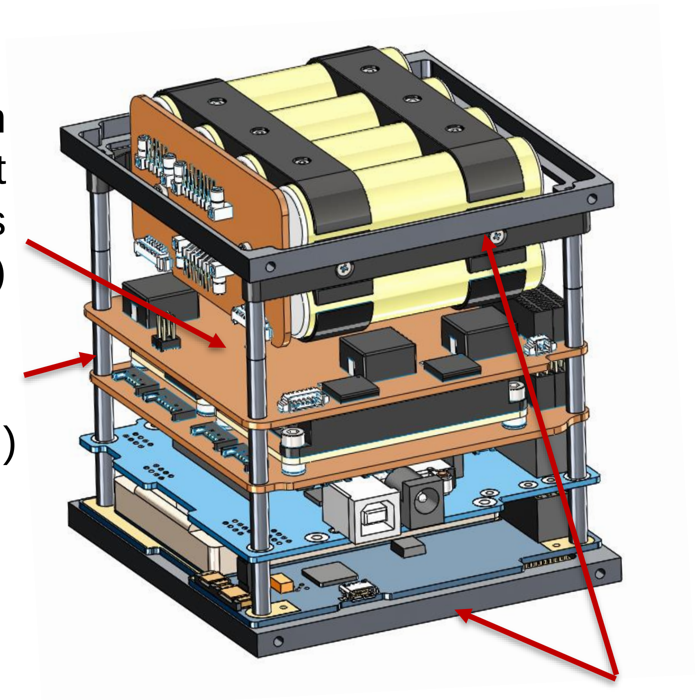




Design Guidelines

- Flexibility for components positioning
- Optical calibration independent of internal assembly
- Flexible clearance at the bottom

Internal Module Assembly



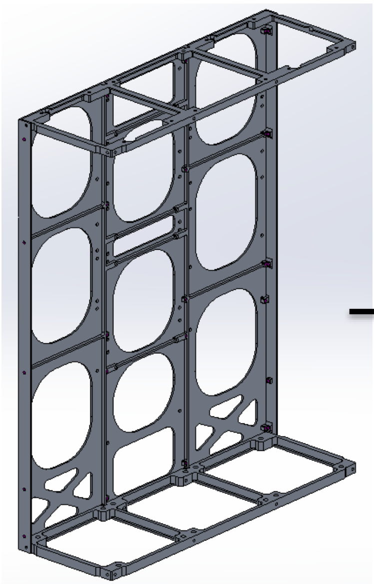
Example: Power system

- Mount internal components in CubeSat standard PCBs
- Group internal components in modules
- Modules are mounted between +X and –X faces contributing to the stiffness and stability of the CoreSat

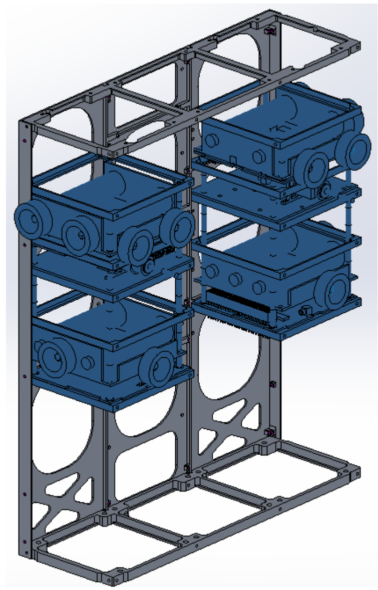
Modular design allows for modules to be assembled, tested, and replaced individually

CAD source: Gomspace

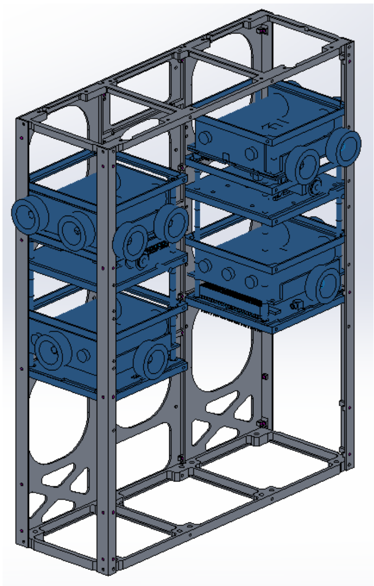
Optical System Assembly



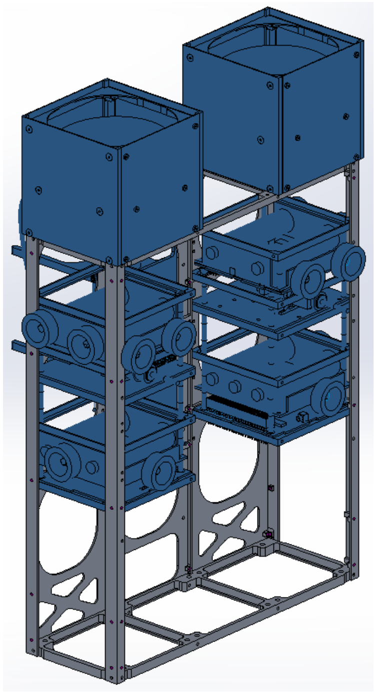
(1)
- -X face
- Top and bottom frames



(2)
- Add docking ports



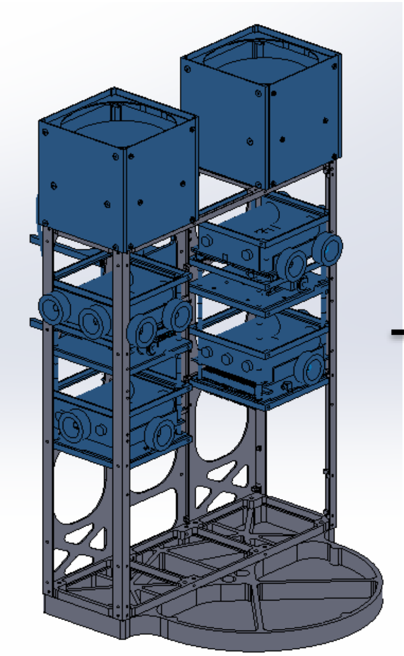
(3)
- Add corner rails



(4)
- Add remaining optical system
- Optical system can be aligned independently of other subsystems

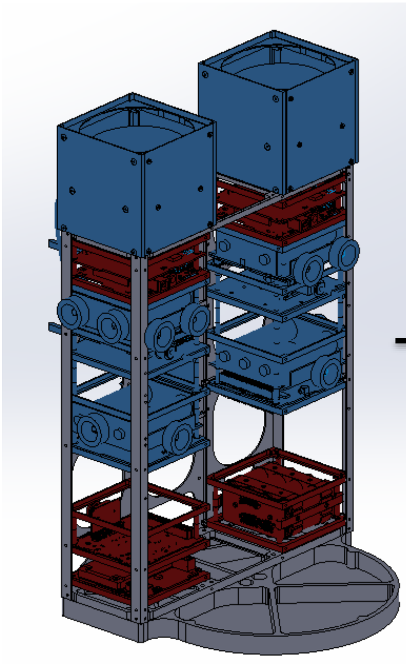
Structure
Optical system

Complete Assembly



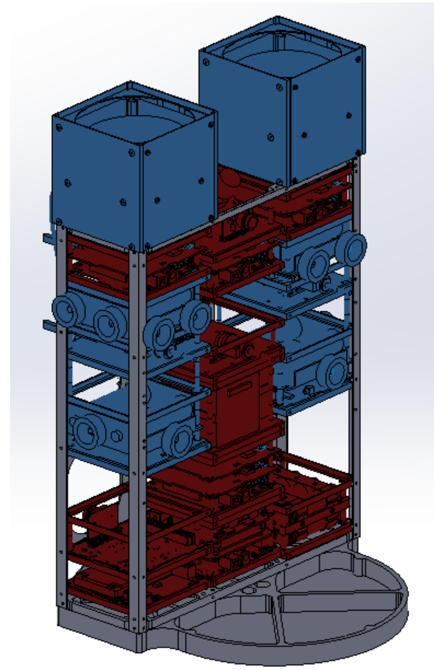
(5)

- Add LVI plate



(6)

- Add side components

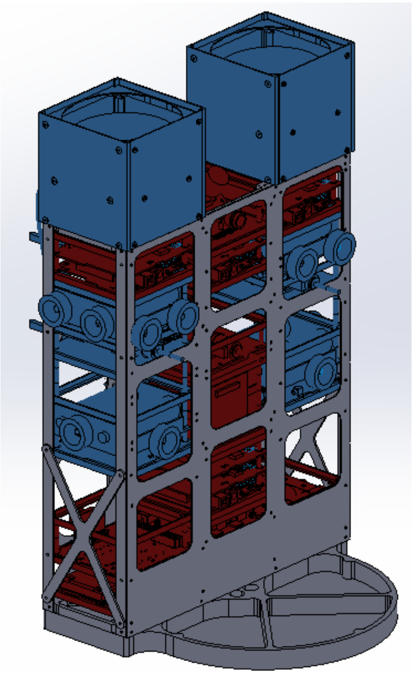


(7)

- Add central components

(8)

- Add solar panels



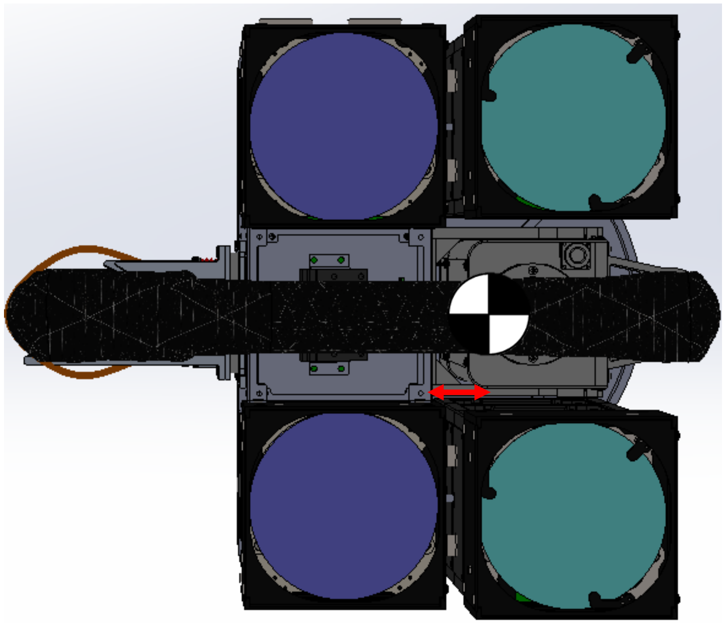
(9)

- Close +X face and stiffeners (with solar panels)

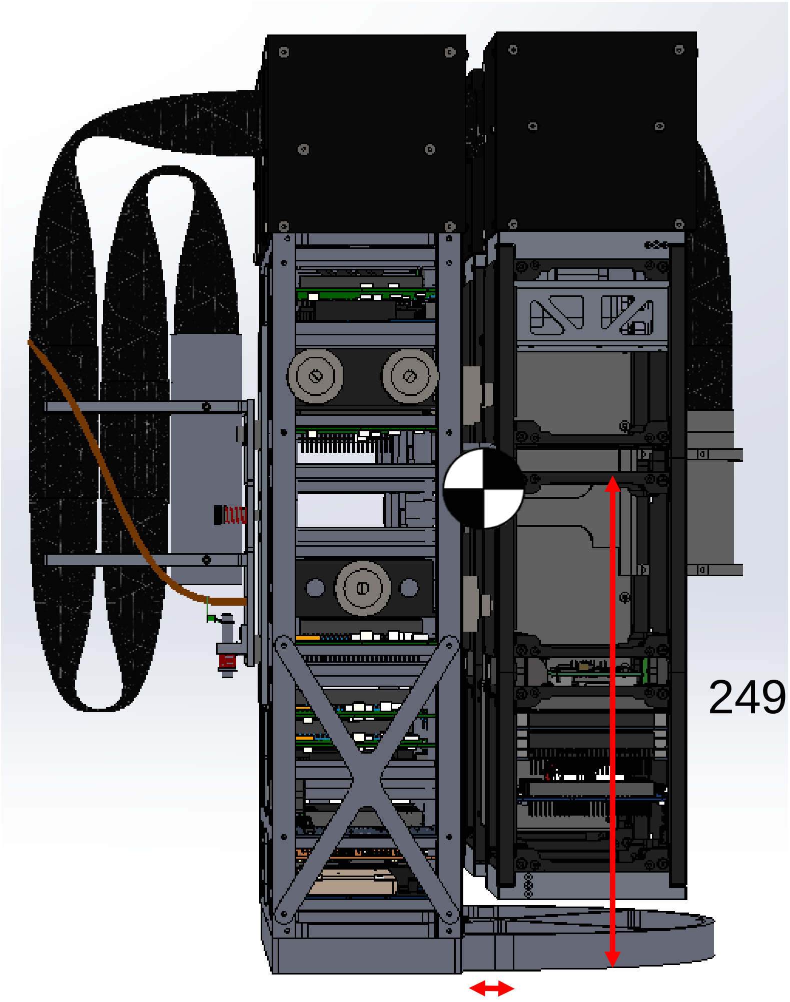
Structure
Optical system
Other components

Modular design allows for flexibility in assembly

CG Location (Launch)



21 mm (in front of the CoreSat)



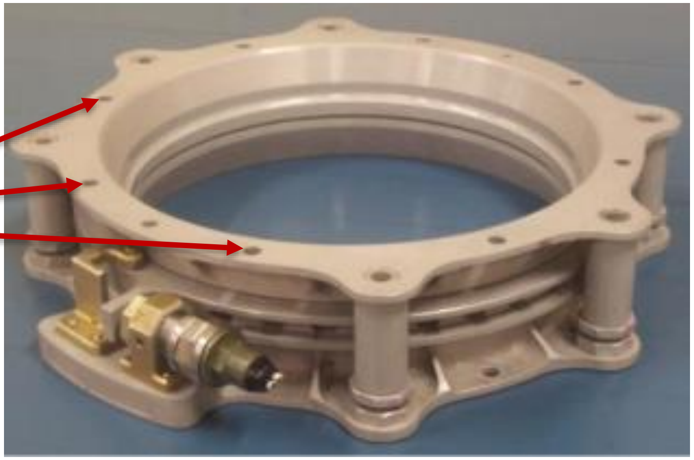
8 mm (from the center of the LVI)

LVI Adapter Plate

- Indian Space Research Organisation (ISRO) IBL230 separation device used in PSLV
  - CoreSat must attach to this ring
- Dimensions and properties
  - 8 M6x1 mounting holes, clearance on ring
  - Pitch Circle Diameter (PCD) of 230 mm
  - 0.6 kg retained on satellite after separation

230 mm PCD

8 equally spaced mounting holes



Part of ring that remains **on launch vehicle** after separation

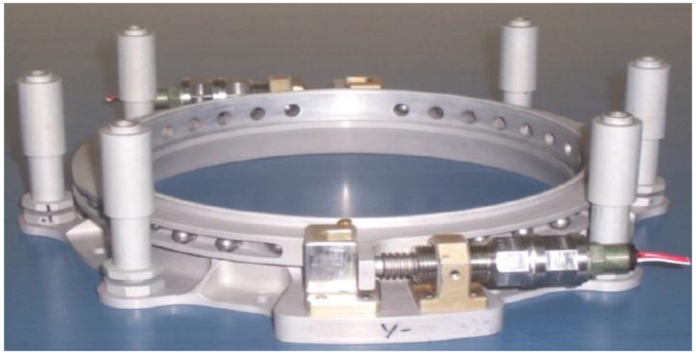
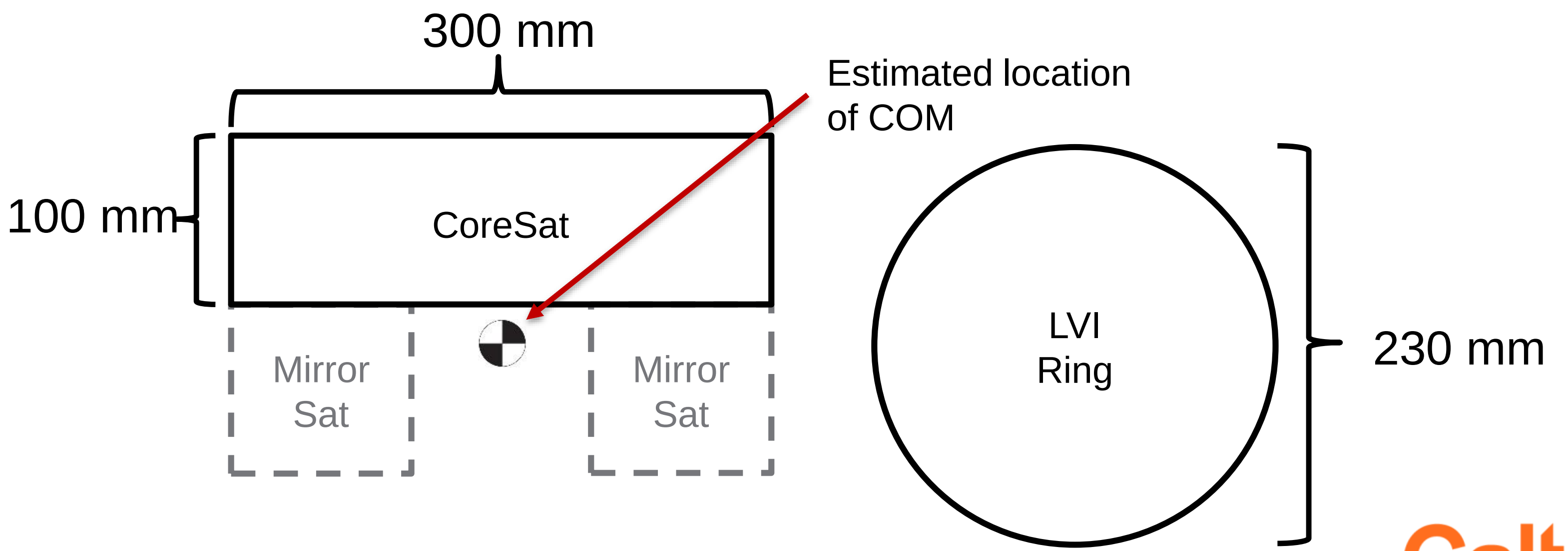


Image Source: IBL230 datasheet

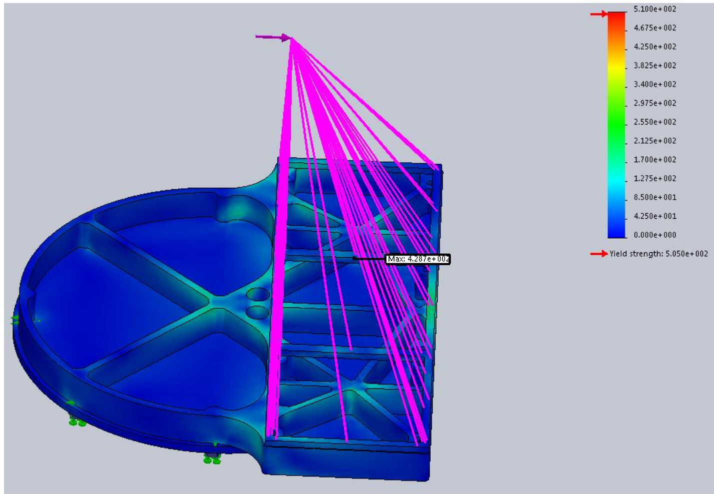
LVI Adapter Plate

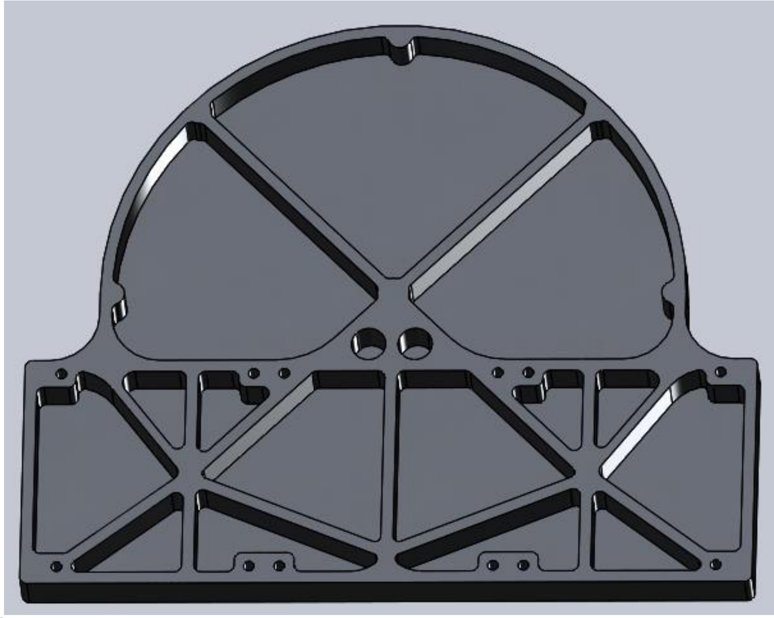
- Must withstand peak accelerations during launch without failure (yield)
- Must place center of mass (COM) of AAReST in its stowed configuration over center of LVI ring
- Should utilize all 8 mounting holes on LVI ring
- Should distribute launch loads evenly
  - Concentration of loads in one location could result in failure

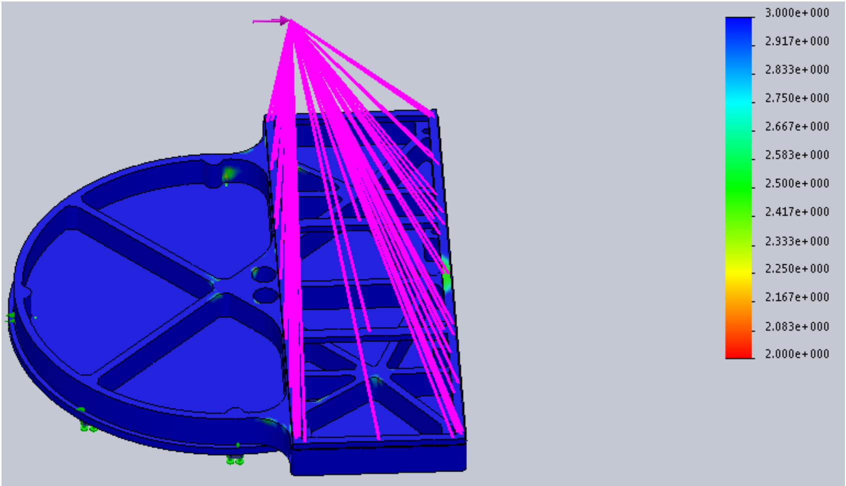


LVI Adapter Plate

- Parameters: 25g steady, 27kg, yielding 505MPa (preliminary study done with NASA standard)
- Latest mass: 980g
- Safety factor 2+ (except at screws)
- Loading at CG: 6 directions + corner







List of Components

- ADCS
- Reaction wheels
- Power
  - EPS
  - Batteries
- HDRM
  - MirrorSats separation devices (x2)
  - Camera separation device
- Docking ports
- Star camera
- Sun sensor (x2)
- Payload Interface Computer (x3)
- Interface board (x3)
- Antenna release mechanism (x2)
- Radio transceiver

Priority for Central Stack:

1. HDRM (camera)
2. Wheels
3. Payload Interface Computer
4. Components using PC/104 (ADCS and EPS)
5. Batteries
6. Transceiver

Other decision drivers:

- Optical alignment
- CG management
- PIC should be close to the mirror boxes
- Sun sensors and star camera must have sufficient field of view
- *(Thermal management)*

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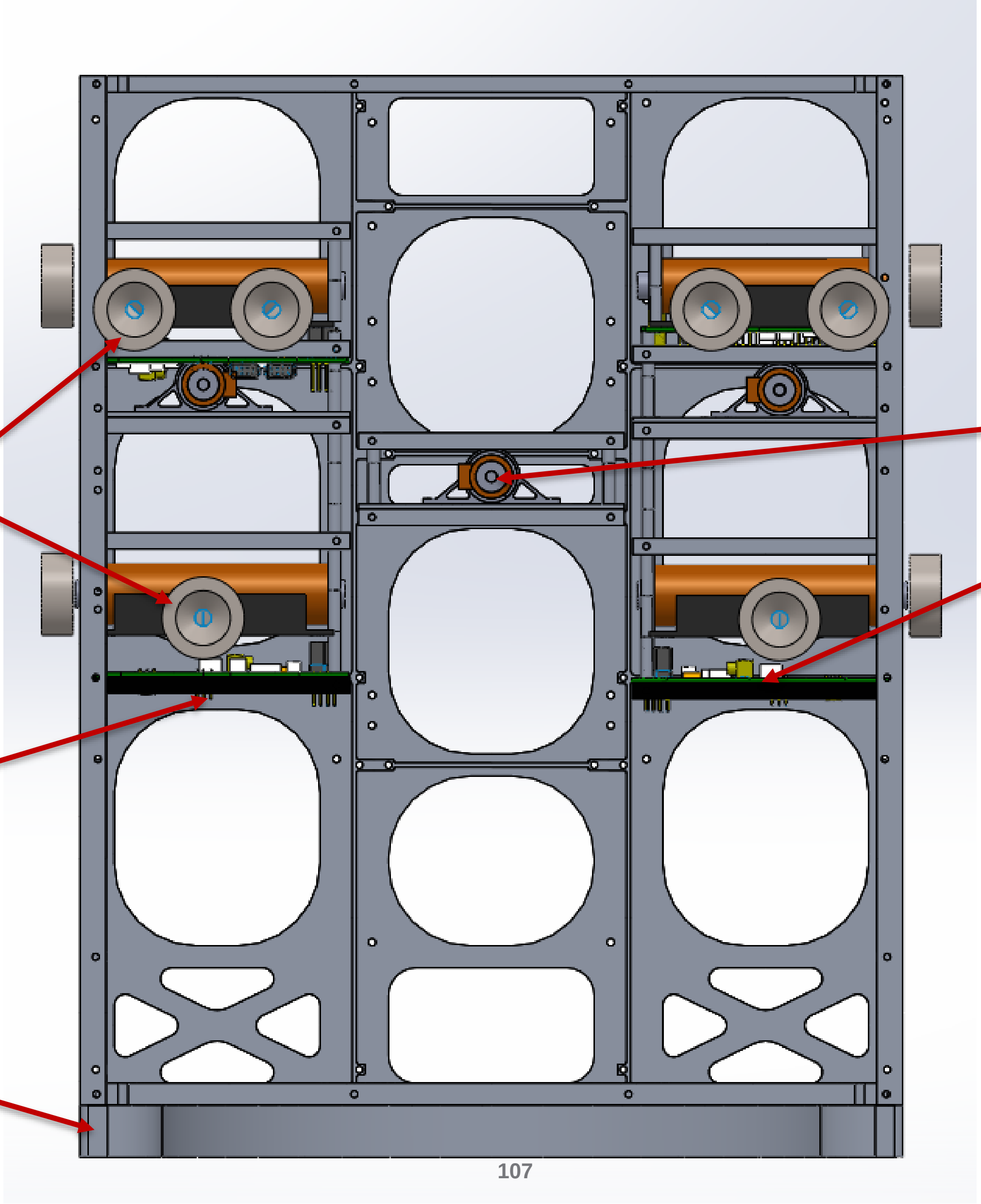
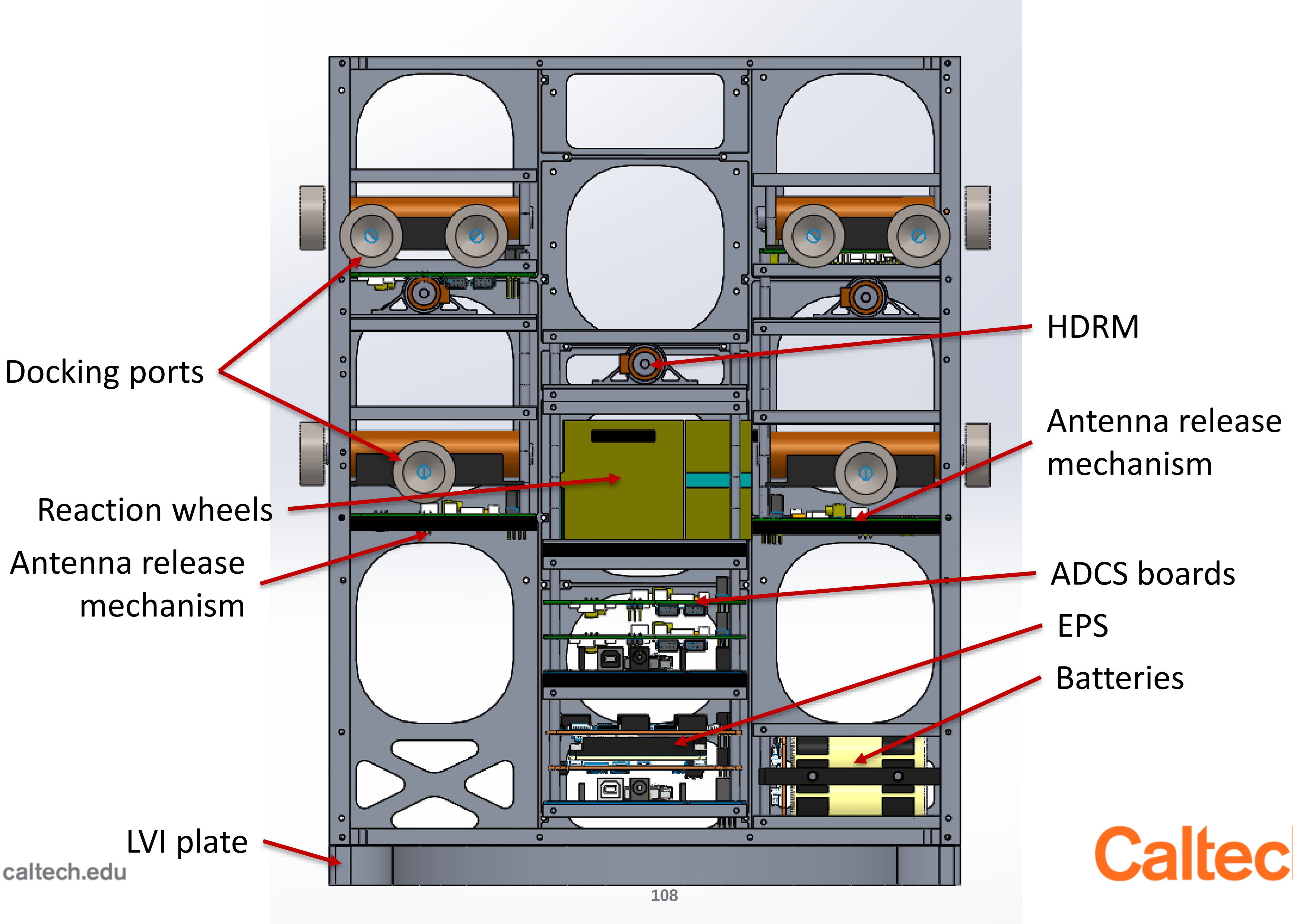
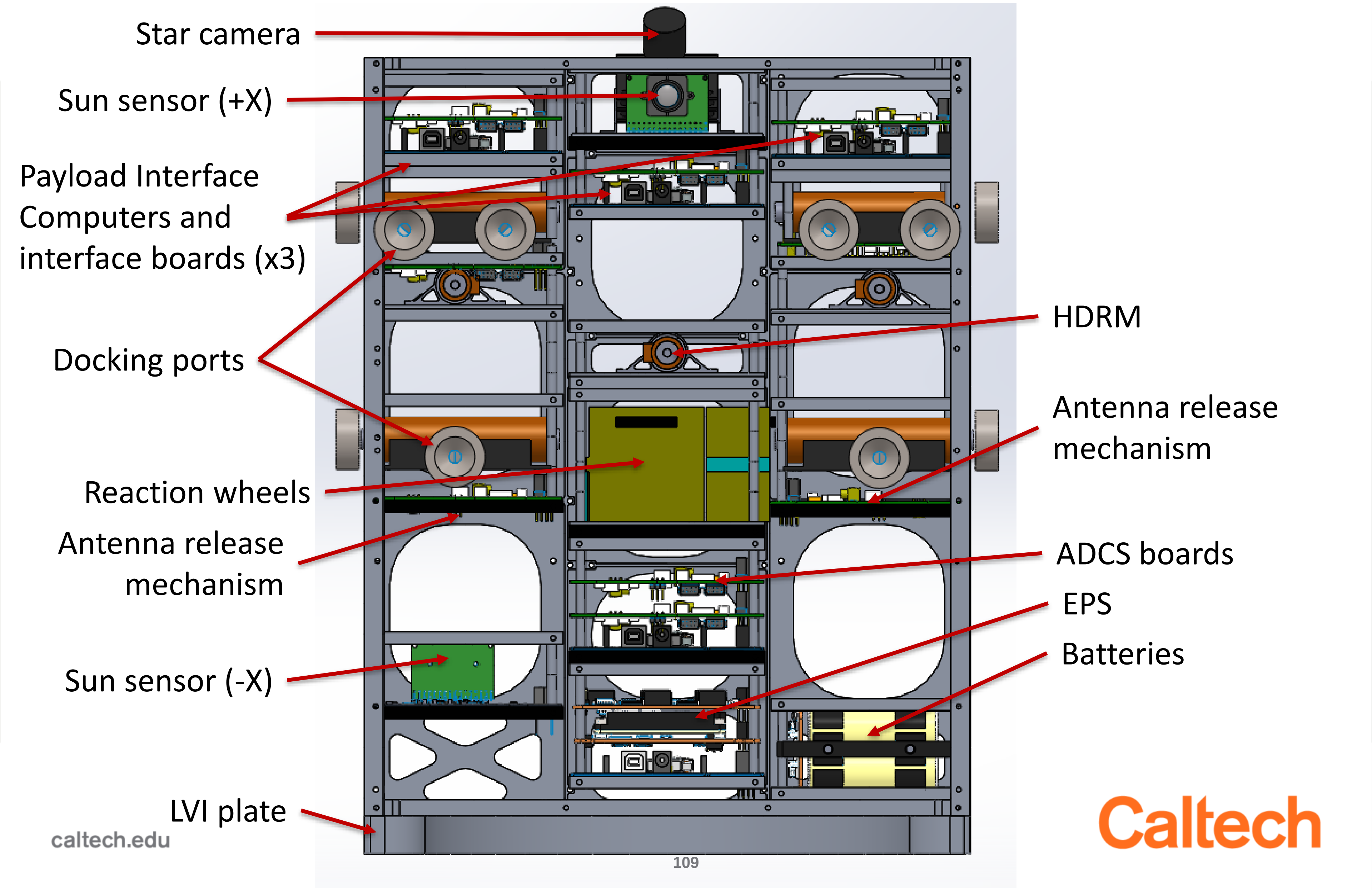
Positioning of Components



Positioning of Components



Positioning of Components



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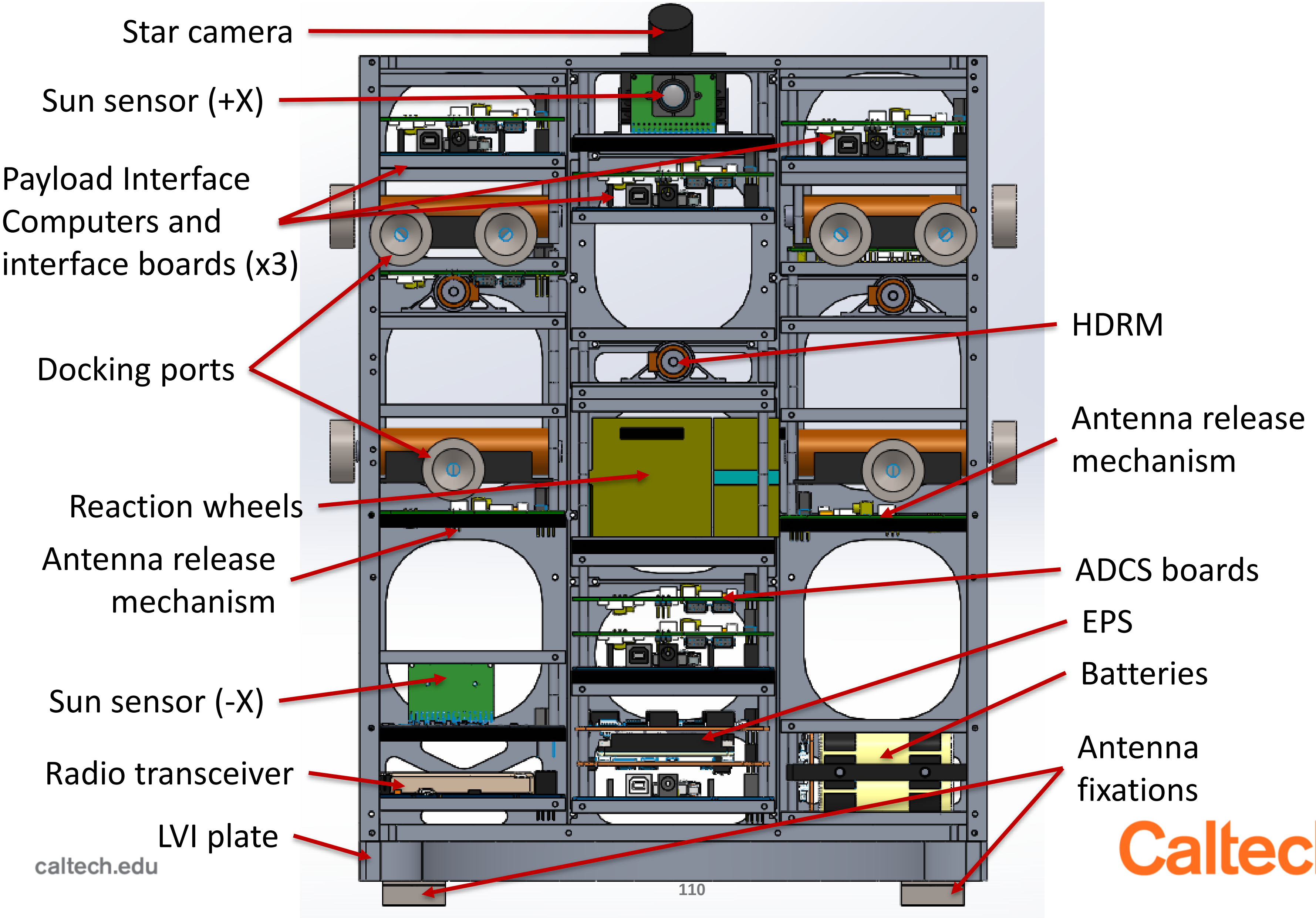
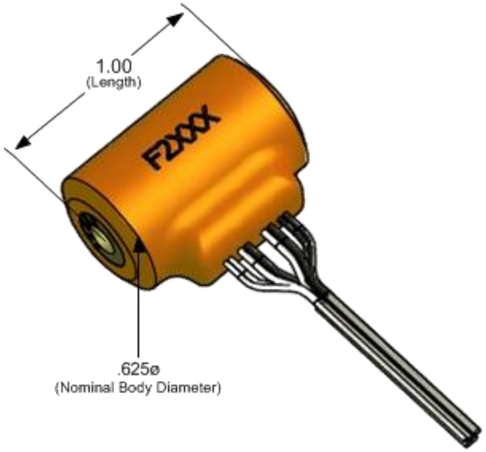
Positioning of Components



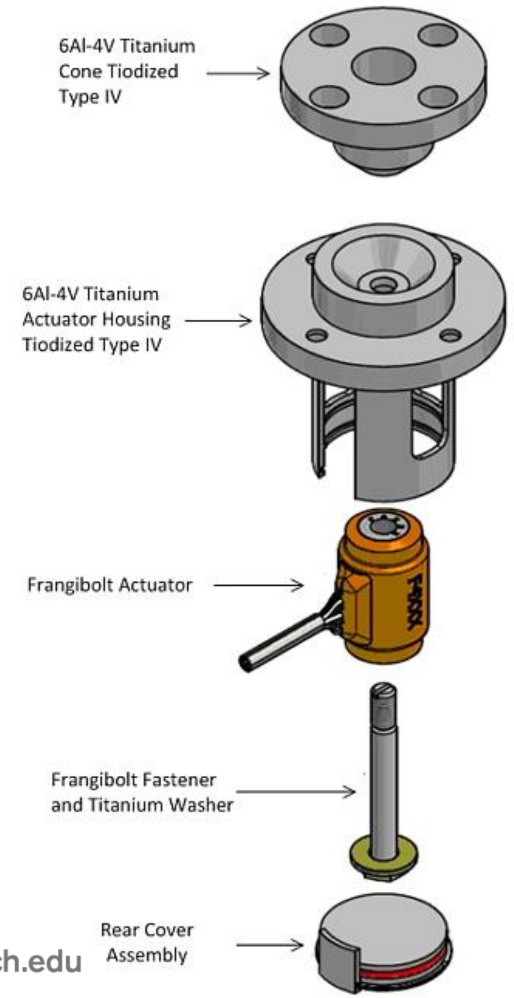
Interfaces

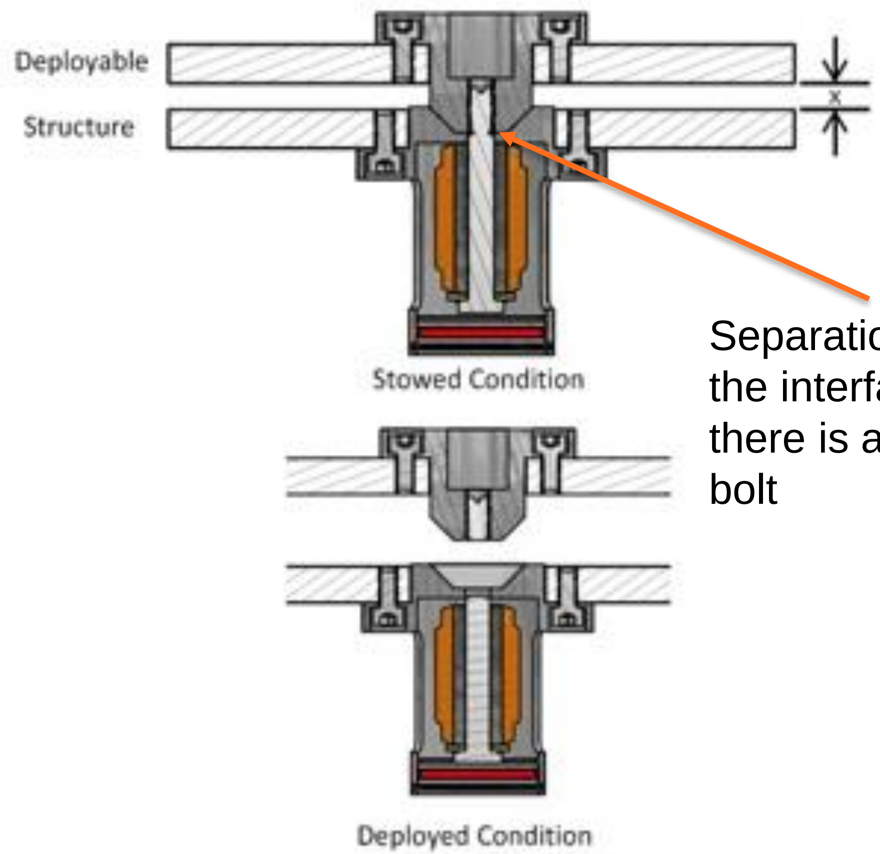
- The CoreSat has deployable interfaces with 2 components:
  - MirroSats
  - Camera
- A study led to the selection of the TiNi FC2 Frangibolt as the Hold Down and Release Mechanism (HDRM) for both types of separation
  - Compatible with power system
  - Sufficient load capacity
  - Small enough to integrate inside the current design



TiNi FC2 Frangibolt

- Standard way of using a Frangibolt is with a single cup and cone interface

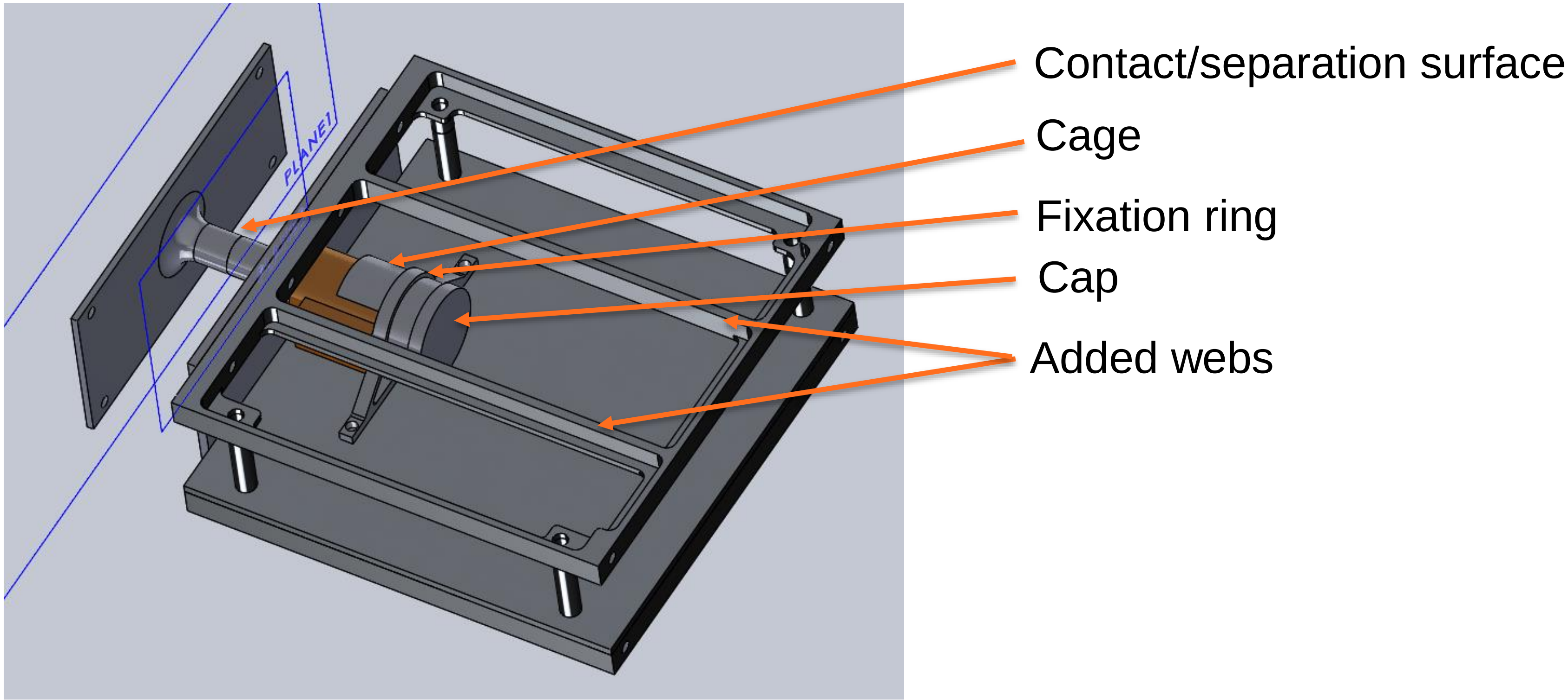




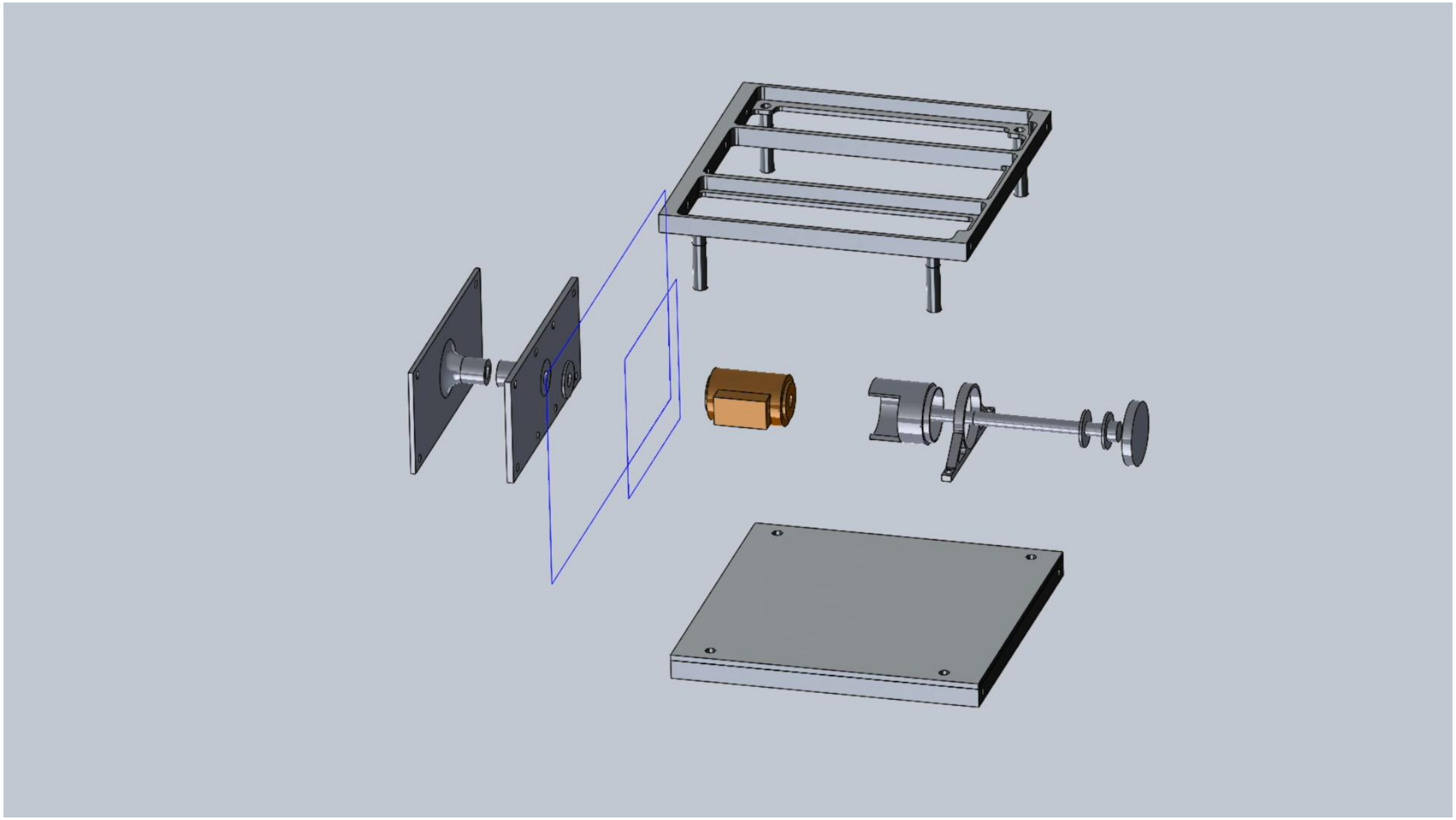
Separation occurs at the interface, where there is a notch in the bolt

TiNi FC2 Frangibolt

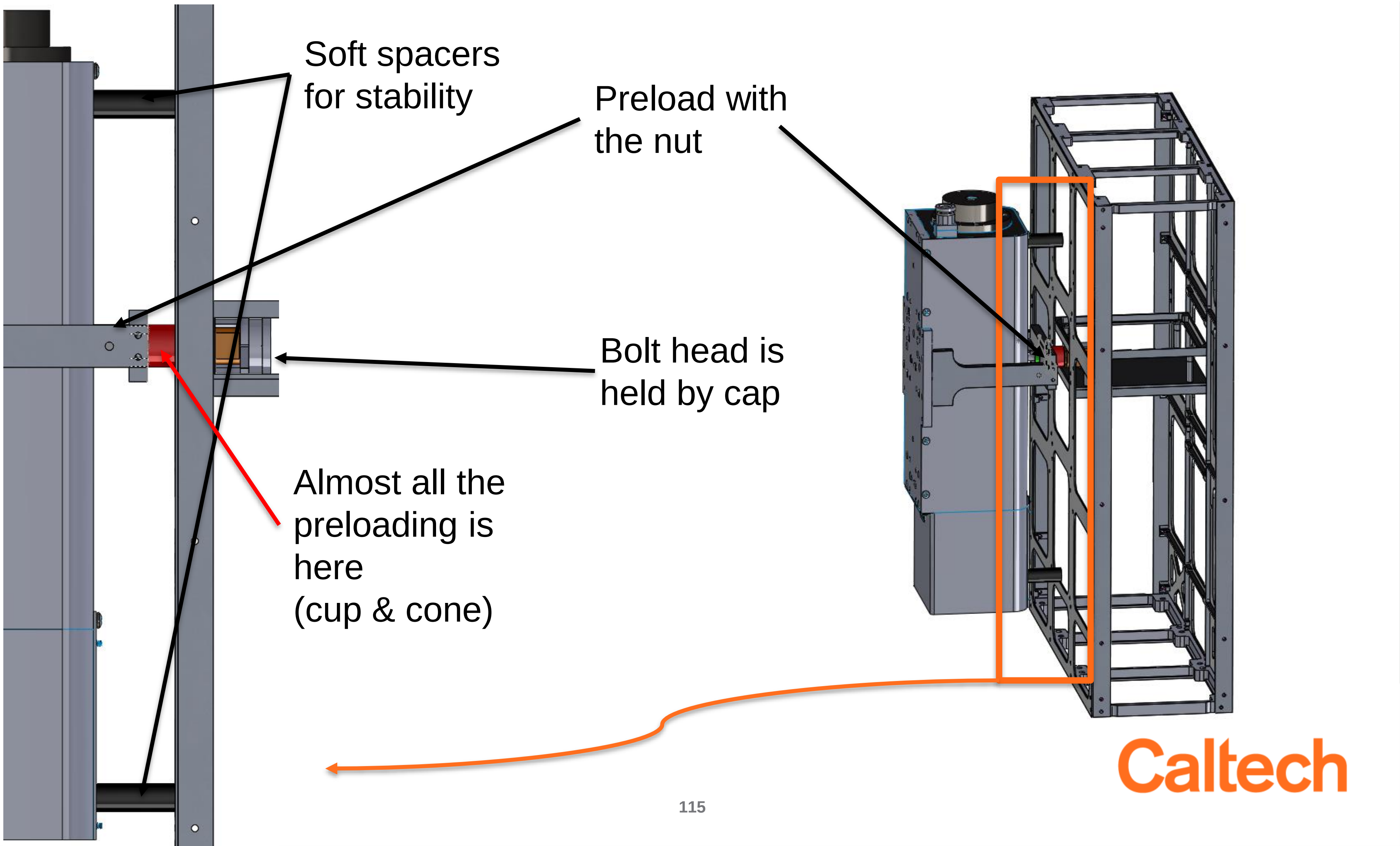
- A new architecture was designed to integrate the Frangibolt in the CoreSat
- Release load: 4 448 N



TiNi FC2 Frangibolt



Interface to Camera



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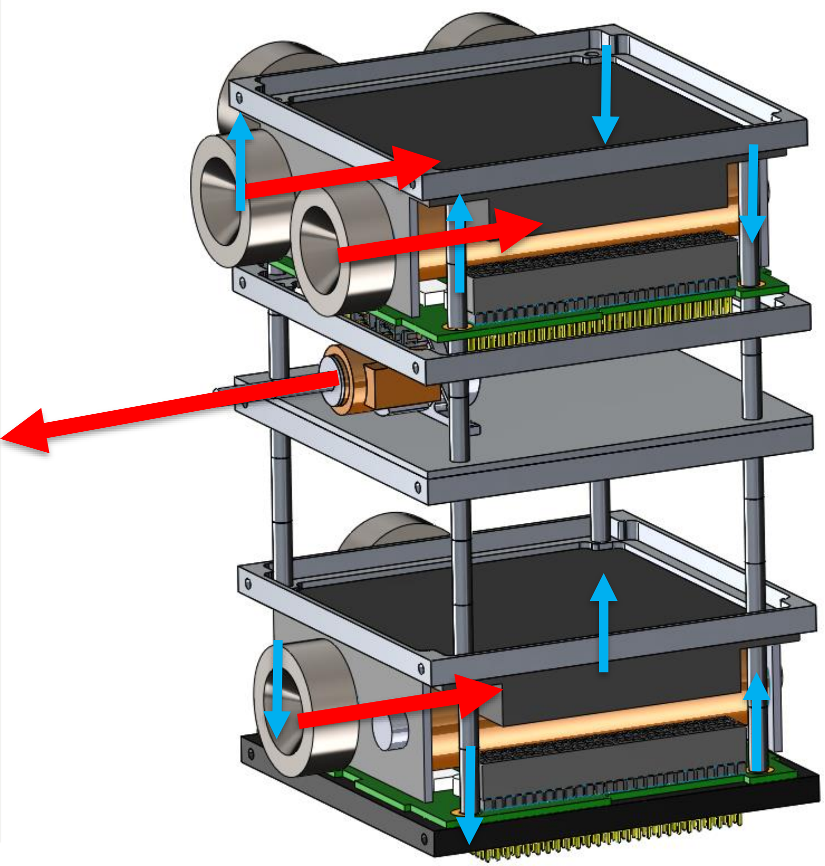
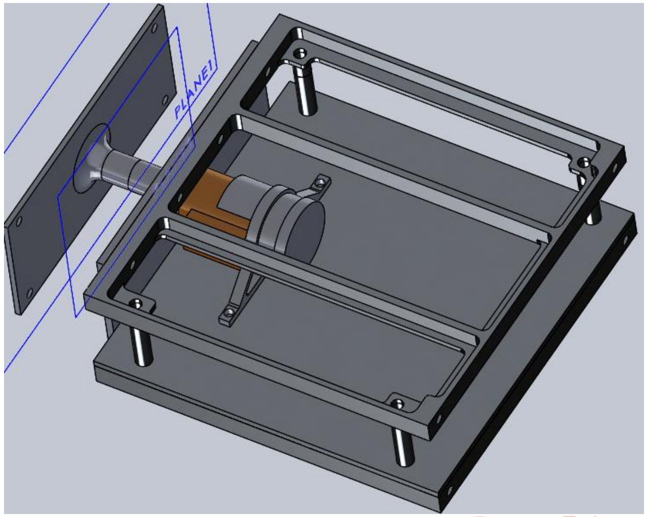
Interface to MirrorSats

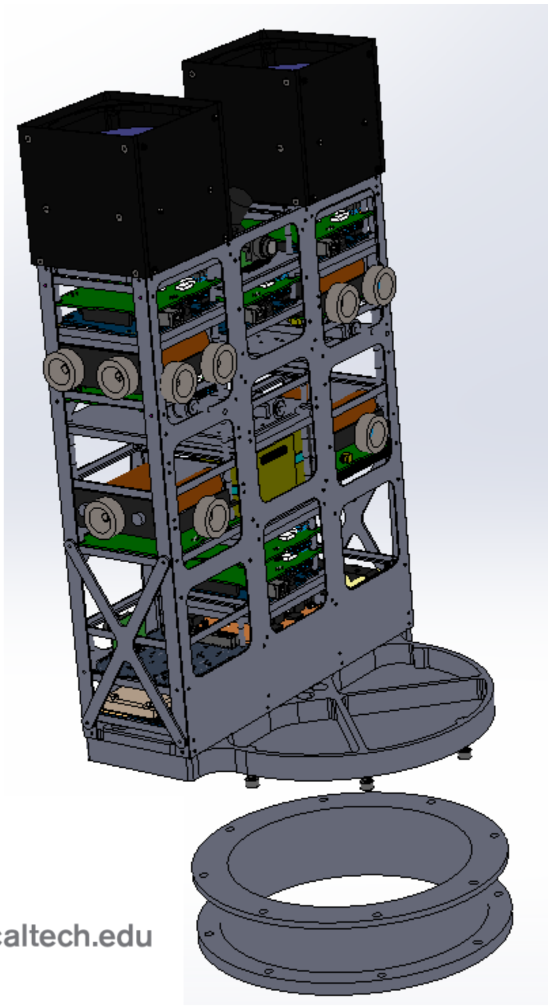


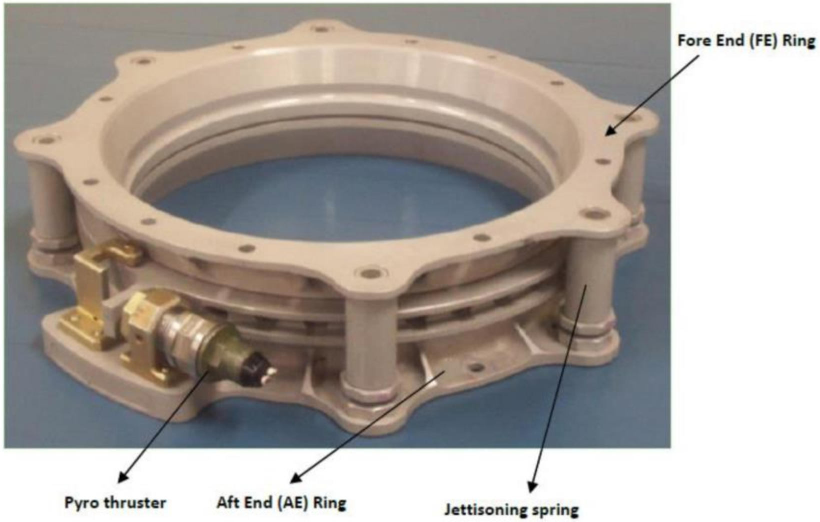
Goal:
- Preload docking ports for launch, gap needed at HDRM
- Contact at HDRM for release loading

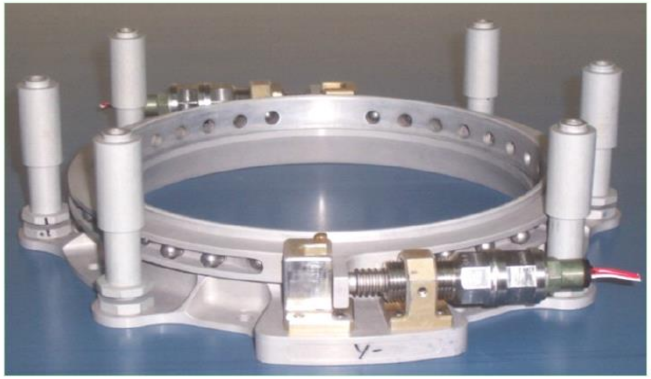


Open Issues

- Location of the separation switch
  - Can we have anything reaching through the LVI ring?

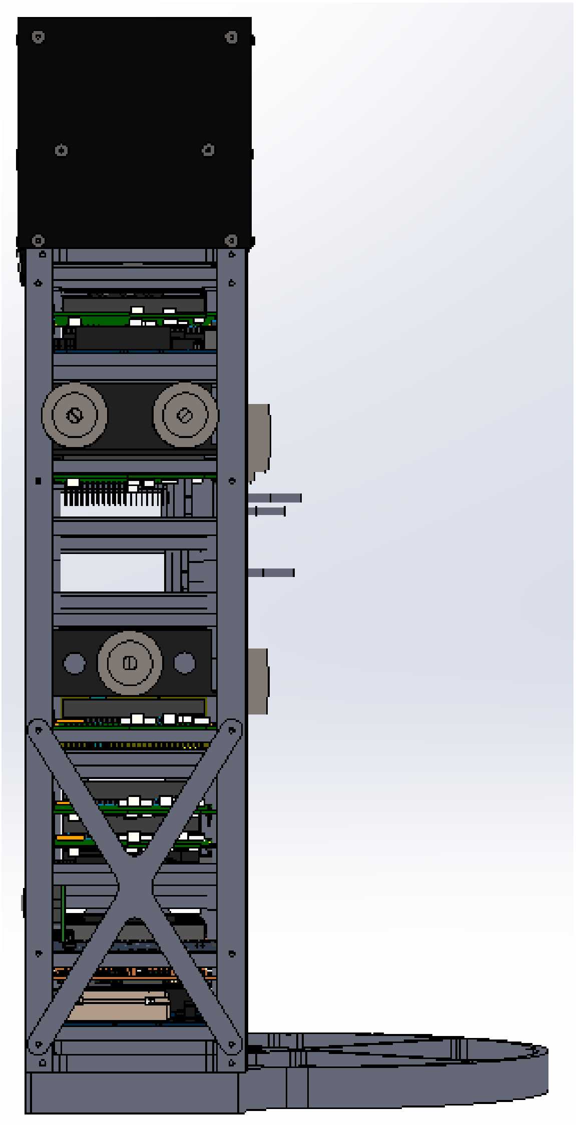




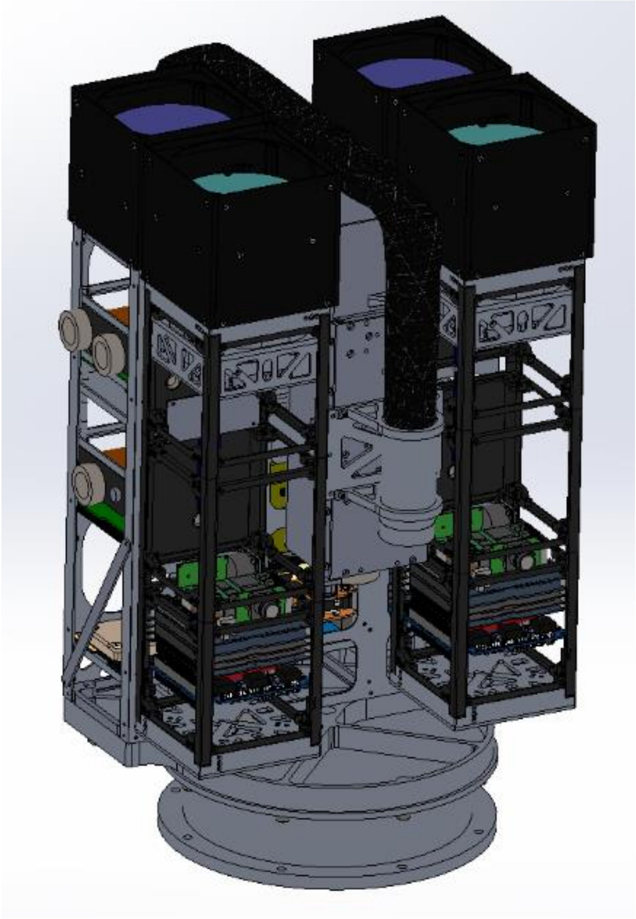


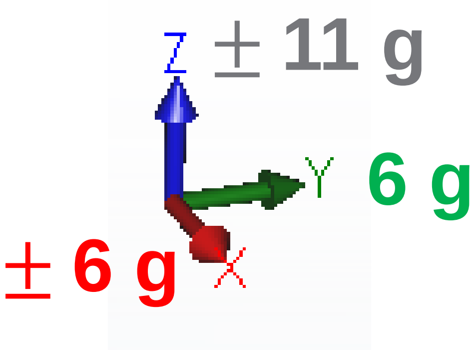
Open Issues

- Unknown location/dimensions of some subsystems (ADCS, docking ports, flight preparation panel, sensors for docking, etc.)
- Is there LIDAR on the CoreSat?
- Interface between CoreSat and MirrorSat
  - The preloading scheme must be improved
  - We must verify that the stored energy will not eject the MirrorSats



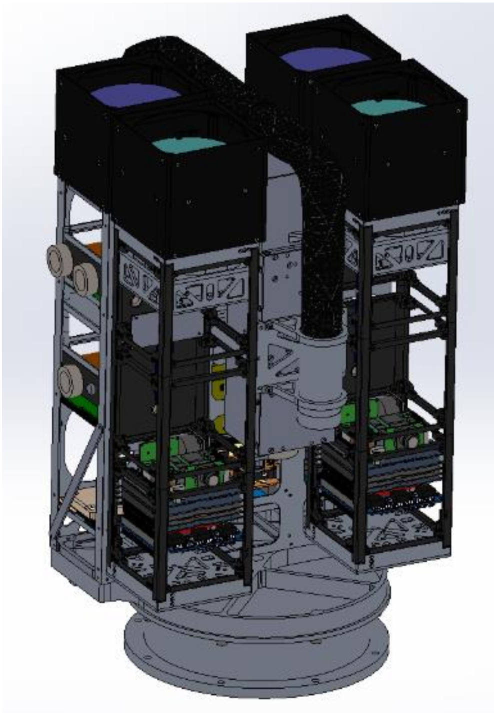
Launch Survivability Analysis



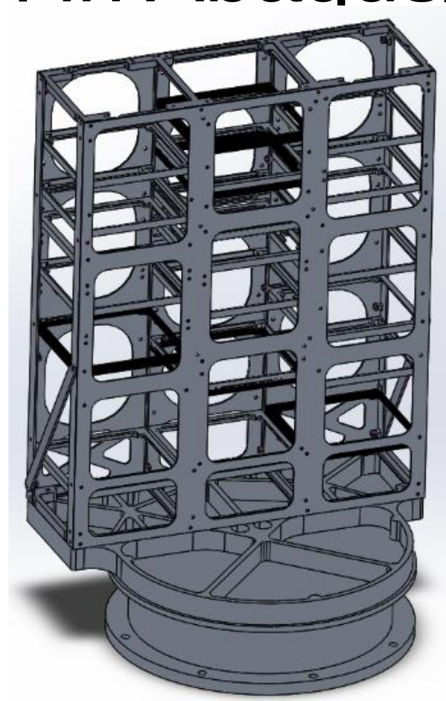


- Static loading at maximum accelerations
- Focus on CoreSat frame

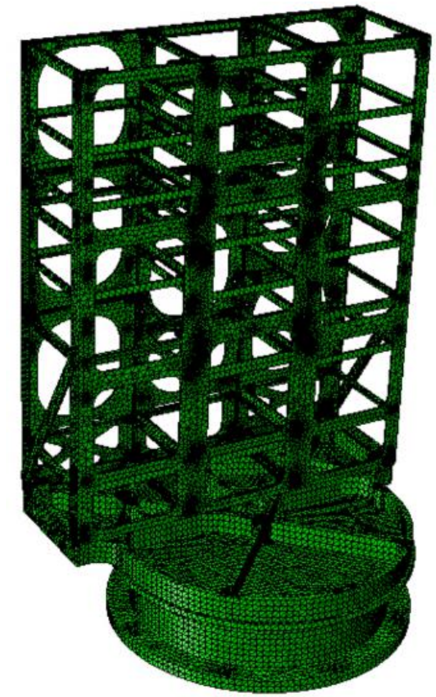
FEM Model in Abaqus/Standard



AAReST



CoreSat Frame



Abaqus Model

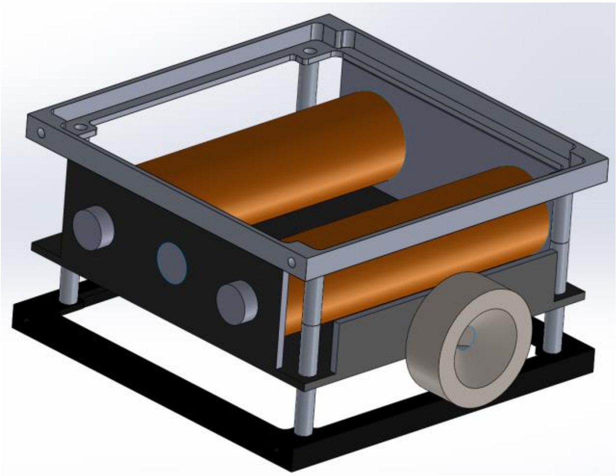
Properties

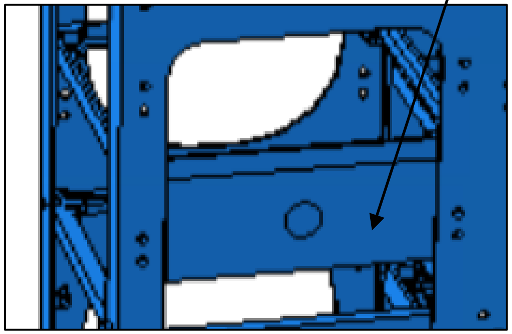
Failure criteria

Material	Density (Kg/m^3)	Poisson's ratio	Young's Modulus (GPa)	Yield point (MPa)	Requirement (von Mises (MPa))
Aluminum	2700	0.34	70	240	120
Delrin	1420	0.34	2.4	62	31

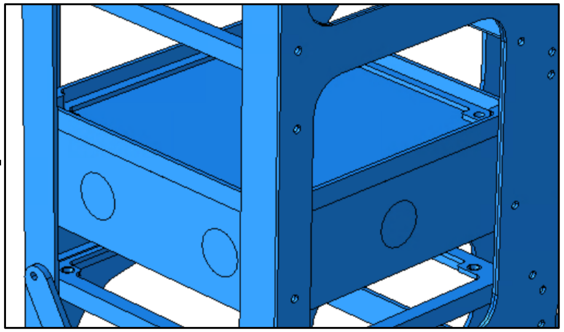
Docking Mount & Frangibolt Models

Load carried by
Delrin “cantilever”



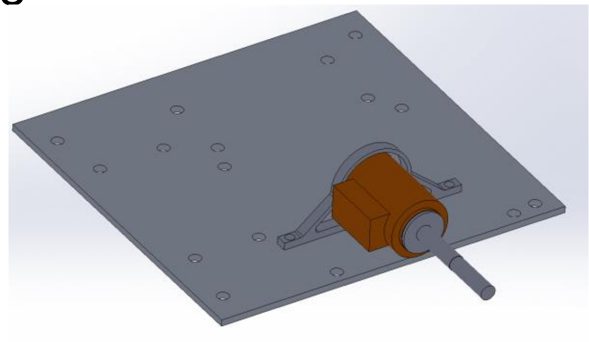


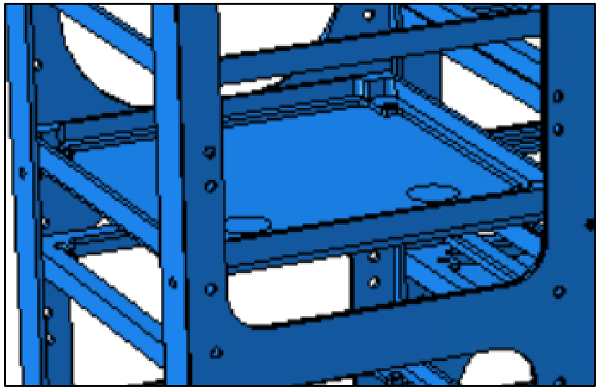
Or



Docking mount: Delrin

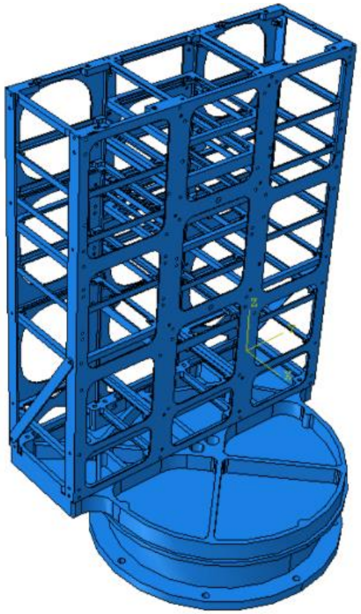
- Frangibolt:



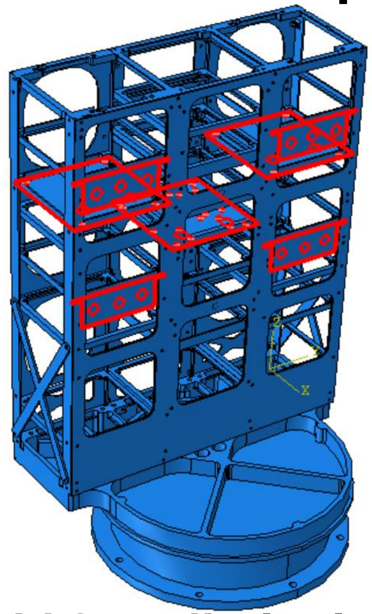


Frangibolt plate: rigid

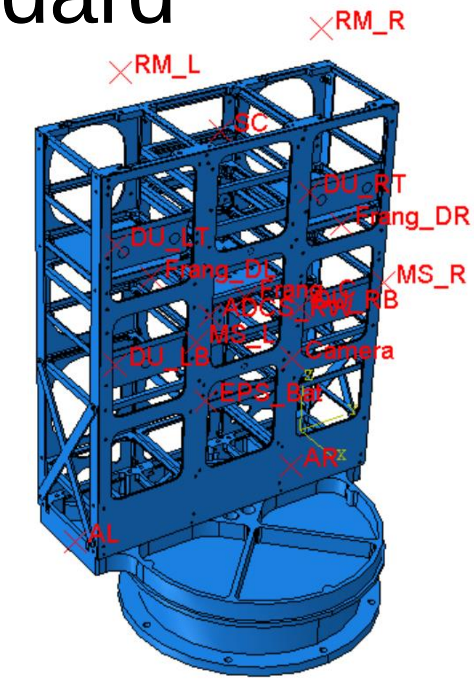
FEM Model in Abaqus/Standard



CoreSat frame
1 part, aluminum



Rigid frangibolt plates
Delrin docking mounts



Point masses

Element		Mass (g)
RM box	*2	821.33
Camera		2735.19
Mirror Sat + DM boxes	*2	4447.63
ADCS+reaction wheels		1105.68
EPS+batteries		674.81
Docking units	*4	424.21
Star camera		165.9
Antennas	*2	99.97

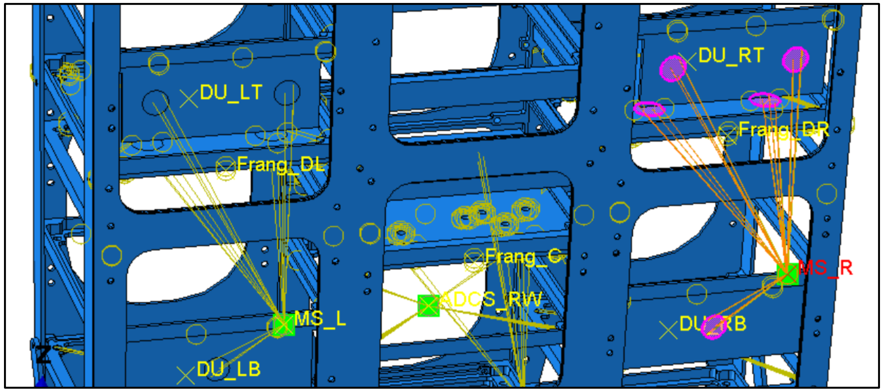
Frame Mass= 3,477 g
Total Mass = 20,357 g

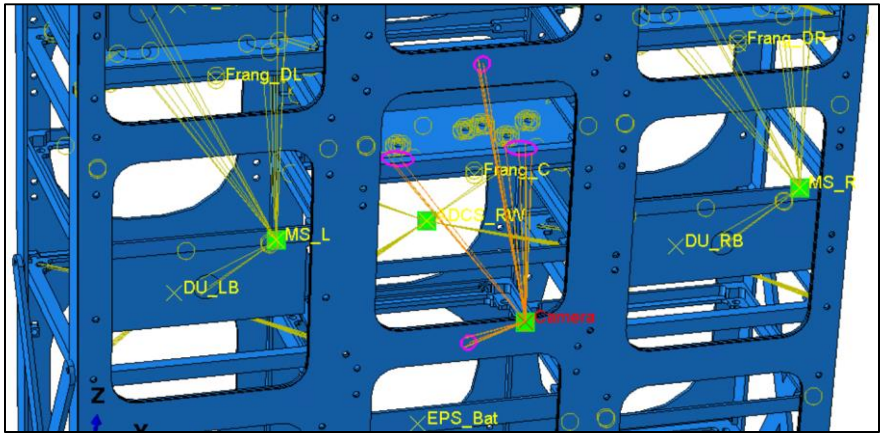
Mass Attachments to CoreSat

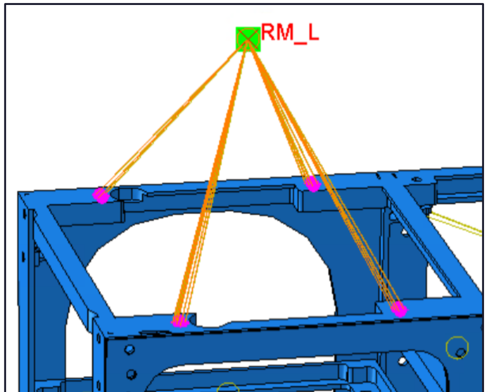
MirrorSat:
- Distributing coupling on 5 surfaces
- No pre constraints

Camera:
- Distributing coupling on 4 surfaces

Other masses:
- Distributing coupling on 4 surfaces







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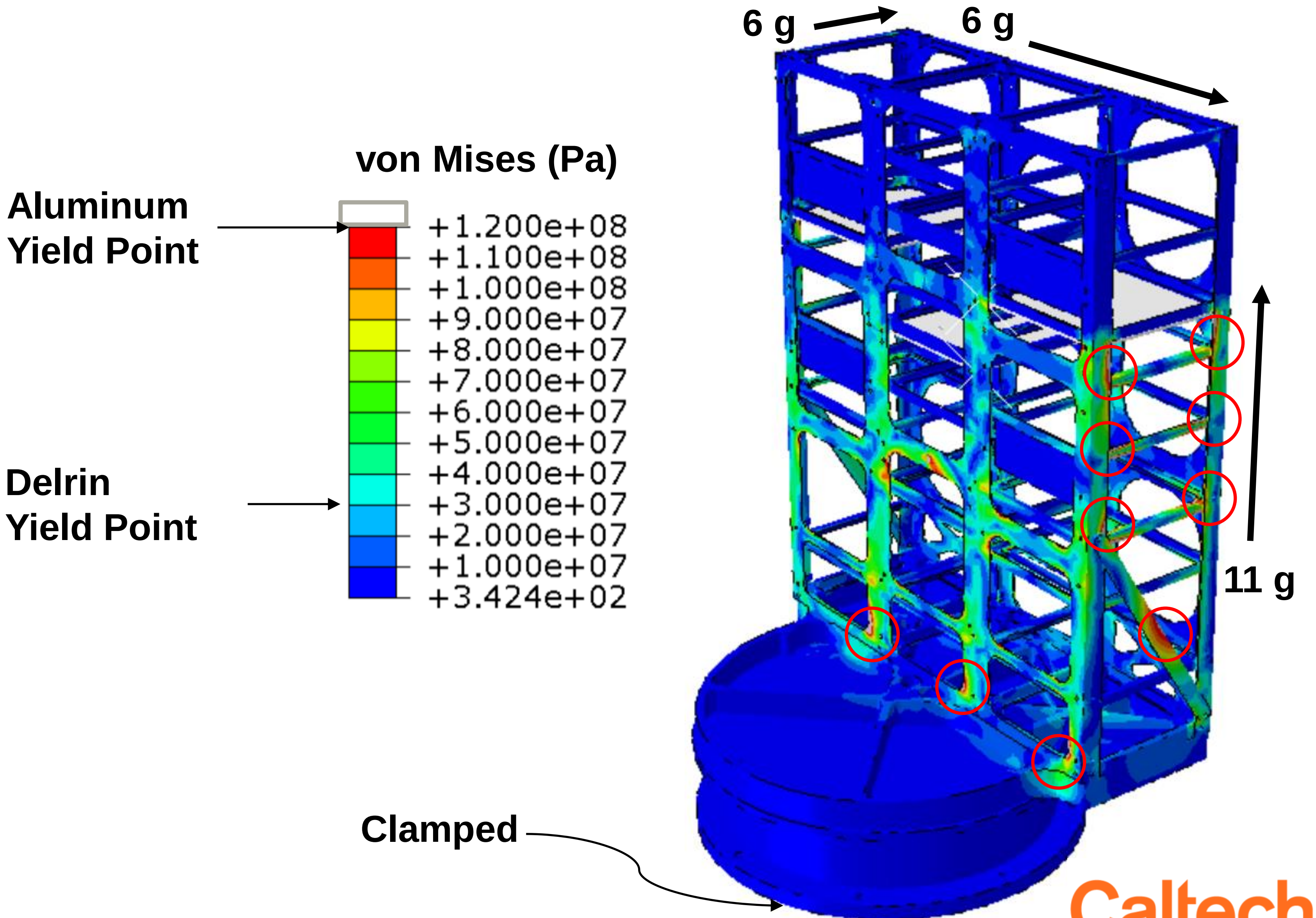
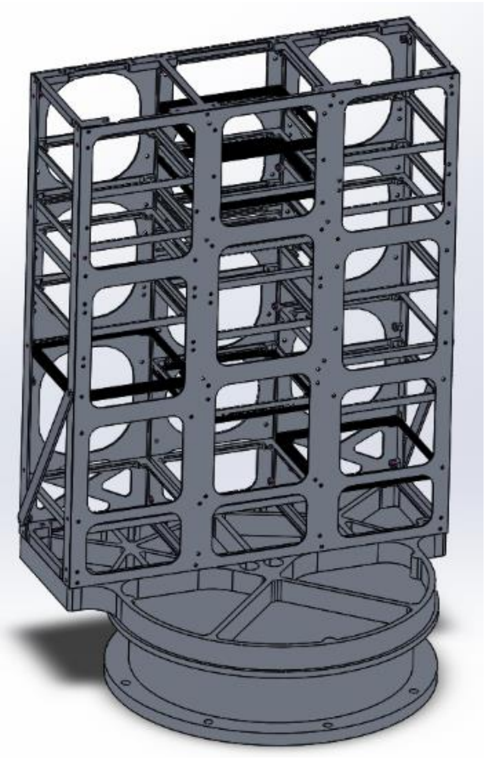
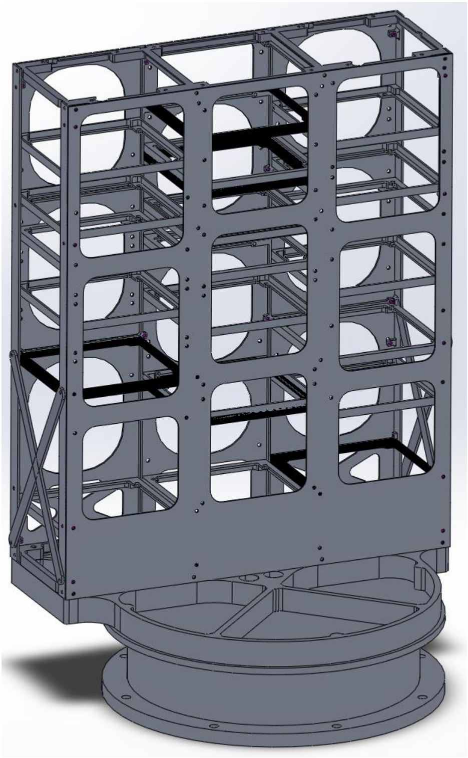
Results: von Mises Stress Distribution



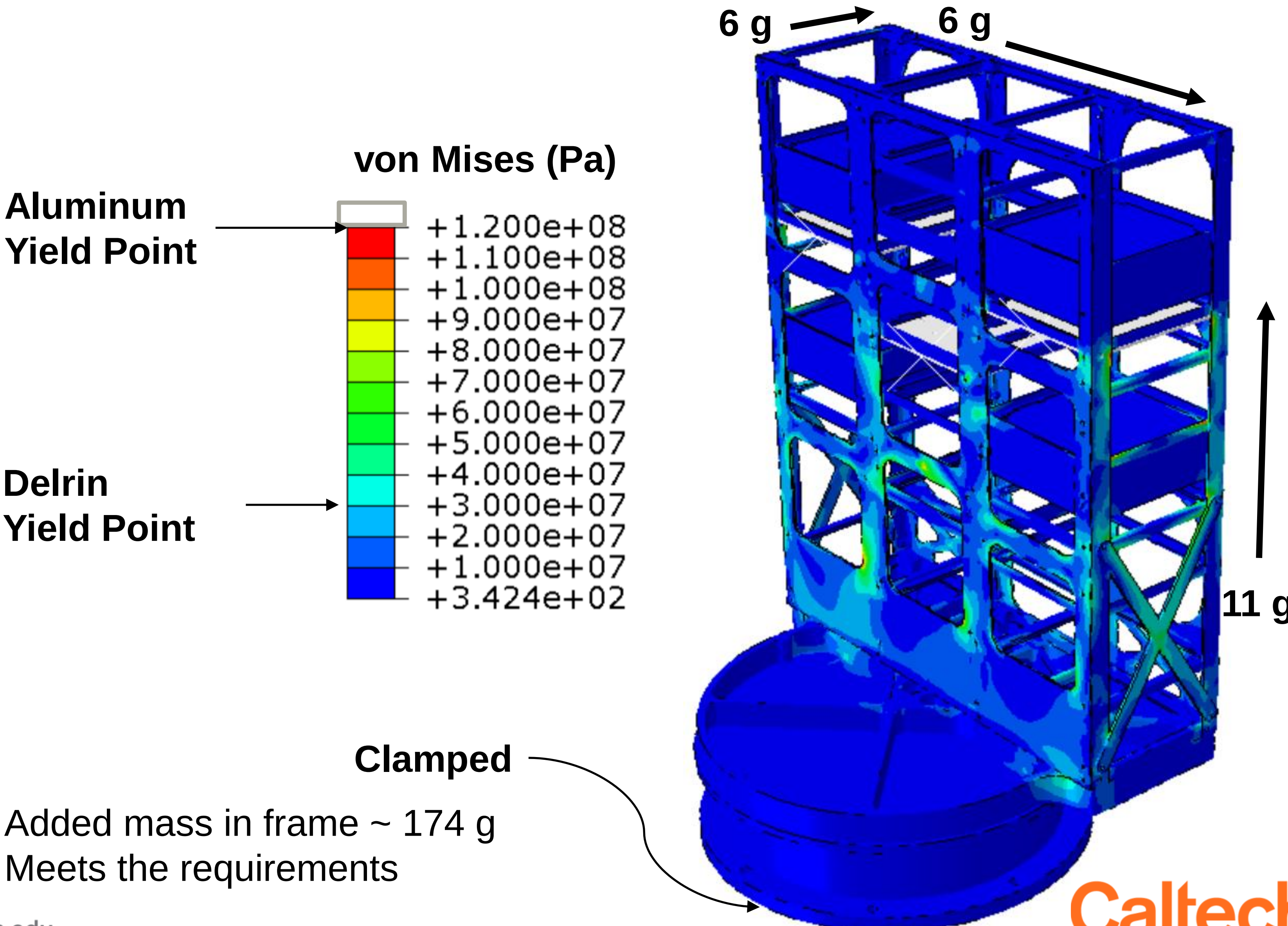
Updated Design





- Additional brackets
- Filled bottom holes
- Front frame thickness from 1mm => 2 mm
- Updated docking mount

Results: von Mises Stress Distribution



⇒ Added mass in frame ~ 174 g

⇒ Meets the requirements

Future Work

- Finalize internal configuration
  - Substitute the actual subsystems
  - Add all missing elements
  - Design internal structures for wheels
- Solve the interface issues (MirrorSats and Camera)
- Detailed model of MirrorSat and Camera attachment to CoreSat in FEM
- Finalize the structural design
- Integrate the separation switch inside the design
- Manufacturing, integration and testing

space structures laboratory

AAReST Communications

Antonio Pedivellano

Eduardo Placentia

Maria Sakovsky

Caltech

Communications Requirements

1. **Comms must use VHF/UHF amateur frequency band**
2. **Antennas should minimize required pointing for comms**
3. **Antennas should minimize losses**
4. **Transceiver must be COTS and conform to CubeSat form factor**
5. **Transceiver must not interface over I2C**
6. **Must be able to downlink live telemetry (ADCS and health data) during separation and docking**
7. **Must be able to downlink the following data:**
   a) Critical health data since last pass
   b) 2 SHWS images, 1 science image during science ops
   c) Full earth/moon images

Outline

1. Data Budgets
2. Component Selection
3. EM Simulations
4. Design and Test

Outline

1. **Data Budgets**
2. Component Selection
3. EM Simulations
4. Design and Test

Data Budget – Nominal Operations

- **Spacecraft and instrument health variables recorded every 5 mins for nominal operation**
- **Health data since last pass downlinked**
  - Worst case: 8 min pass to downlink 10 hrs of data (max time between passes)
- **Total health data = 150.72 kb/pass; data rate = 0.31 kbps**

Subsystem	Component	# of sensors	# measurements /pass	Data rate [kb /pass]
Camera	Temperature	6	720	5.76
	State Variables	4	480	3.84
Def mirrors	Voltages	82	9840	78.72
	Temperatures	10	1200	9.6
	Picomotors	6	720	5.76
Ref mirrors	Temperatures	2	240	1.92
	Picomotors	6	720	5.76
MirrorSats	Temps	6	720	5.76
CoreSat	Temperature sensors	5	600	4.8
ADCS	Quarternions	4	480	7.68
	Rates	3	360	5.76
EPS	Solar Panels Voltages	6	720	5.76
	Solar Panel Currents	6	720	5.76
	Battery voltages	2	240	1.92
	Battery currents	2	240	1.92

Data Budget – Reconfiguration

- **ADCS readings at 1 Hz for 8 min pass + health data**
- **Total maneuver data = 128.55 kb/pass; data rate = 0.27 kbps**

Class	Component	# of sensors	Frequency [#/hr]	# measurements /pass	Data rate [kb /pass]
Camera	Temperature	6	12	9.6	0.0768
	State Variables	4	12	6.4	0.0512
Def mirrors	Voltages	82	12	131.2	1.0496
	Temperatures	10	12	16	0.128
	Picomotors	6	12	9.6	0.0768
Ref mirrors	Temperatures	2	12	3.2	0.0256
	Picomotors	6	12	9.6	0.0768
MirrorSats	Quarternions	4	3600	1920	30.72
	Rates	3	3600	1440	23.04
	Temps	6	12	9.6	0.0768
SC	Temperature sensors	5	12	8	0.064
ADCS	Quarternions	4	3600	1920	30.72
	Rates	3	3600	1440	23.04
	Sensors	5	3600	2400	19.2
EPS	Solar Panels Voltages	6	12	9.6	0.0768
	Solar Panel Currents?	6	12	9.6	0.0768
	Battery voltages	2	12	3.2	0.0256
	Battery currents	2	12	3.2	0.0256

Data Budget

- **Max data rates:**
  - UHF: 9.6 kbps - downlink
  - VHF: 1.2 kbps - uplink
- **Assume 8 min passes; no overhead included**
- **Docking video taken and downlinked over several passes**

Mode	Health data [kbps]	Ops data [kbps]	Data rate required for single pass [kbps]	Total Data Size (kBytes)	Notes
Nominal	0.31	0	0.31	19	
Docking data	0.31	0.27	0.58	35	ADCS and health data
Star imaging	0.31	1.4*	1.71	103	2 windowed SHWS images, 1 windowed star image
Earth/Moon imaging	0.31	5.1*	5.41	325	PNG image (no windowing)

* Computed from image size from flight detectors

Outline

1. Data Budgets
2. **Component Selection**
3. EM Simulations
4. Design and Test

Transceiver Selection

- **All options are compatible with CubeSat form factor and have SMA/MCX connections for antenna**
- **Astrodev helium radio is the top choice due to low cost and UART interface**

Product	Cost	Mass (g)	Max Downlink Bit Rate (kbps)	Bus Interface	Data Protocol
AstroDev Helium Radio	+	78	9.6	UART	AX.25, HDLC
ClydeSpace CPUT VUTRX	++	90	9.6	I2C (UART/CAN @ extra $)	AX.25
ISIS UHF Down/VHF Up Transceiver	++	75	9.6	I2C	AX.25, HDLC

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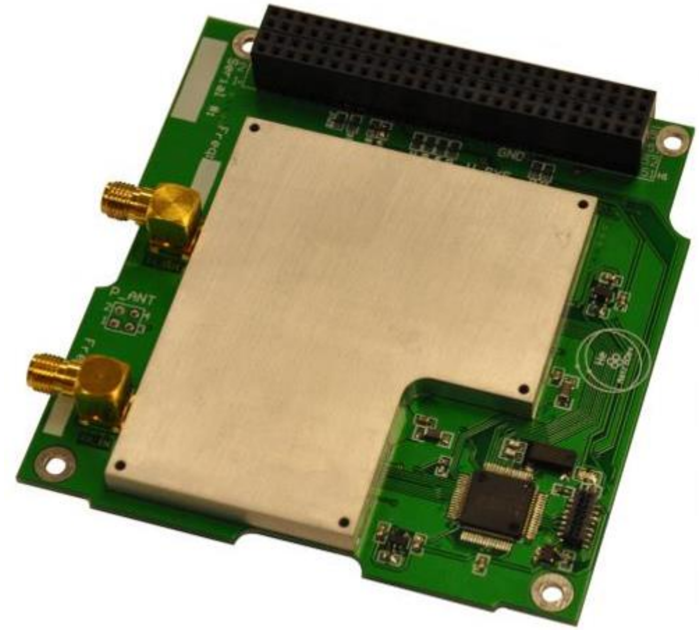
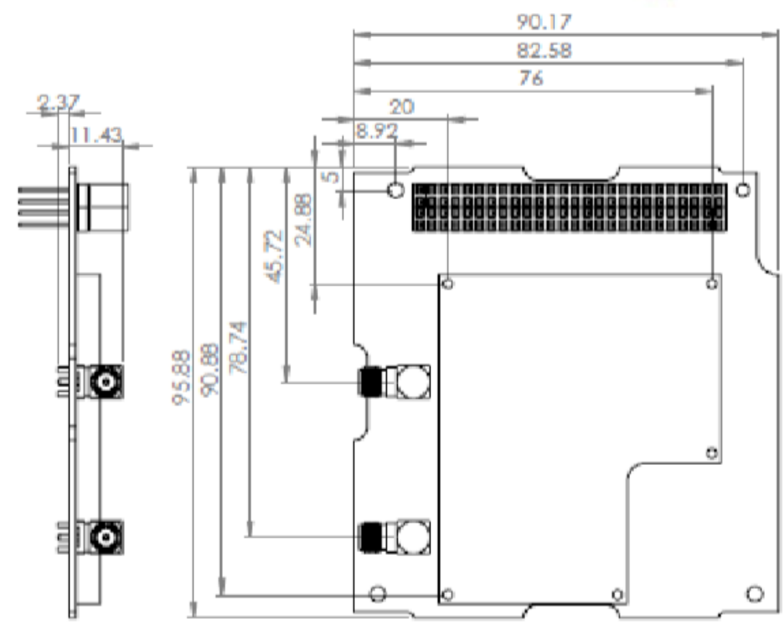
Astrodev Helium Radio

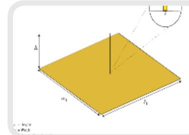
- **Modulation: FSK**
- **Power**
  - Output transmit power: 100 mW – 7W
  - Power usage: receive < 200 mW; transmit < 16 W
- **Interfaces**
  - Input voltages: 3.3 V logic; 5-13 V transceiver
  - Serial interface: 3.3 V UART
- **Mechanical**
  - Operating temperature: -30 – 70^{o}C
  - CubeSat form factor
  - MCX connectors at right angle
- **Sold with breakout board, software to configure radio**



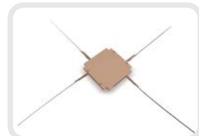


Antenna Type Tradeoff

- **COTS solutions unreliable in deployment**
- **Design considerations**
  - Large beamwidths
  - Large gains
  - Ease of packaging/deployment
  - Size
- **Monopole antenna selected**
  - Small, easy to deploy solution
  - Acceptable electromagnetic performance
  - Common solution for CubeSats

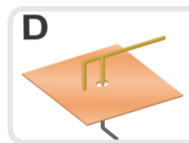


Monopole
- **Pros**: good gain, cheap, easy to manufacture
- **Cons**: Linear polarization, ground plane required



Dipole
- **Pros**: good gain, no ground plane
- **Cons**: very long

Crossed monopoles
- **Pros**: cross polarization
- **Cons**: space limitations



Inverted F monopole
- **Pros**: compact, easily tunable
- **Cons**: Less efficient than monopole, difficult to deploy

Helical antenna
- **Pros**: circular polarization
- **Cons**: Quite massive, difficult to manufacture

Spiral antenna
- **Pros**: Circular polarization
- **Cons**: Large, difficult to manufacture

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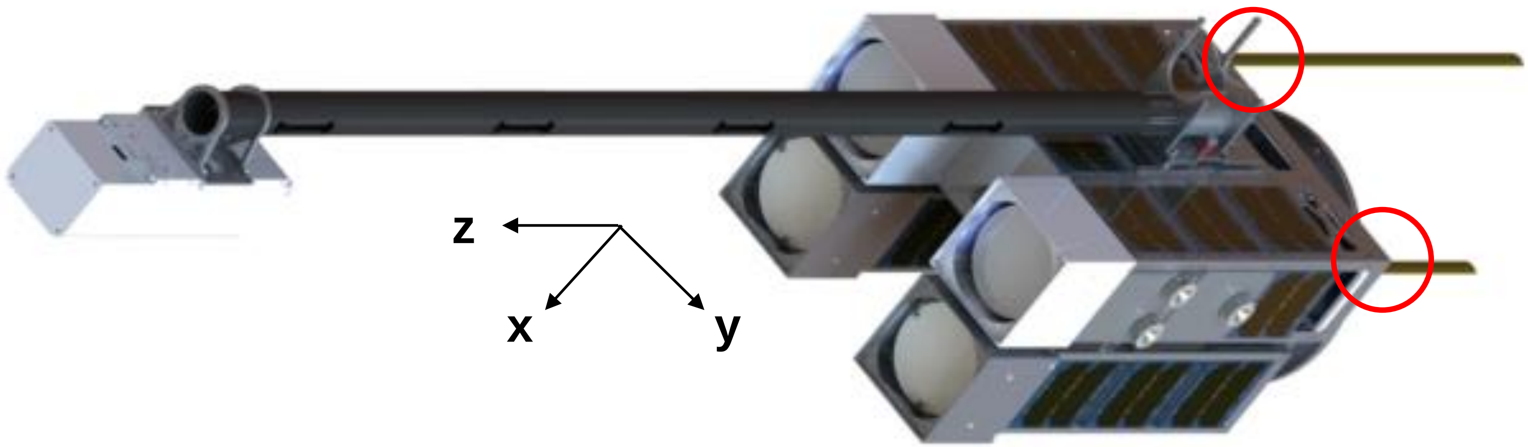
Antenna Positioning

- **Antennas mounted on –Z face at corners**
  - +Z (mirror boxes)
  - +/-Y, +X (reserved for MirrorSat docking)
  - -X face (reduces space available for solar panels)
- **Electromagnetic analysis required to understand effect of LVI ring**



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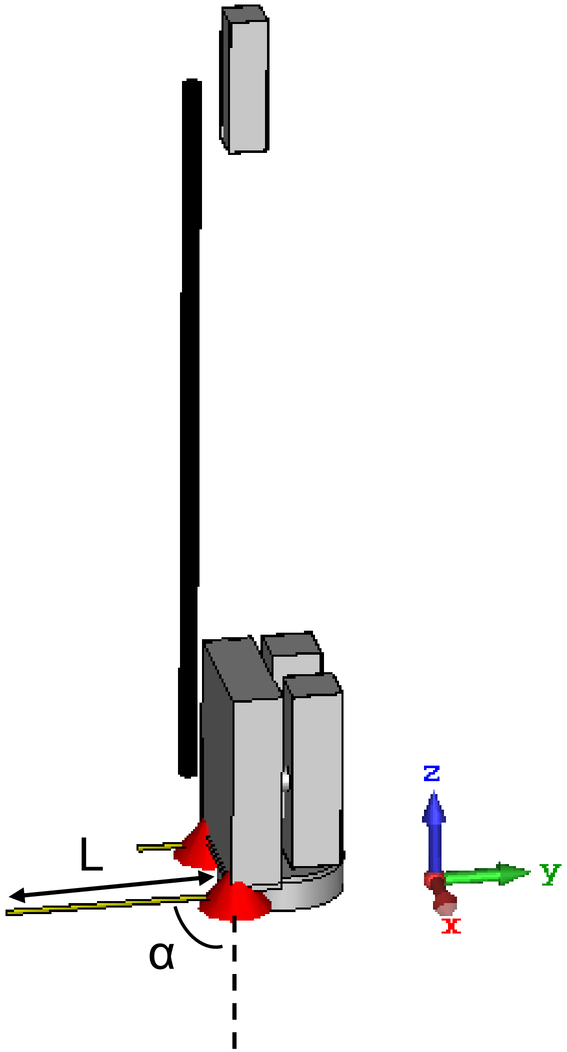
Outline

1. Data Budgets
2. Component Selection
3. **EM Simulations**
4. Design and Test

Antenna Electromagnetic Simulations

- **Software: CST Student Edition**
  - max 30,000 elements
- **Model elements:**
  - CoreSats, MirrorSats, mirror boxes, camera: 1 mm thick Al shells
  - LVI ring: Al cylinder
  - Boom: carbon fiber; isolated from spacecraft
  - Antenna: steel, tape measure profile
    - 50 Ω discete ports
  - Entire spacecraft used as RF ground
  - Narrow configuration
- **Missing from model: cutouts in boom and chassis**
- **Simulation parameters:**
  - Antenna length + angle



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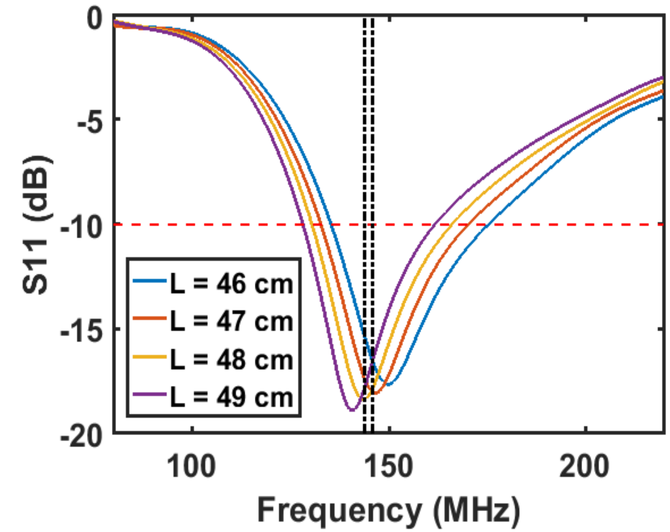
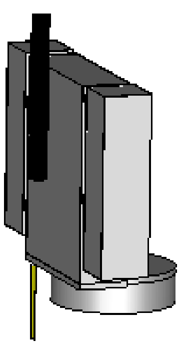
VHF Antenna Performance

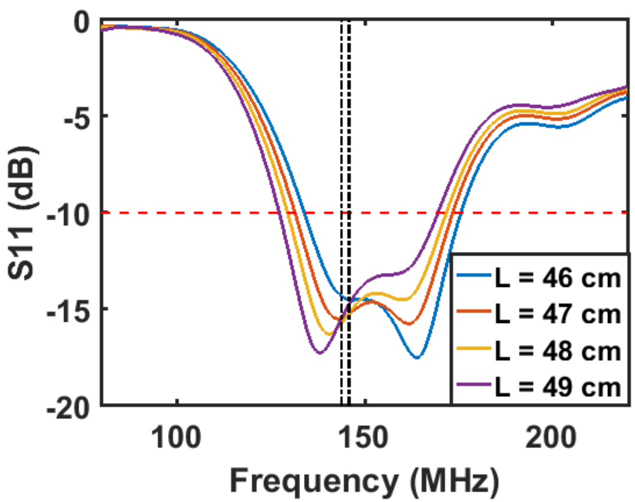
- **Performance metric: reflection coefficient s_{11} < -10 dB**
- **Presence of boom significantly affects antenna performance**
- **0º configuration (antennas point along z-axis)**
  - Boom resonates at λ corresponding to L/2
- **Boom resonance not seen in 90º configuration**

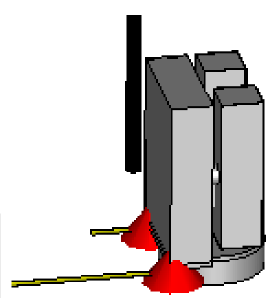
Model w/out Boom



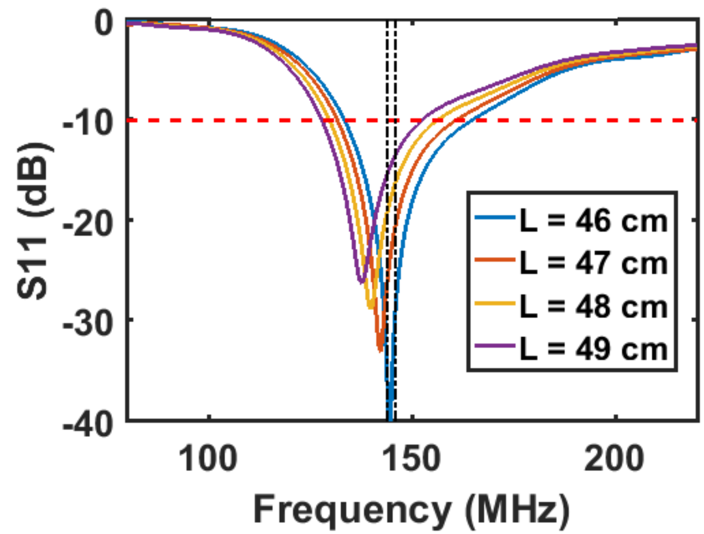
Full Model – 0º







Full Model – 90º



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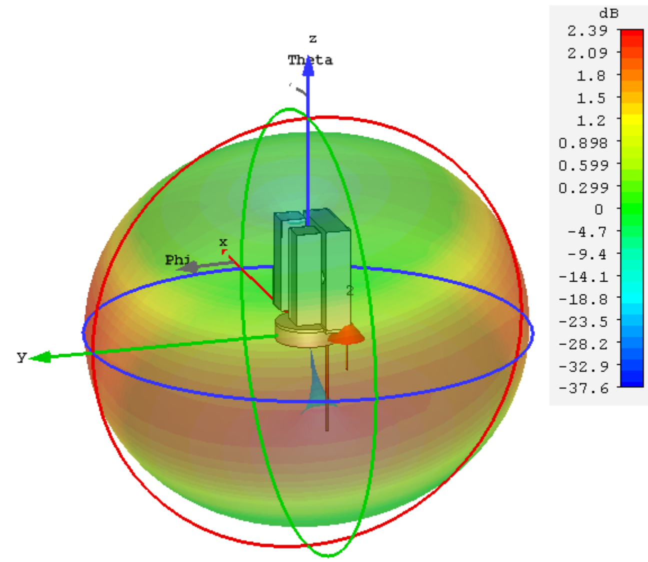
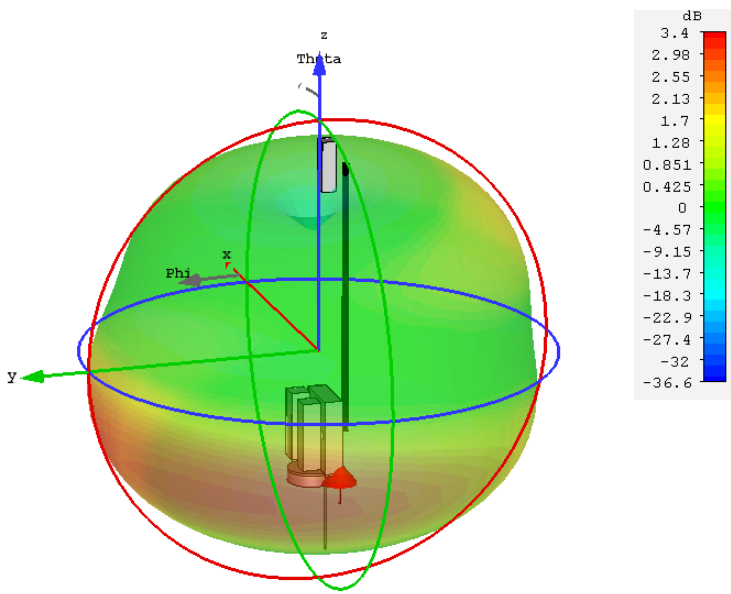
VHF Antenna Performance

- **Radiation pattern (145 MHz) for tuned antenna length (L)**
- **Expected radiation pattern is doughnut shaped around antenna axis**
  - LVI ring tilts axis of doughnut
  - Presence of boom results in additional lobes

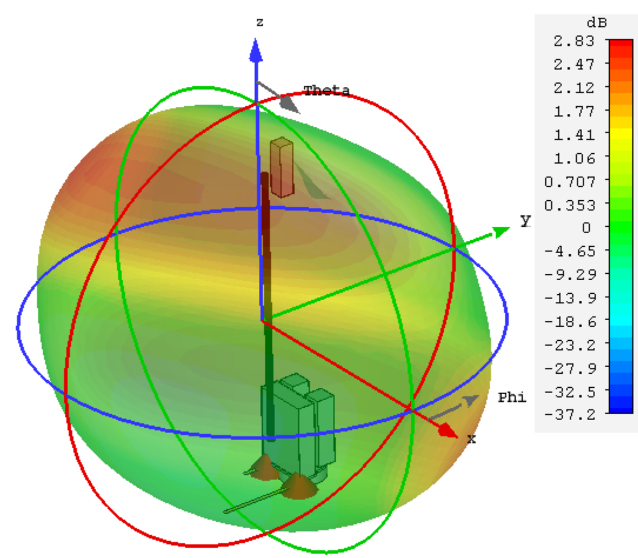
Model w/out Boom (L = 48 cm)



Full Model – 0º (L = 48 cm)



Full Model – 90º (L = 46 cm)



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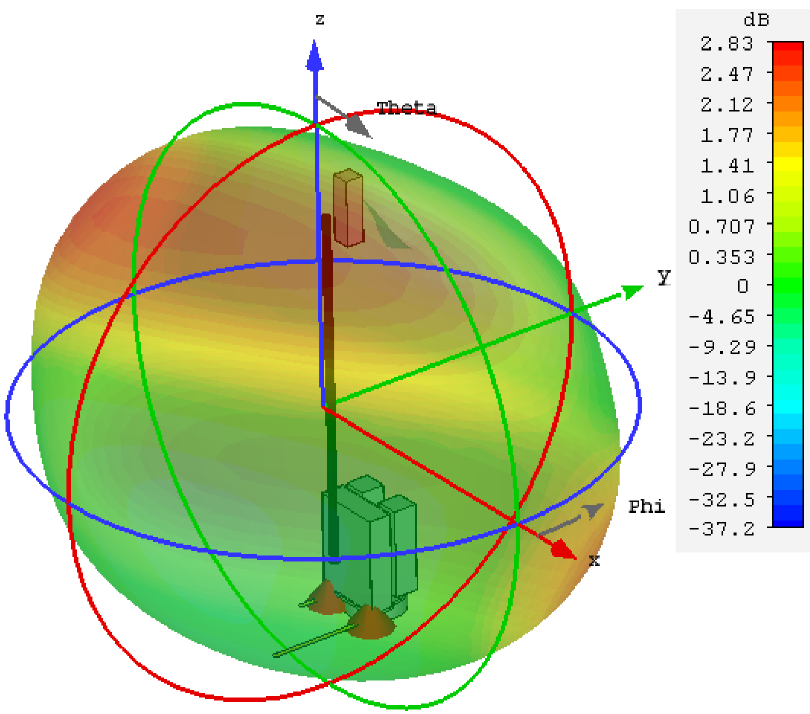
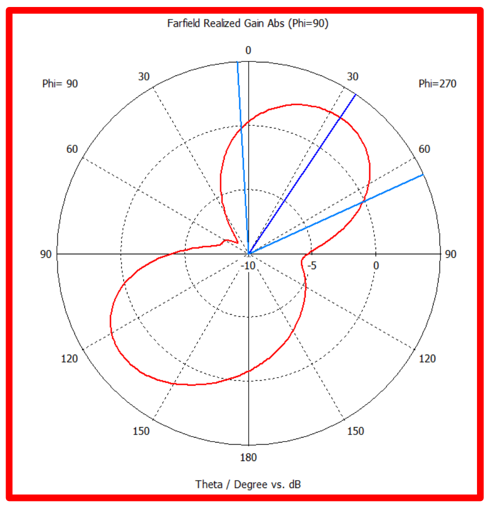
VHF Antenna Performance – 90º Configuration

- 90º antenna configuration closest to expected performance
- Deviation from theory due to ring, boom, and finite ground plane
- Radiation pattern shows good gains (2.83 dB) and large beamwidths (~90º)

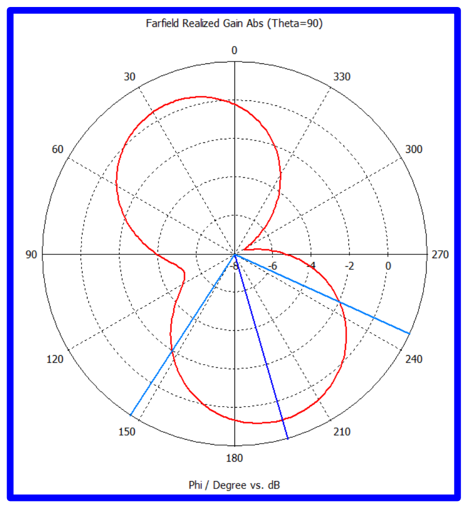


Y-Z Plane



Frequency = 145 MHz
Main lobe magnitude = 2.81 dB
Main lobe direction = 34.0 deg.
Angular width (3 dB) = 69.0 deg.

X-Y Plane



Frequency = 145 MHz
Main lobe magnitude = 0.969 dB
Main lobe direction = 196.0 deg.
Angular width (3 dB) = 98.5 deg.

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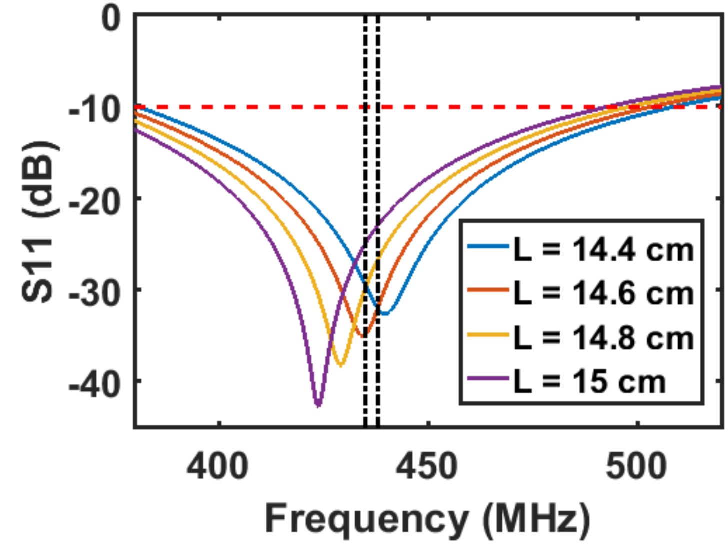
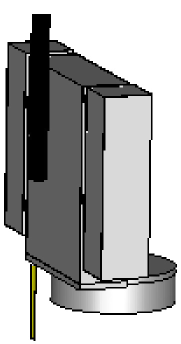
UHF Antenna Performance

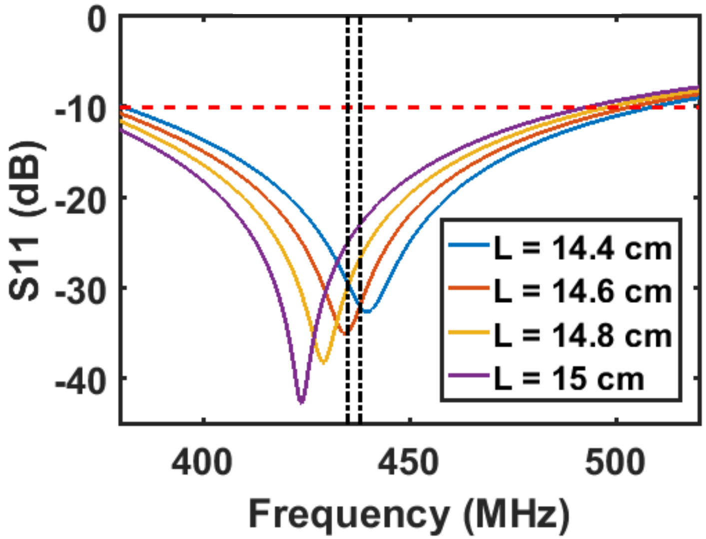
- Performance metric: reflection coefficient s_{11} < -10 dB
- No boom resonance seen in desired UHF downlink frequency
- Performance in 90^{o} configuration wideband

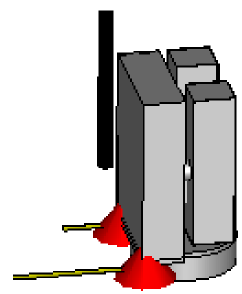
Model w/out Boom



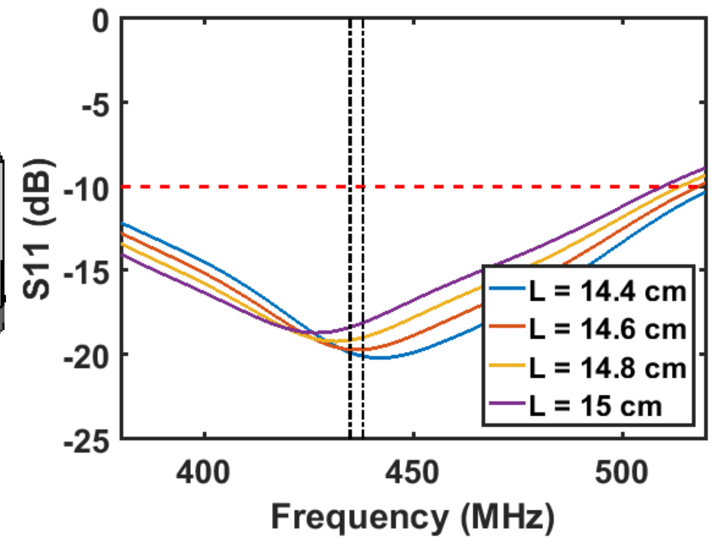
Full Model – 0^{o}







Full Model – 90^{o}



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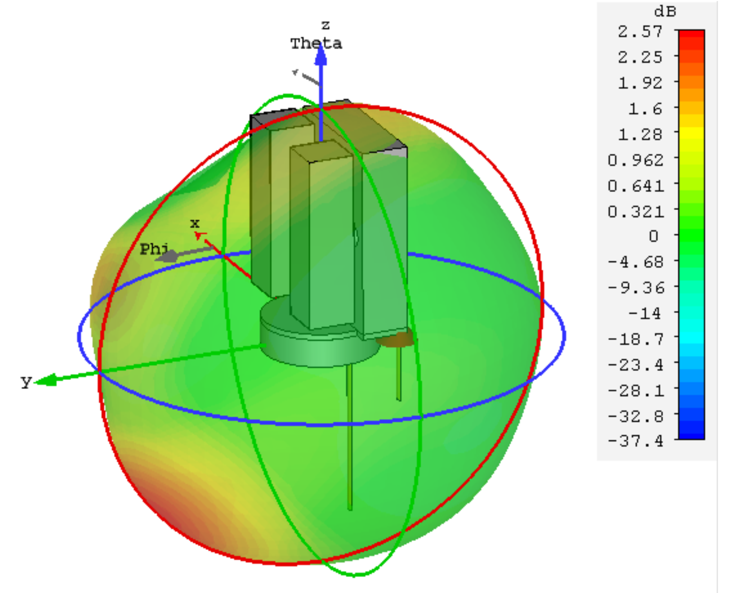
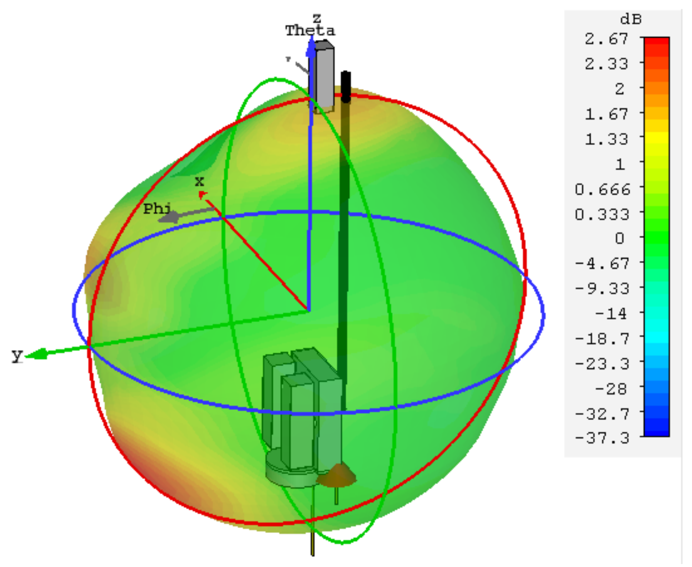
VHF Antenna Performance

- **Radiation pattern (365.5 MHz) for tuned antenna length (L)**
- **UHF radiation pattern significantly affected by LVI but not boom**
  - Effects of LVI minimized in 90º configuration
  - 0º configuration has a significant number of addition lobes

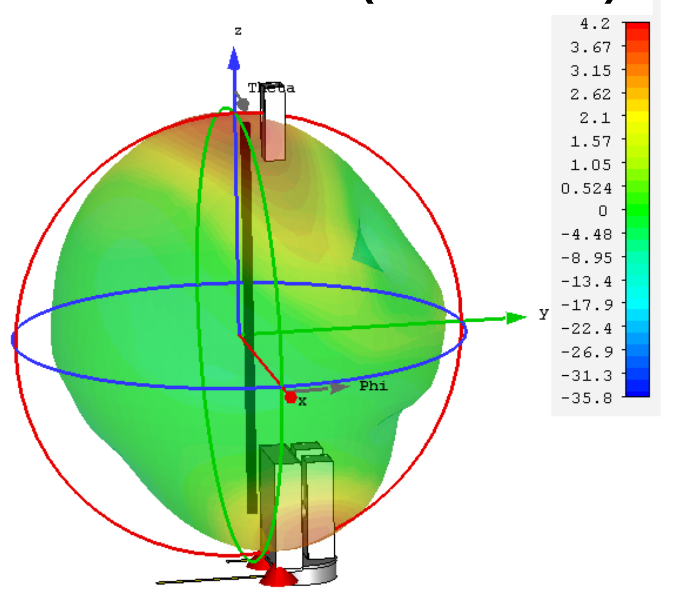
Model w/out Boom (L = 14.6 cm)



Full Model – 0º (L = 14.6 cm)



Full Model – 90º (L = 14.6 cm)



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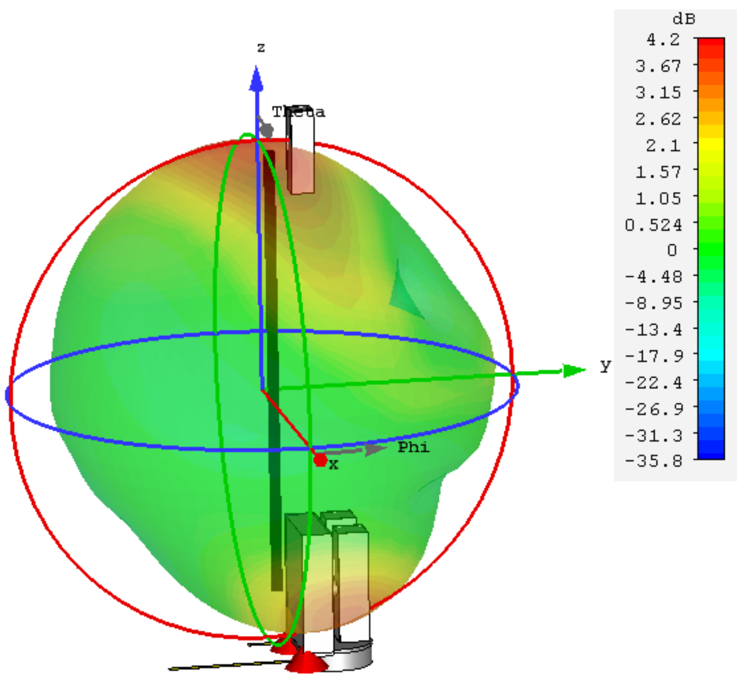
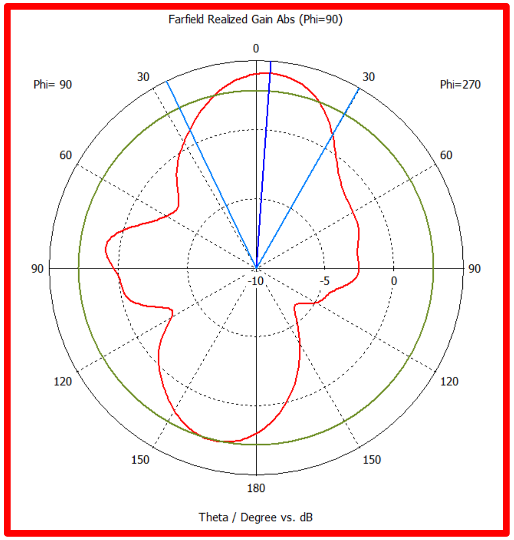
UHF Antenna Performance – 90º Configuration

- **90º antenna configuration closest to expected performance**
- **Deviation from theory due to ring, boom, and finite ground plane**
- **Radiation pattern shows good gains (4.2 dB) and large beamwidths (~55º)**

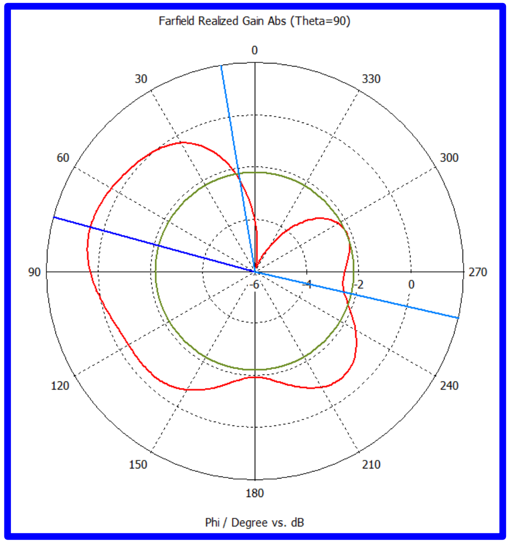


Y-Z Plane



Frequency = 436.5 MHz
Main lobe magnitude = 4.1 dB
Main lobe direction = 4.0 deg.
Angular width (3 dB) = 55.3 deg.
Side lobe level = -1.2 dB

X-Y Plane



Frequency = 436.5 MHz
Main lobe magnitude = 0.515 dB
Main lobe direction = 75.0 deg.
Angular width (3 dB) = 247.8 deg.
Side lobe level = -2.7 dB

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EM Simulations Summary

- **Antenna performance deviates from theoretical doughnut shape**
  - LVI and finite ground plane tilts pattern and introduces extra lobes
  - Boom resonates at VHF when parallel to antennas
- **Best performance seen in 90º configuration**
- **VHF operation**
  - S11 ~ -40 dB at 46 cm length, 145 MHz
  - Close to expected monopole radiation pattern
  - Gain = 2.83 dB; 3-dB Beamwidth = ~90º
- **UHF operation**
  - S11 ~ -20 dB at 14.6 cm length, 436.5 MHz
  - Close to expected monopole radiation pattern with additional side lobes
  - Gain = 4.2 dB; 3-dB Beamwidth = ~55º

Outline

1. Data Budgets
2. Component Selection
3. EM Simulations
4. **Design and Test**

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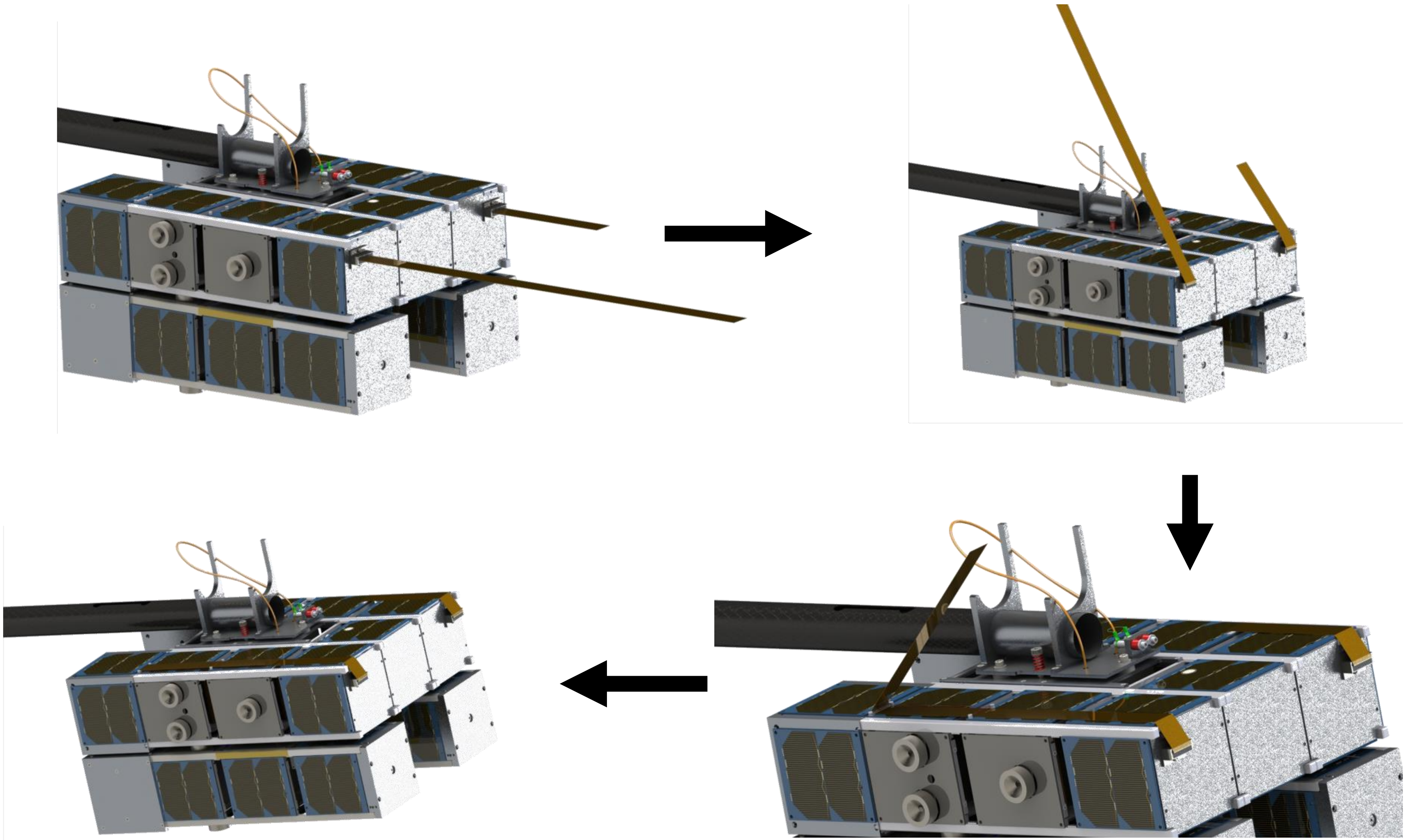
Antenna Folding Sequence



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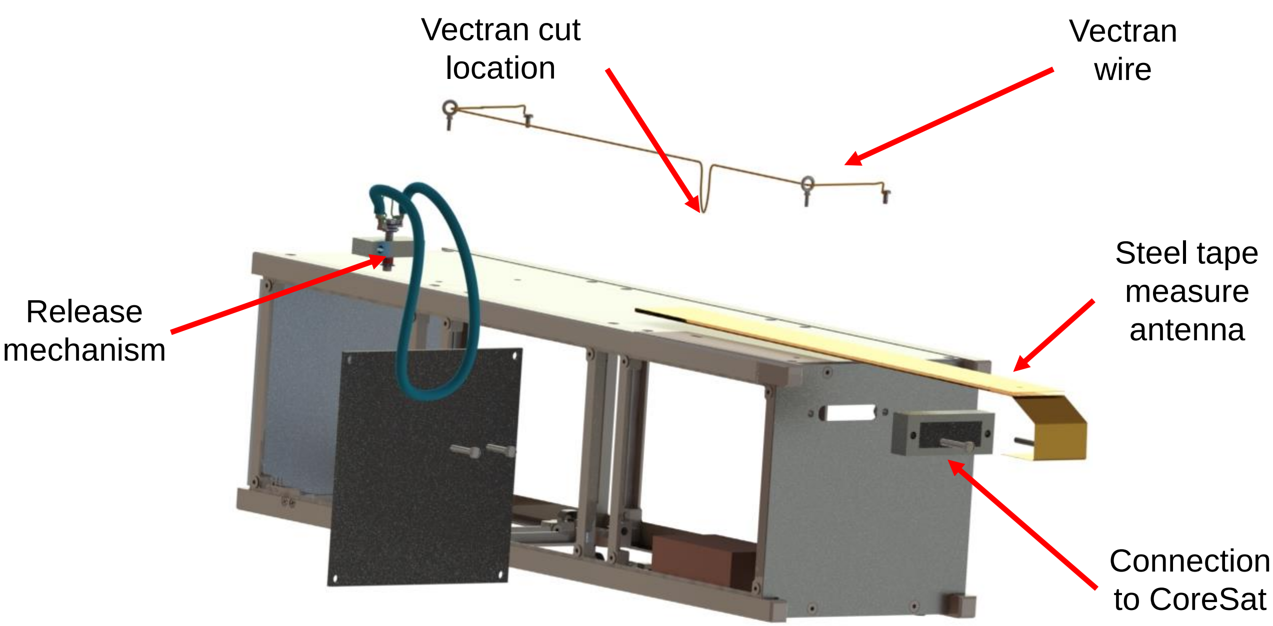
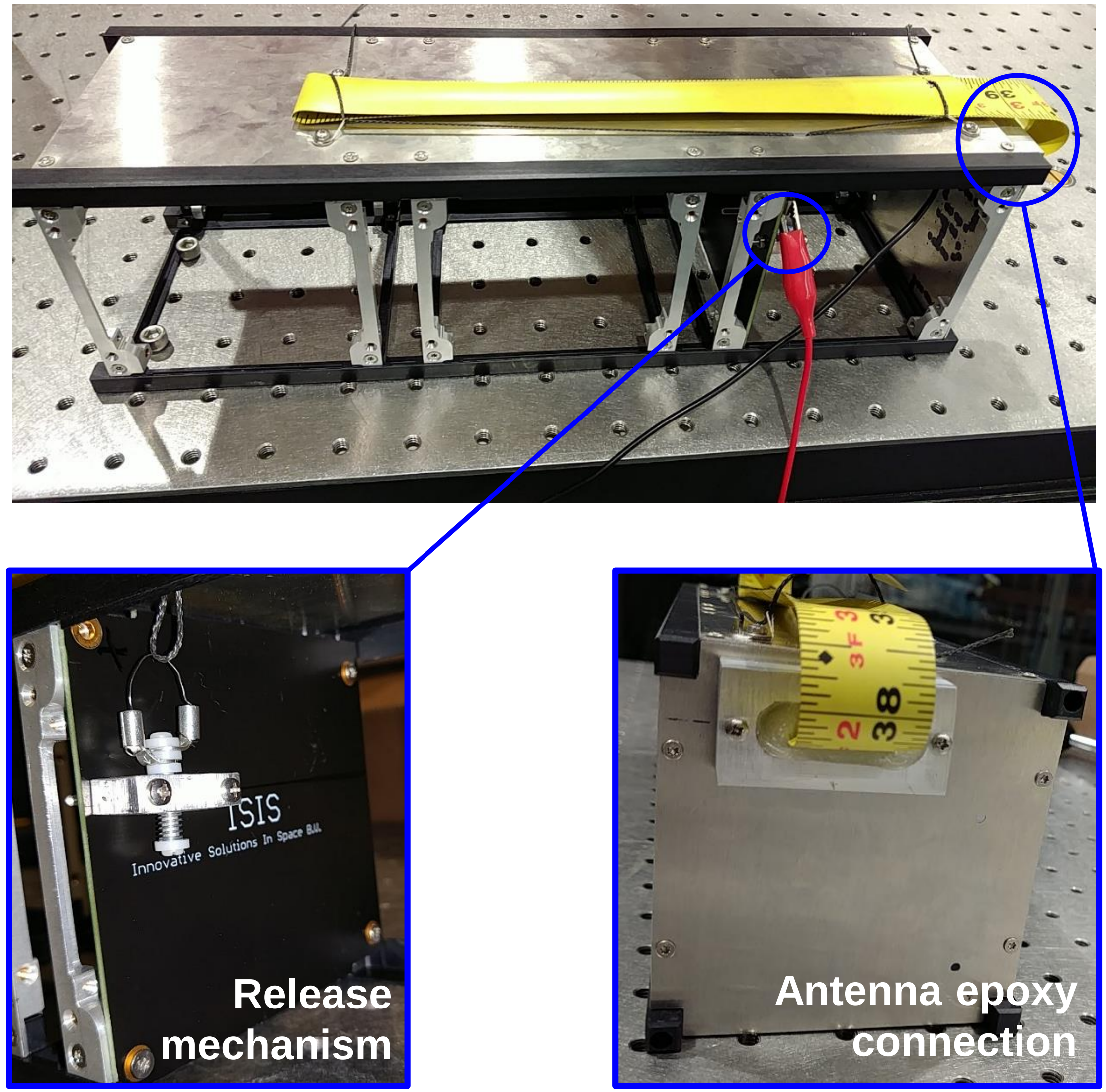
Deployment Mechanism Design

- **Connection to CoreSat: epoxy filled slot to hold antenna**
  - Isolates antenna from ground (chassis)
- **One release mechanism per antenna (reused from mirror boxes)**
- **Vectran wire restrains each antenna against launch vibrations**
  - Threaded through holes in antennas to prevent antenna sliding during launch
- **Non-conductive spacers between antenna and -X face of CoreSat**
  - Preserve functionality in case of failed deployment



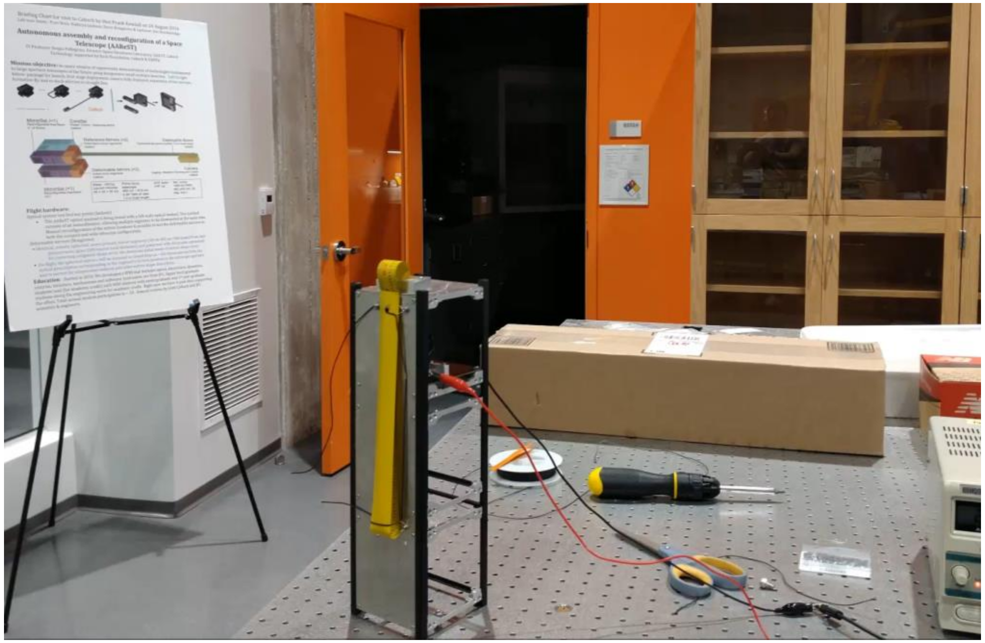
Antenna Structural Testing

- **Test setup built with ISIS 3U CubeSat Kit and waterjet panels**
- **Test plan**
  - Mechanical design check
  - Deployment reliability
  - Launch vibration survivability



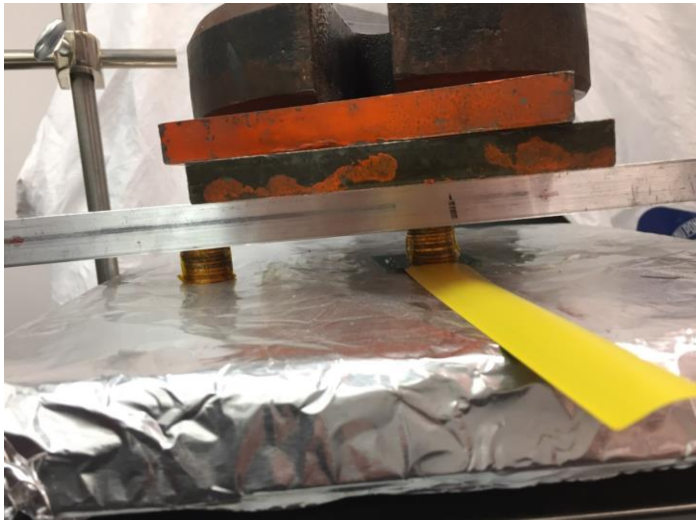
Deployment Testing

- **Antenna tested with CubeSat positioned vertically (deployment against gravity) and horizontally**
  - 2 A, 1.2 V; deployment ~ 12 s
  - 3 tests total, successful deployment in all cases
- **Tests will be repeated to verify repeatability of antenna deployment trajectory**



Antenna Electrical Connections

- **Objective: test connection reliability**
- **Procedure:**
  - Sand paint from antenna
  - Tin the PCB and inner face of antenna with solder
  - Using kapton tape, tape PCB and antenna assembly on hot plate
  - Stack weights on assembly
  - Heat at 200^{o}C for 15 min



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Electromagnetic Test Plan

- **Build representative model**
  - CoreSat chassis, mock LVI, COTS MirrorSats, boom, camera
- **Antenna length tuning**
  - Reflection coefficient measurements using network analyzer on campus
- **Radiation pattern measurements**
  - Measurements with power meter
- **EM compatibility testing**

Summary and Open Issues

- **Subsystem specs:**
  - Downlink over UHF, uplink over VHF
  - Astrodev Helium transceiver
  - Deployable monopole antennas
- **Subsystem analysis:**
  - UHF sufficient to transmit health data, debug data, and camera images in a single 8 min pass
  - 90^{o} configuration minimizes boom interference
    - VHF and UHF radiation patterns close to theoretical
    - Acceptable gains and wide beamwidths
  - Antenna structural design complete and testing in progress
- **Open issues**
  - Boom interference with antenna performance
  - Vibration testing
  - Frequency allocation

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Backup

space structures laboratory

Combined Simulation Data

9/10/17

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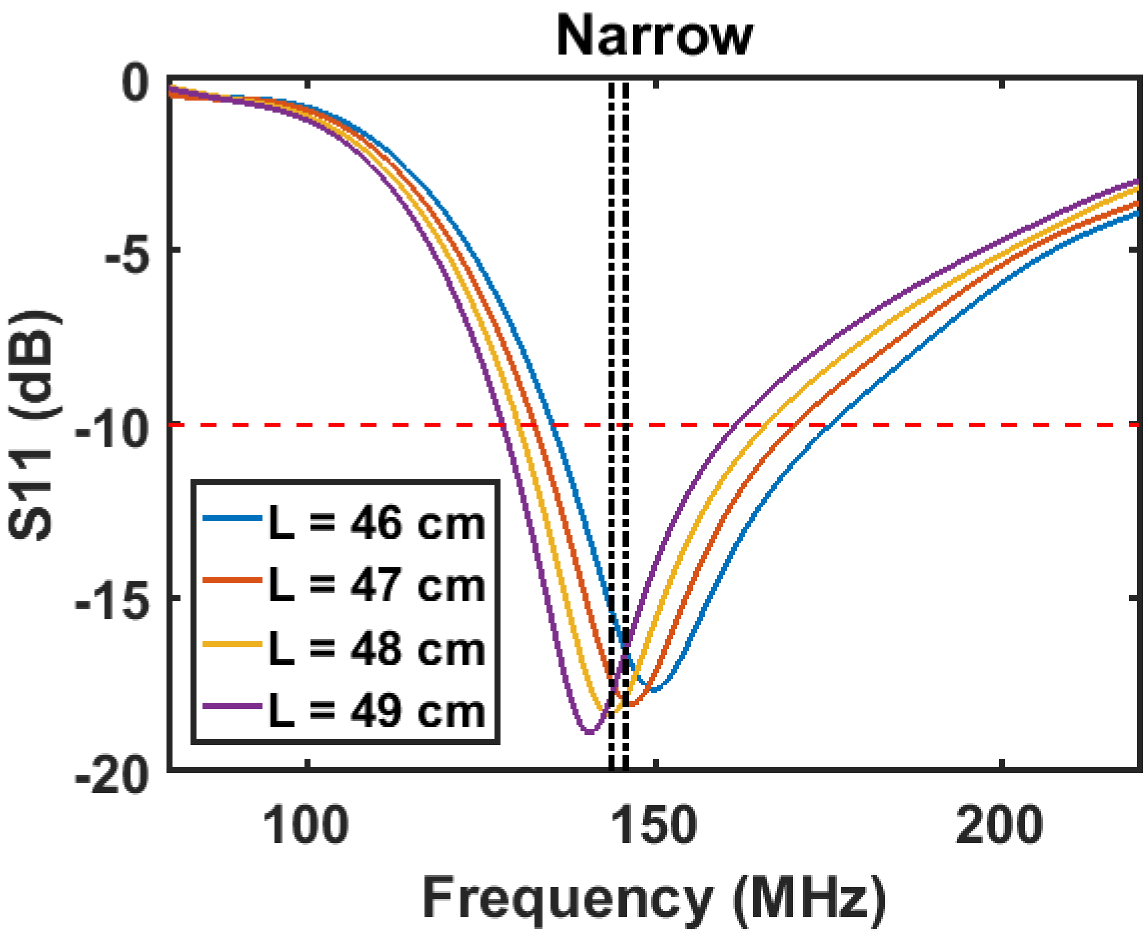
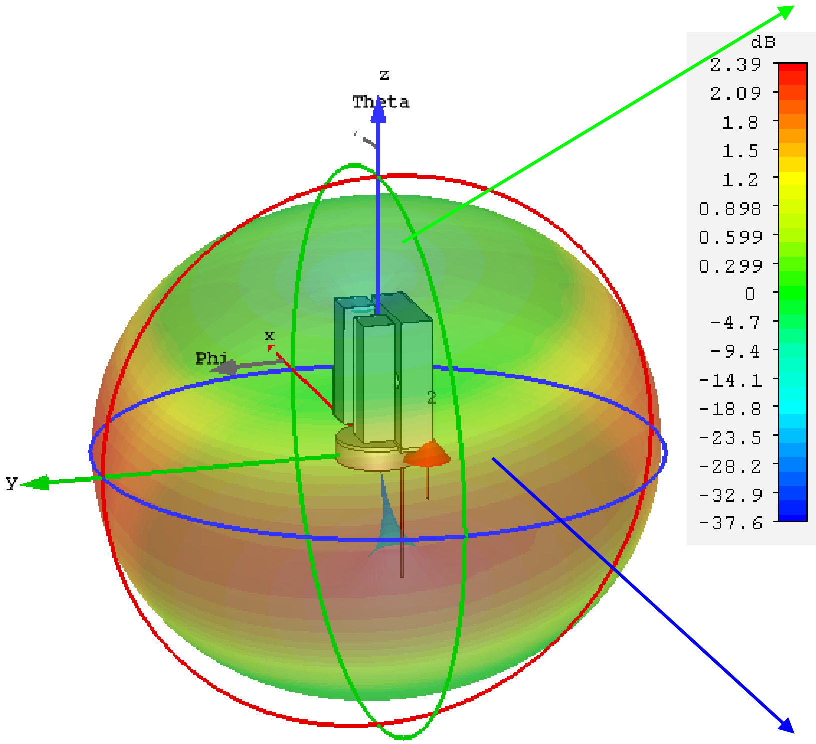
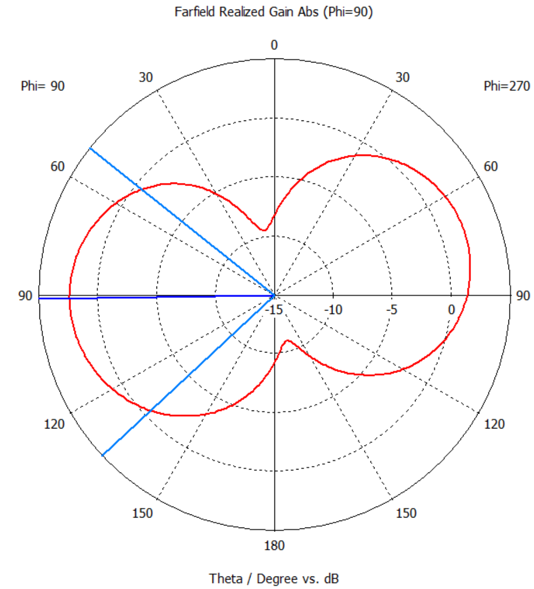
Overall model – VHF, no boom + camera

- text

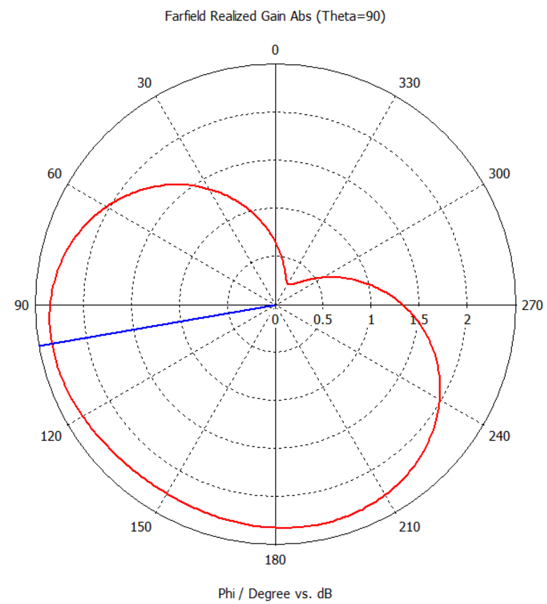


Overall model – VHF, with boom + camera





Frequency = 145 MHz
Main lobe magnitude = 2.34 dB
Main lobe direction = 91.0 deg.
Angular width (3 dB) = 81.7 deg.



Frequency = 145 MHz
Main lobe magnitude = 2.36 dB
Main lobe direction = 100.0 deg.

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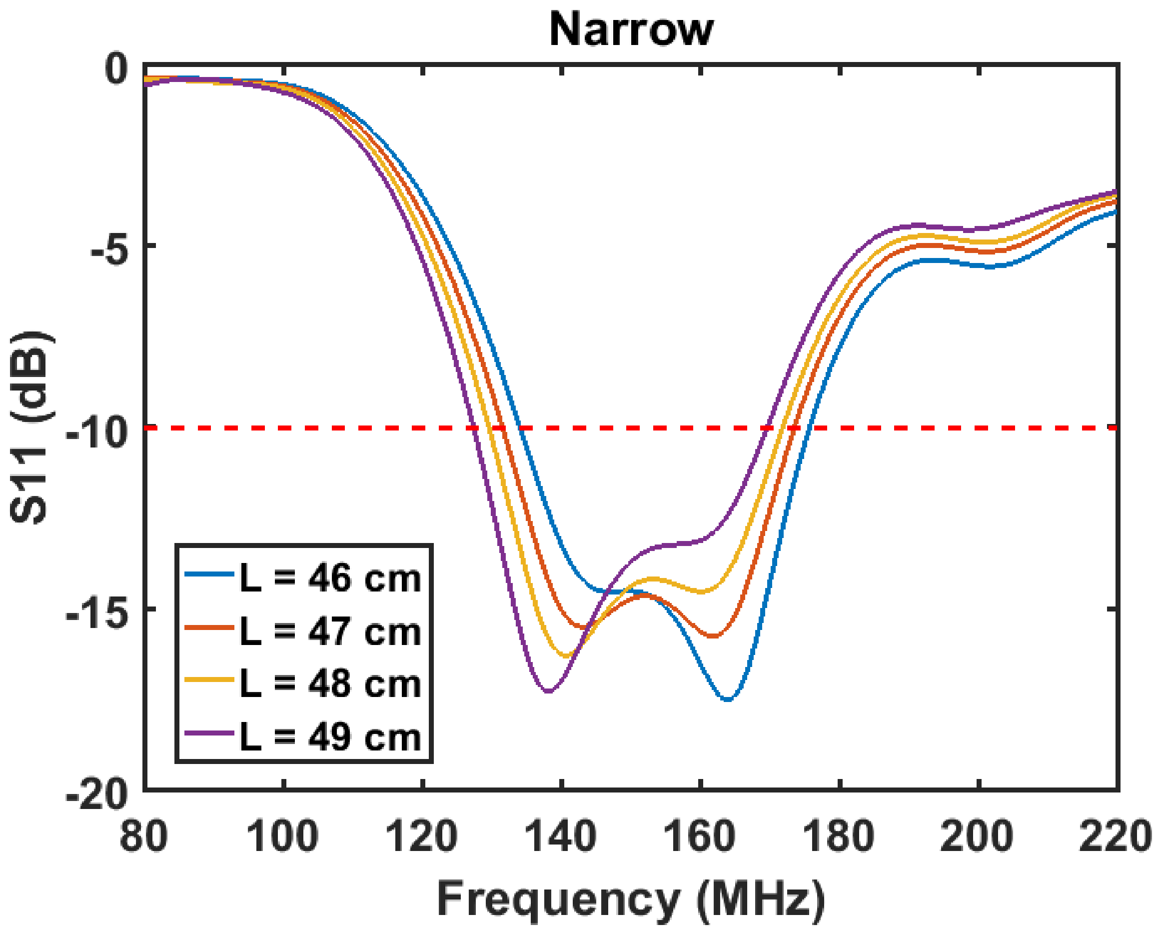
Overall model – VHF, with boom + camera

- text



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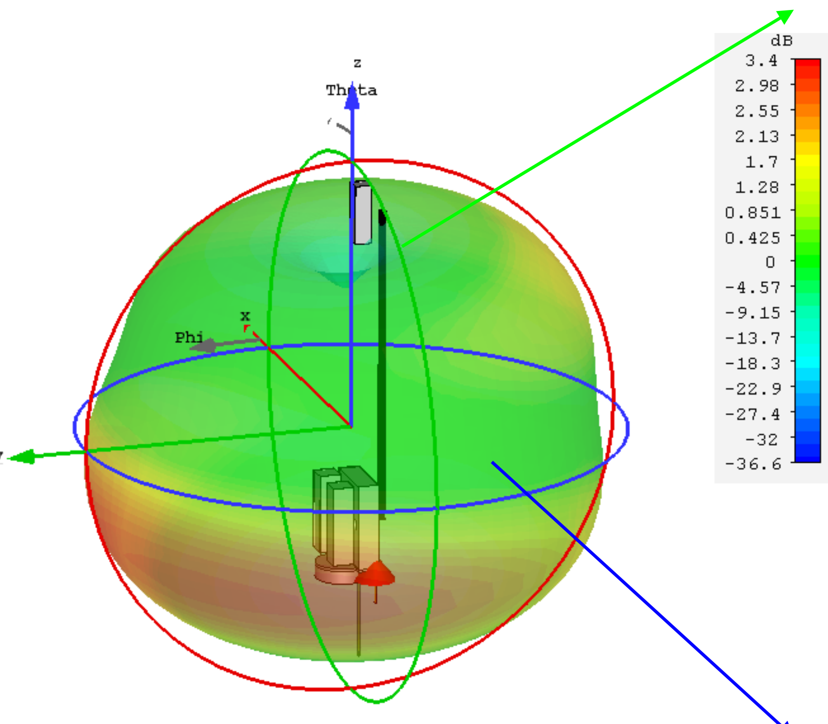
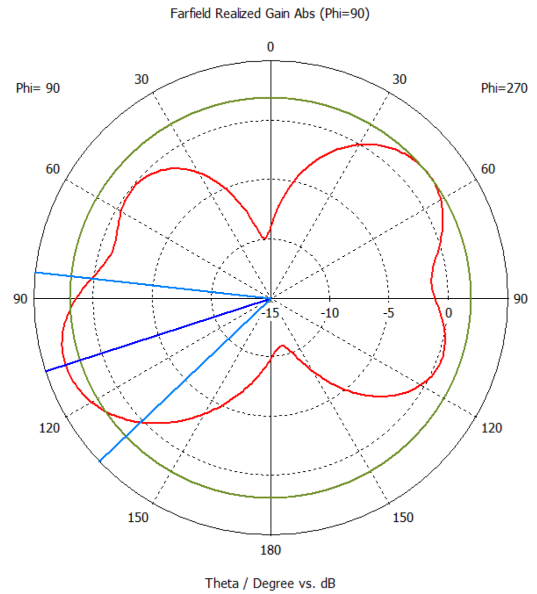
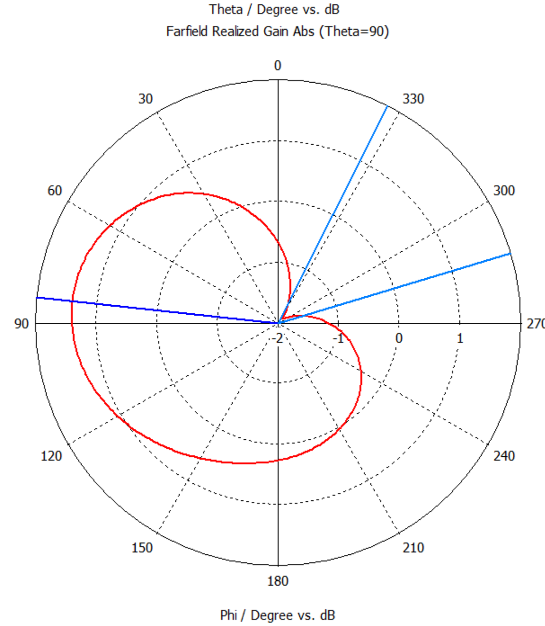
Overall model – VHF, with boom + camera





Frequency = 145 MHz
Main lobe magnitude = 3.17 dB
Main lobe direction = 108.0 deg.
Angular width (3 dB) = 50.0 deg.
Side lobe level = -1.3 dB



Frequency = 145 MHz
Main lobe magnitude = 1.4 dB
Main lobe direction = 84.0 deg.
Angular width (3 dB) = 313.4 deg.

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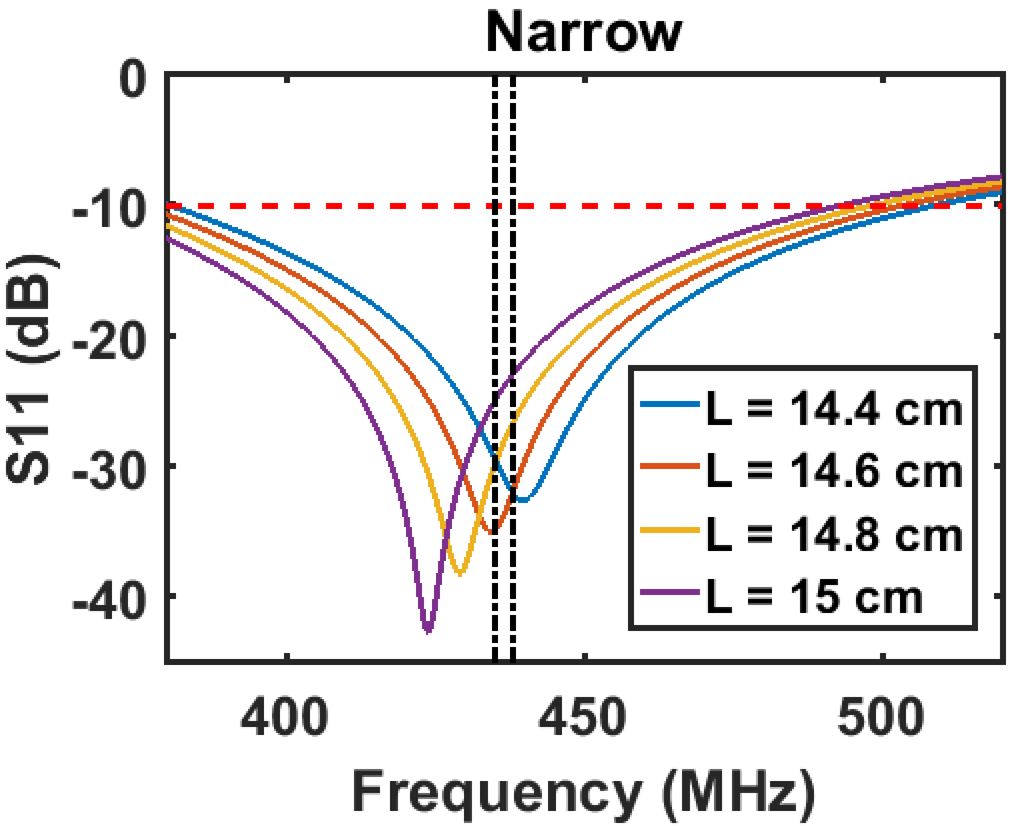
Overall model – UHF, no boom + camera

- text



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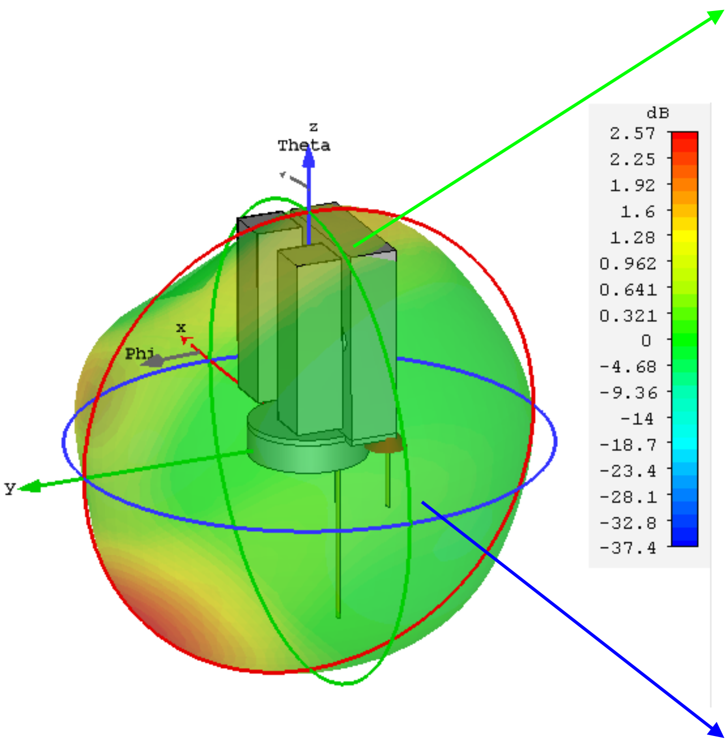
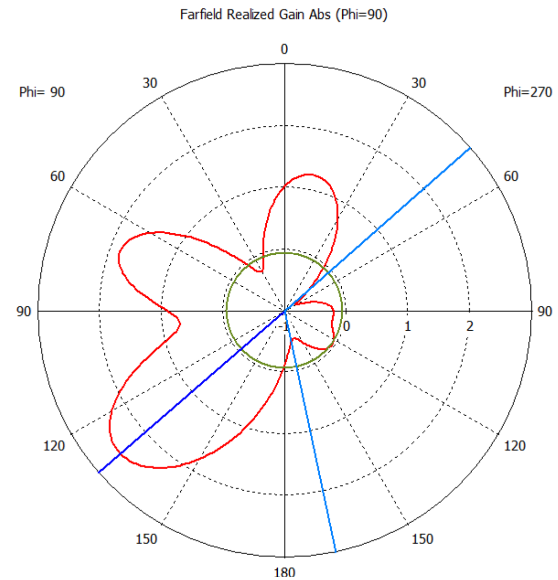
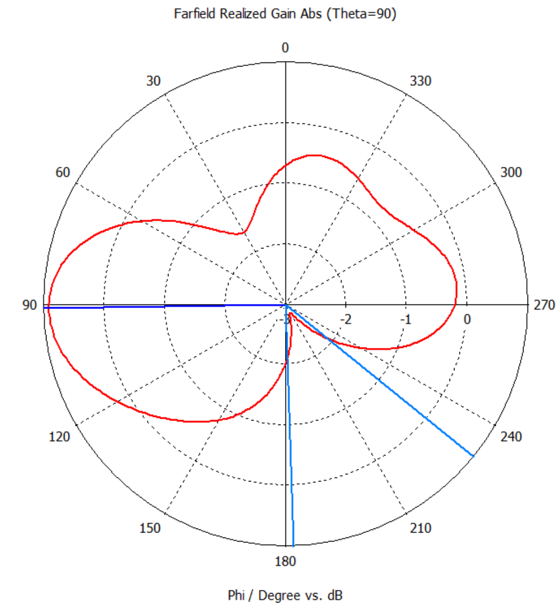
Overall model – UHF, no boom + camera







Frequency = 436.5 MHz
Main lobe magnitude = 2.52 dB
Main lobe direction = 131.0 deg.
Angular width (3 dB) = 240.6 deg.
Side lobe level = -2.6 dB

Frequency = 436.5 MHz
Main lobe magnitude = 0.901 dB
Main lobe direction = 91.0 deg.
Angular width (3 dB) = 311.0 deg.

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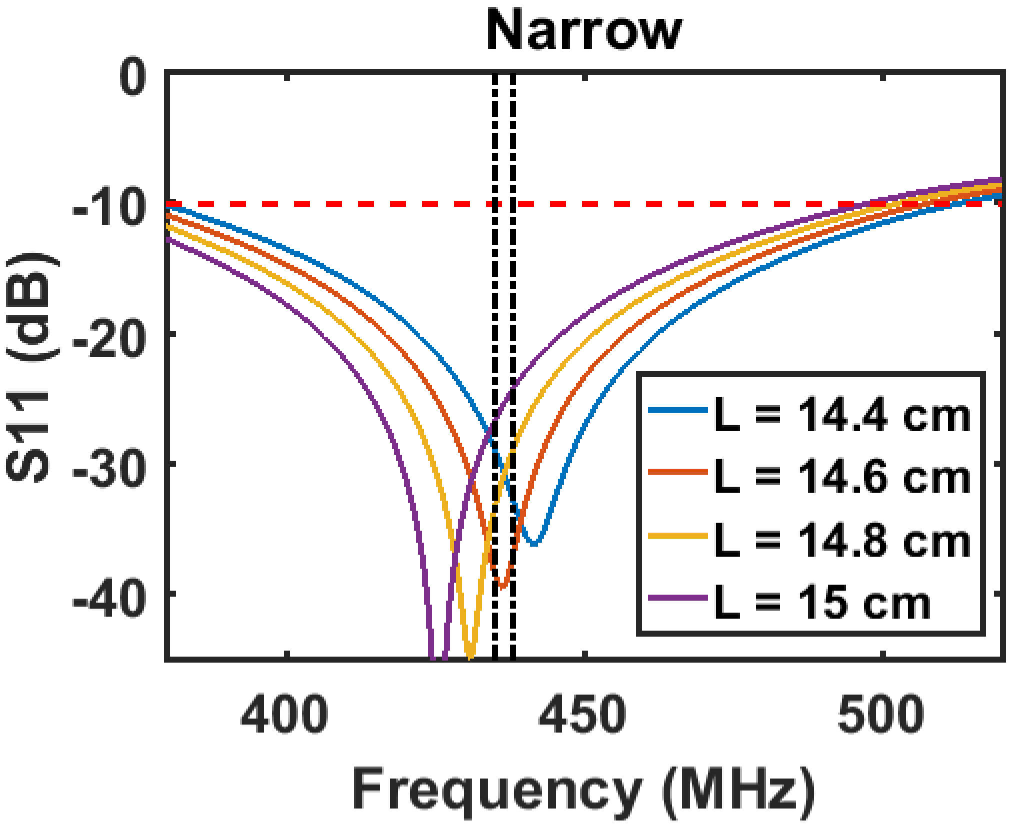
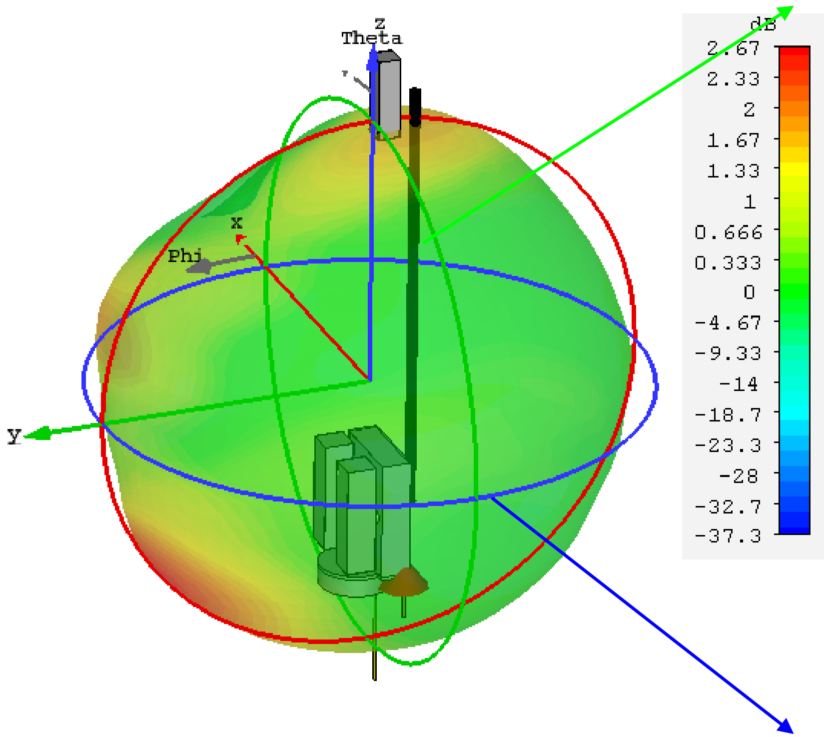
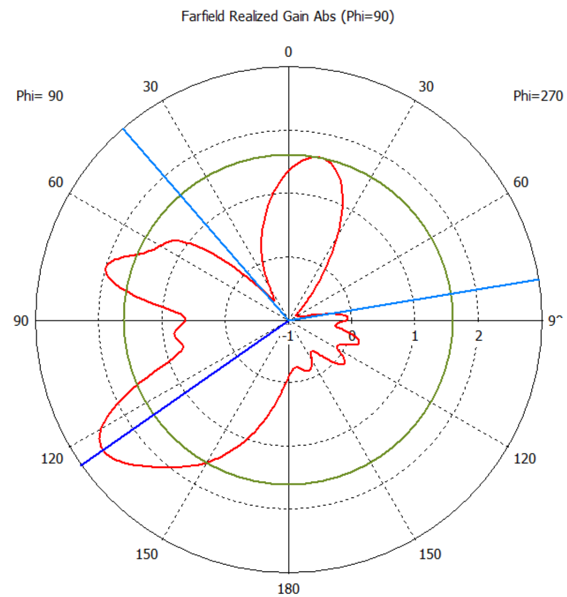
Overall model – UHF, with boom + camera

- text

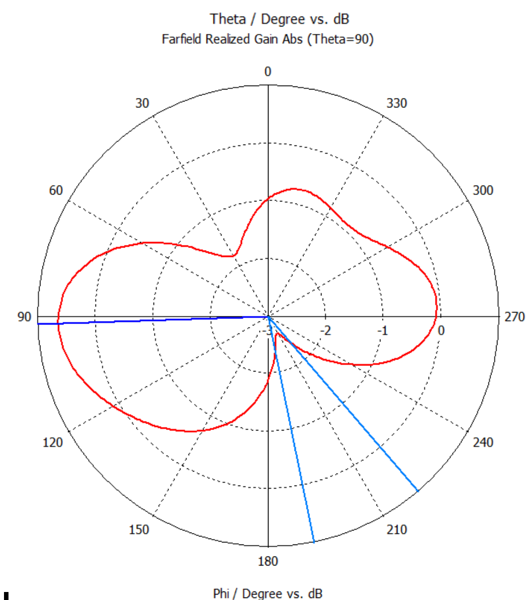


Overall model – UHF, with boom + camera; 14.6 cm





Frequency = 436.5 MHz
Main lobe magnitude = 2.58 dB
Main lobe direction = 125.0 deg.
Angular width (3 dB) = 238.4 deg.
Side lobe level = -1.0 dB



Frequency = 436.5 MHz
Main lobe magnitude = 0.633 dB
Main lobe direction = 92.0 deg.
Angular width (3 dB) = 330.7 deg.

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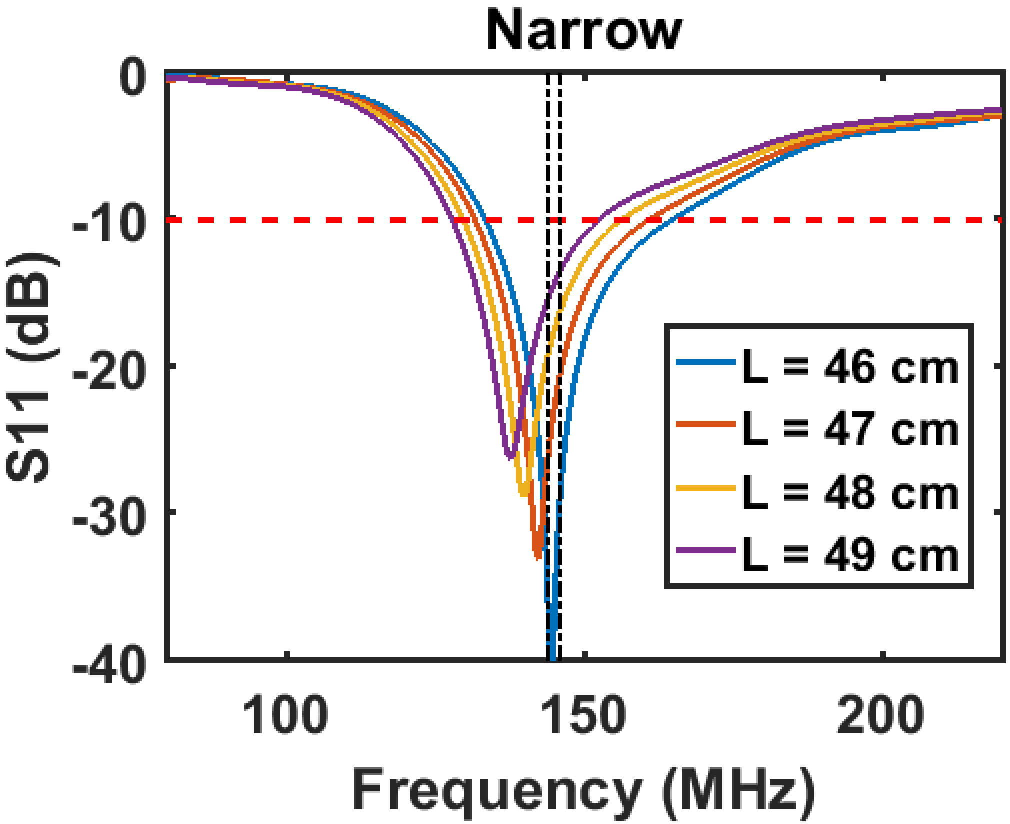
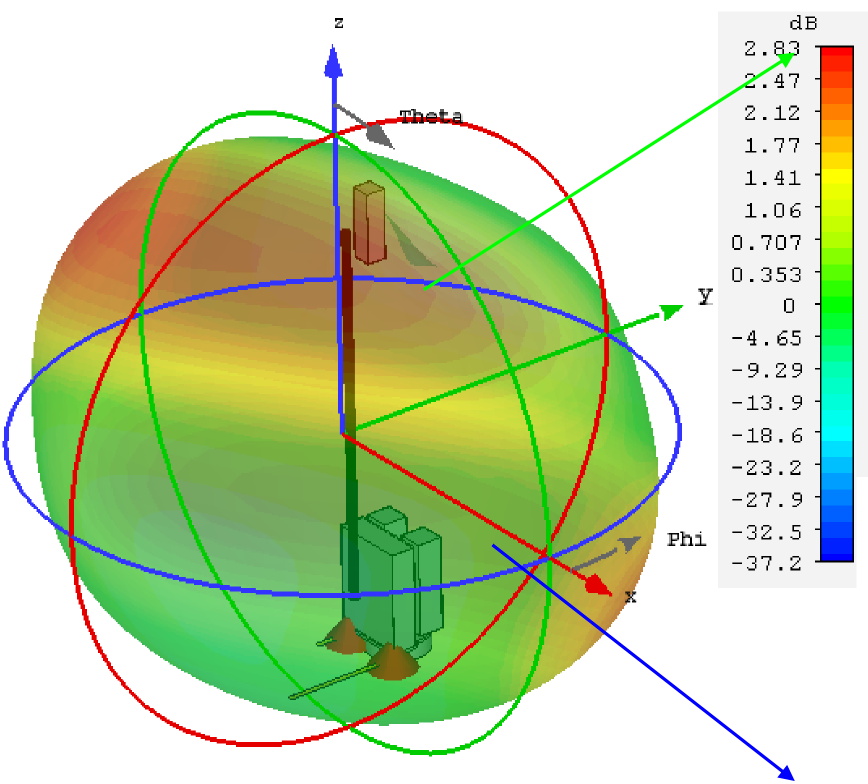
Overall model – VHF, 90 deg

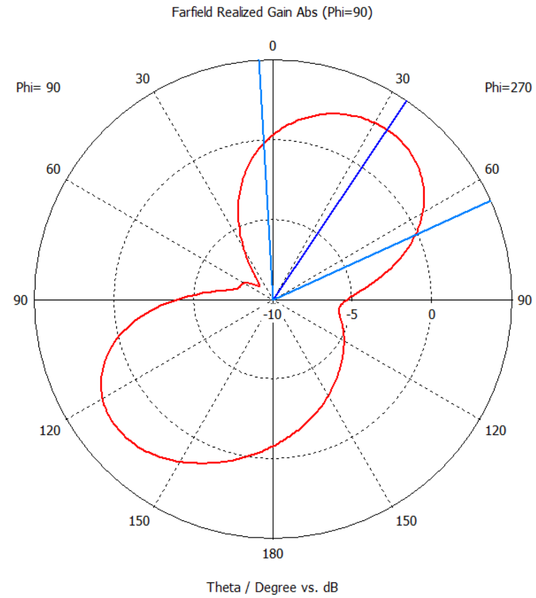
- text



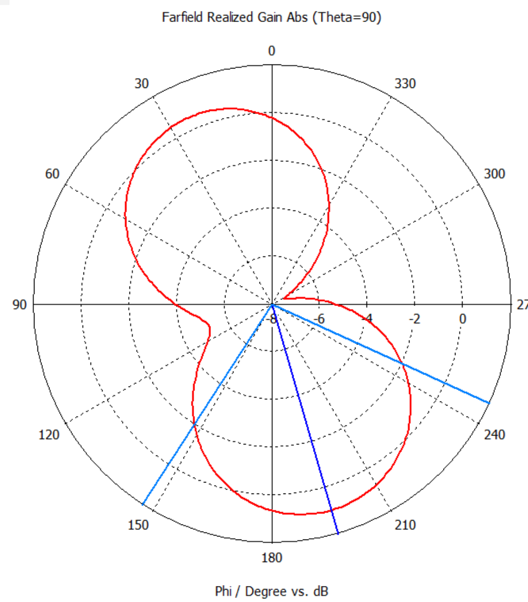
Caltech

Overall model – VHF 90 deg





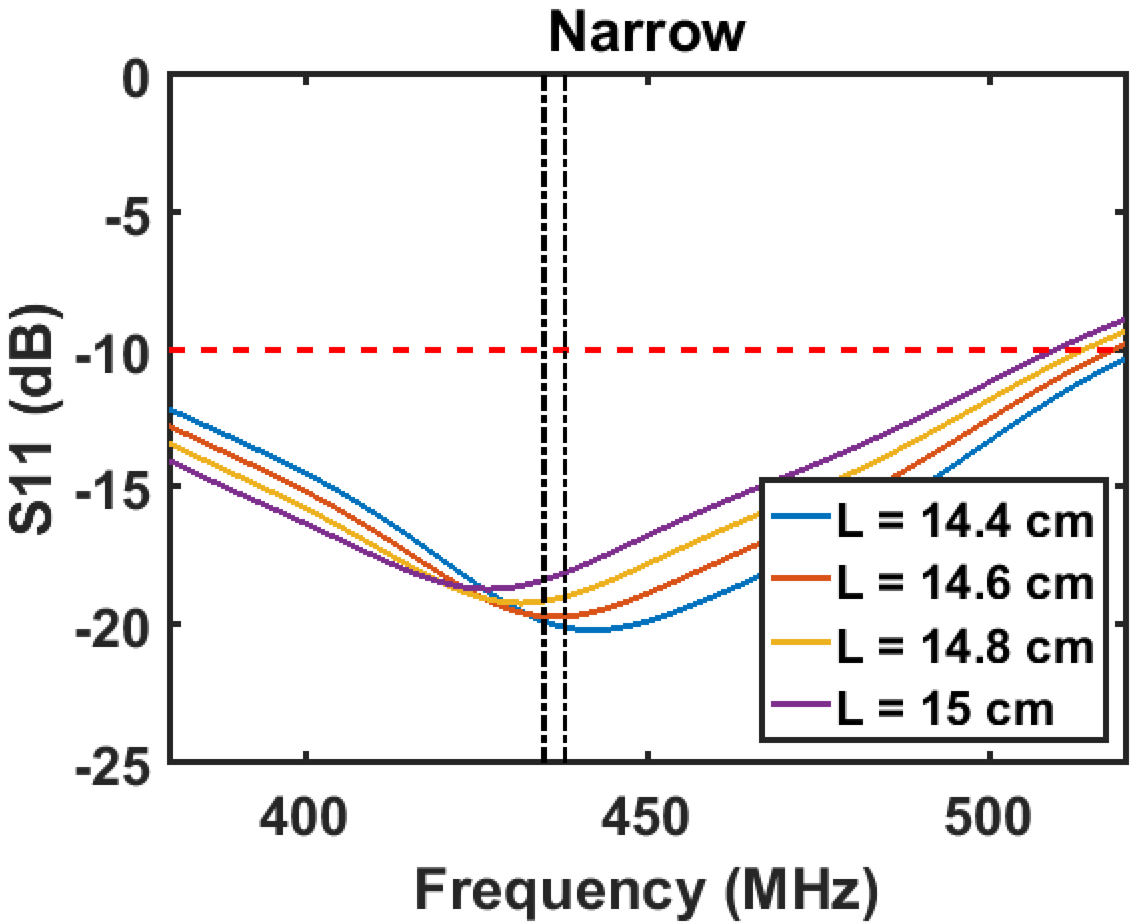
Frequency = 145 MHz
Main lobe magnitude = 2.81 dB
Main lobe direction = 34.0 deg.
Angular width (3 dB) = 69.0 deg.



Frequency = 145 MHz
Main lobe magnitude = 0.969 dB
Main lobe direction = 196.0 deg.
Angular width (3 dB) = 98.5 deg.

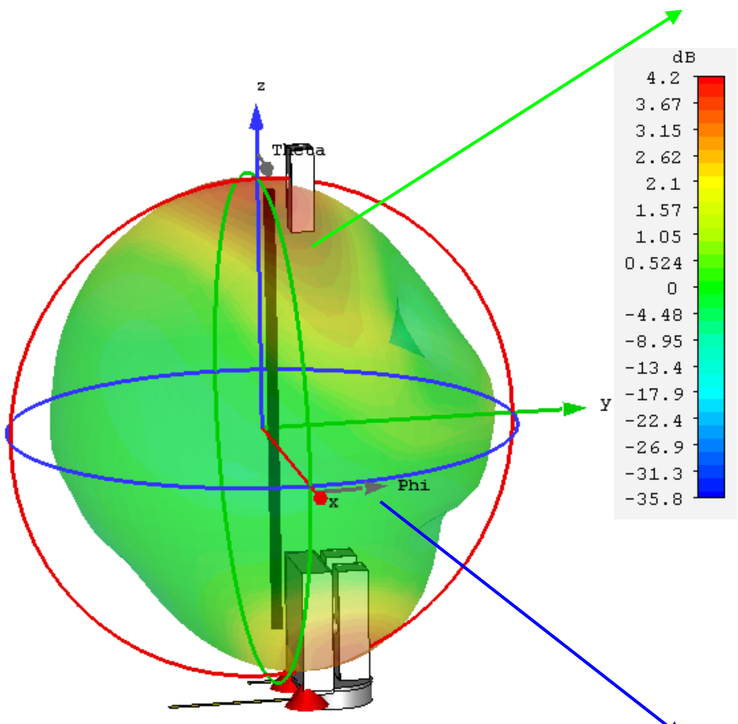
Overall model – UHF, 90 deg

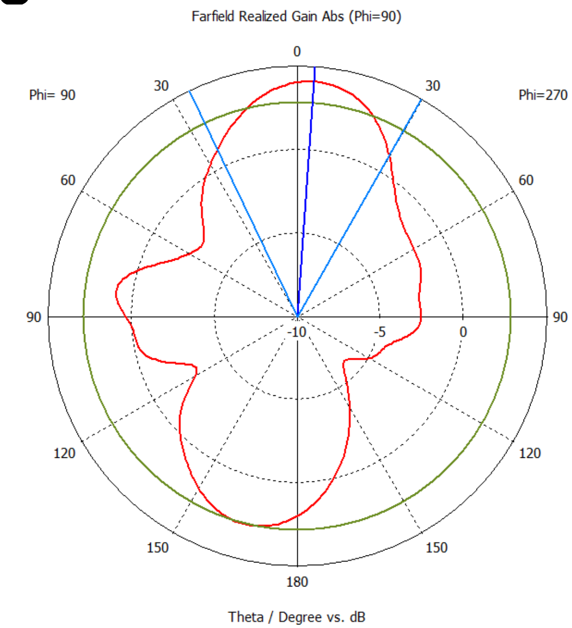
- text



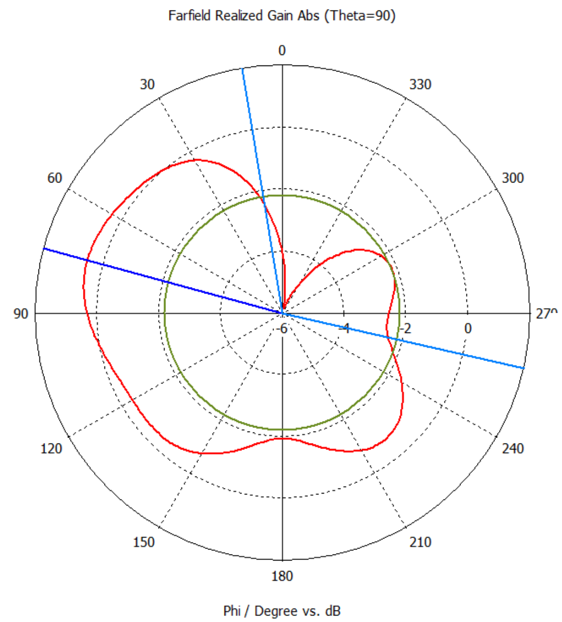
Caltech

Overall model – UHF 90 deg 14.6 cm





Frequency = 436.5 MHz
Main lobe magnitude = 4.1 dB
Main lobe direction = 4.0 deg.
Angular width (3 dB) = 55.3 deg.
Side lobe level = -1.2 dB



Frequency = 436.5 MHz
Main lobe magnitude = 0.515 dB
Main lobe direction = 75.0 deg.
Angular width (3 dB) = 247.8 deg.
Side lobe level = -2.7 dB

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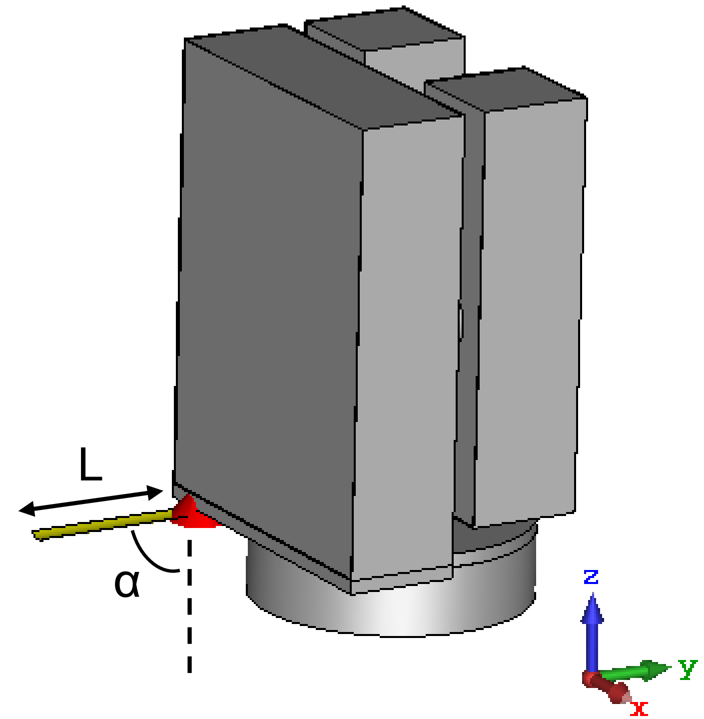
Simulations w/out boom

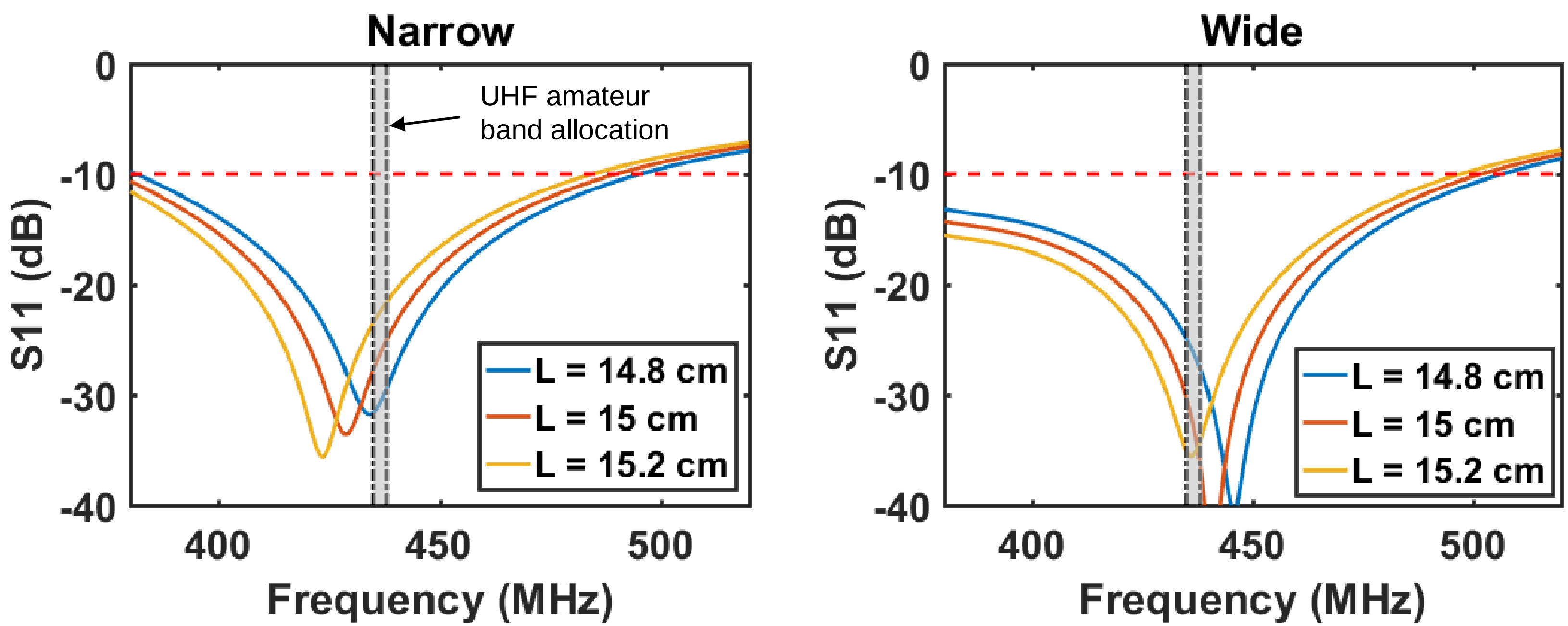
Simulation Setup

- **CST Student Edition – max 30,000 elements**
- **Satellite (including mirror boxes): 1 mm thick Aluminum shell**
  - CoreSat: 40 X 30 X 10 cm
  - MirrorSats: 10 X 10 X 37 cm
- **LVI ring: Al cylinder, 1 cm thick, 12.4 cm OD, 6 cm height**
- **LVI plate: 1 cm thick plate**
- **Antenna: steel, tape measure profile**
  - Variable length, angle relative to CoreSat
- **All components assumed to be in electrical contact**



UHF antenna, α = 0º – Reflection Coefficient

- Antenna operating frequencies shift with changing configurations
- L = 15 cm a compromise between two configurations (close to expected $\frac{\lambda}{4}$)



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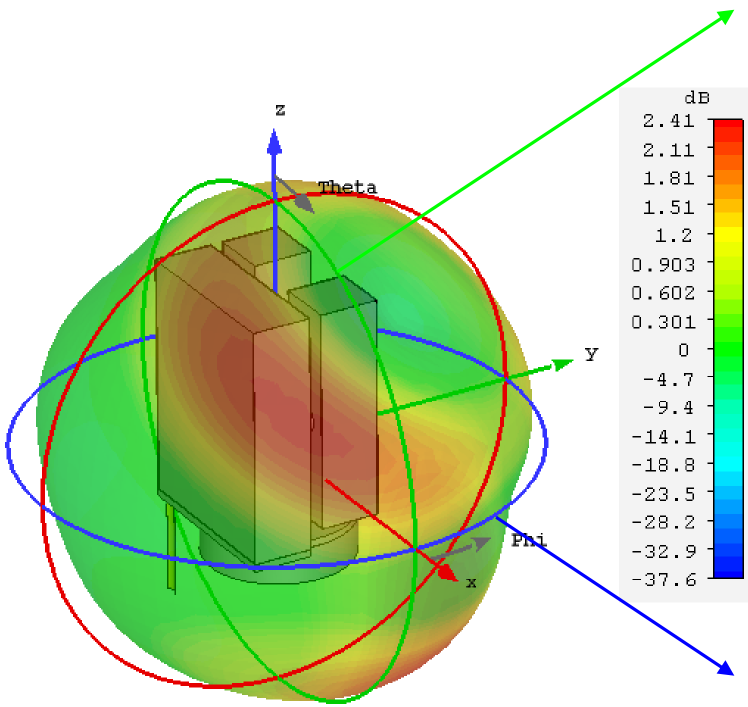
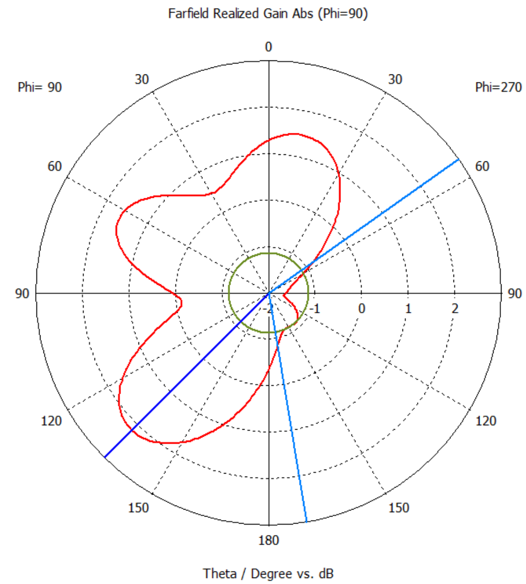
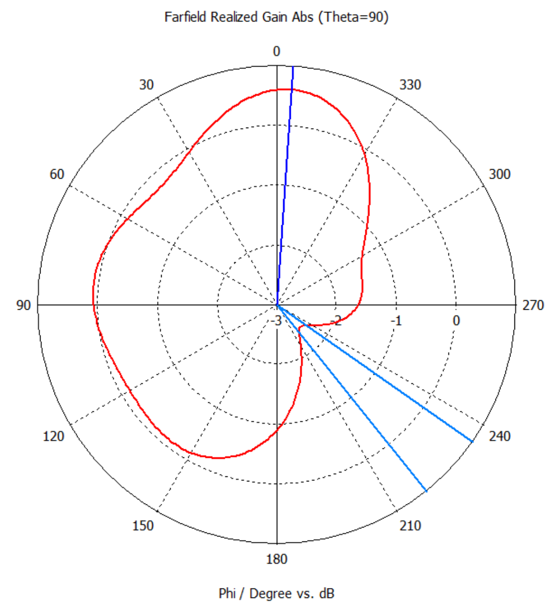
UHF antenna, narrow, α = 0º, L = 15 cm (437.5 MHz)





Frequency = 437.5
Main lobe magnitude = 2.16 dB
Main lobe direction = 135.0 deg.
Angular width (3 dB) = 244.2 deg.
Side lobe level = -3.3 dB



Frequency = 437.5
Main lobe magnitude = 0.603 dB
Main lobe direction = 356.0 deg.
Angular width (3 dB) = 343.6 deg.

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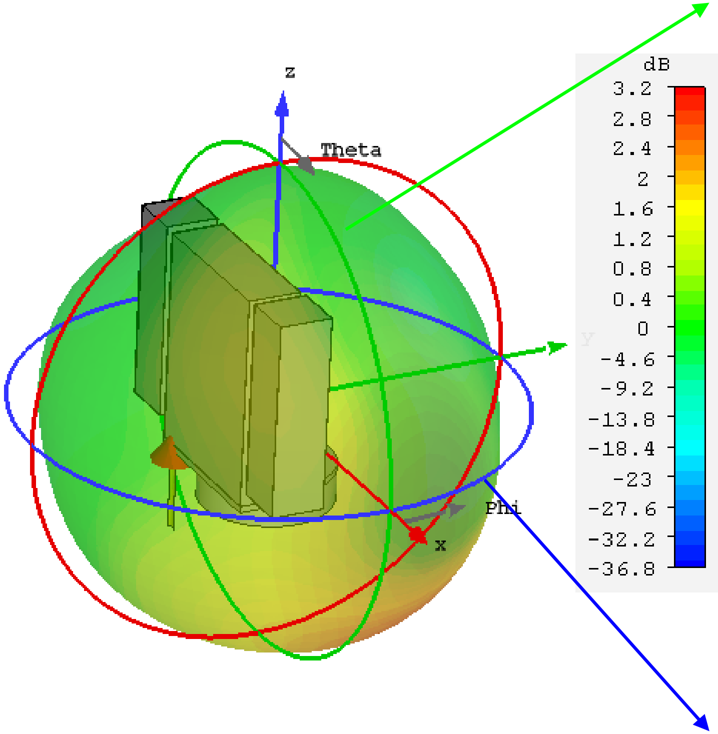
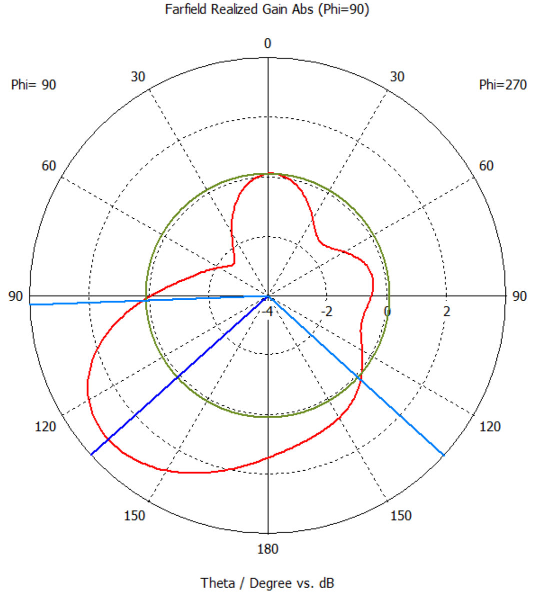
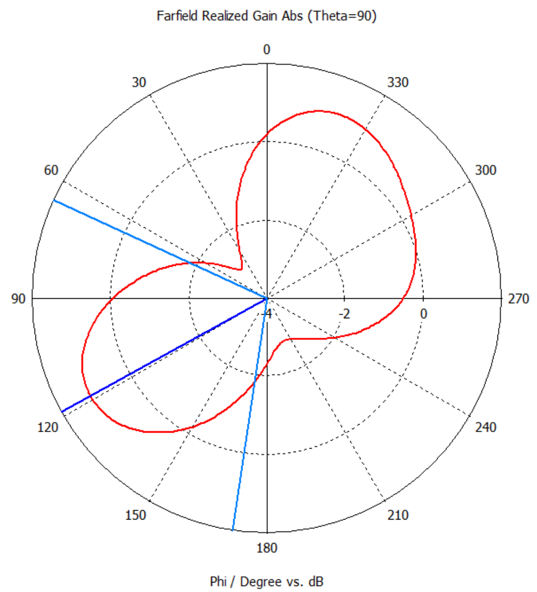
UHF antenna, wide, α = 0º, L = 15 cm (437.5 MHz)





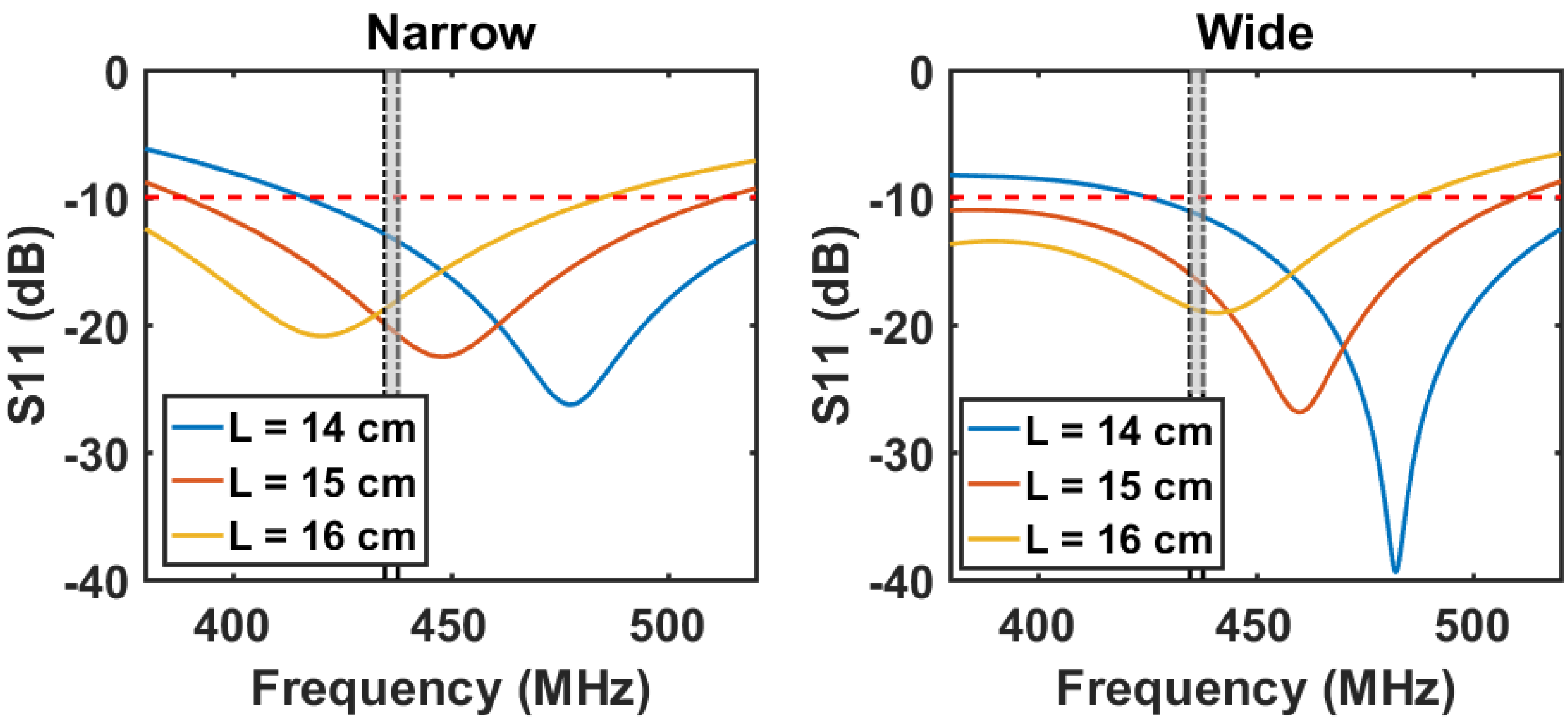
Frequency = 437.5
Main lobe magnitude = 3.2 dB
Main lobe direction = 132.0 deg.
Angular width (3 dB) = 135.6 deg.
Side lobe level = -3.1 dB



Frequency = 437.5
Main lobe magnitude = 1.15 dB
Main lobe direction = 119.0 deg.
Angular width (3 dB) = 106.3 deg.

UHF antenna, α = 90º – Reflection Coefficient

- **Resonance shifted to higher frequencies but still good performance**
- **L = 16 cm compromise between configurations**



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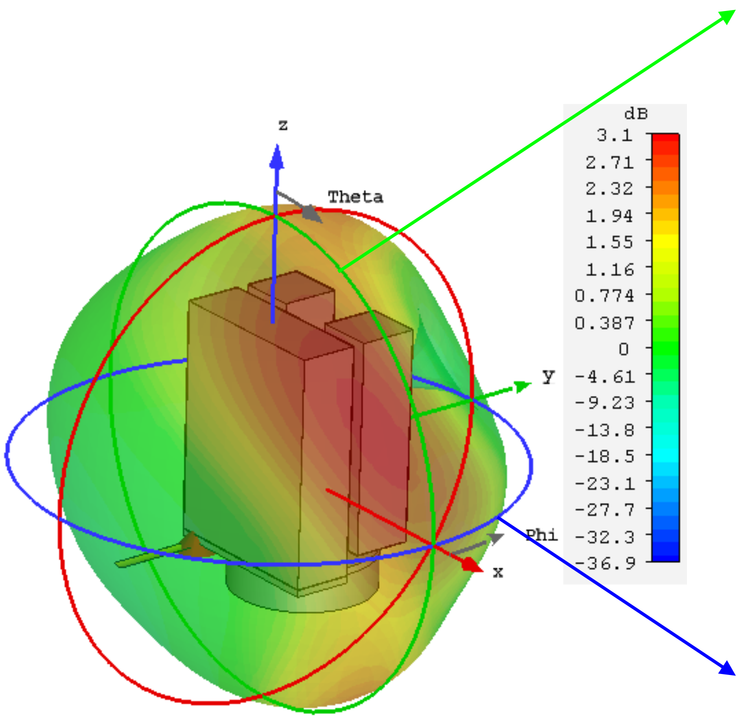
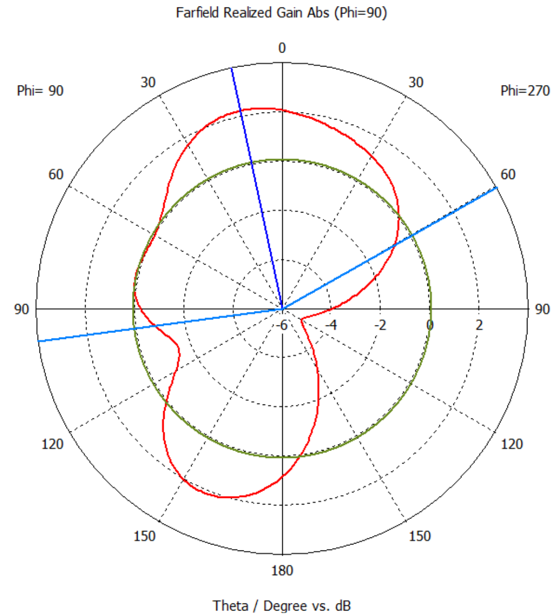
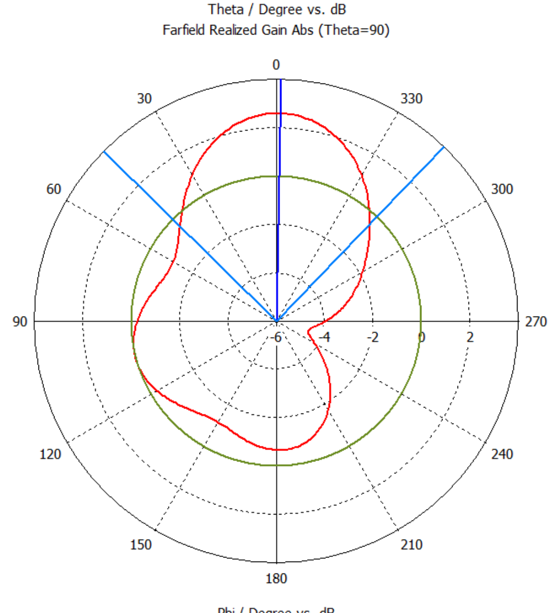
UHF antenna, narrow, α = 90º, L = 16 cm (437.5 MHz)





Frequency = 437.5
Main lobe magnitude = 2.21 dB
Main lobe direction = 12.0 deg.
Angular width (3 dB) = 158.1 deg.
Side lobe level = -2.1 dB



Frequency = 437.5
Main lobe magnitude = 2.59 dB
Main lobe direction = 359.0 deg.
Angular width (3 dB) = 89.1 deg.
Side lobe level = -2.6 dB

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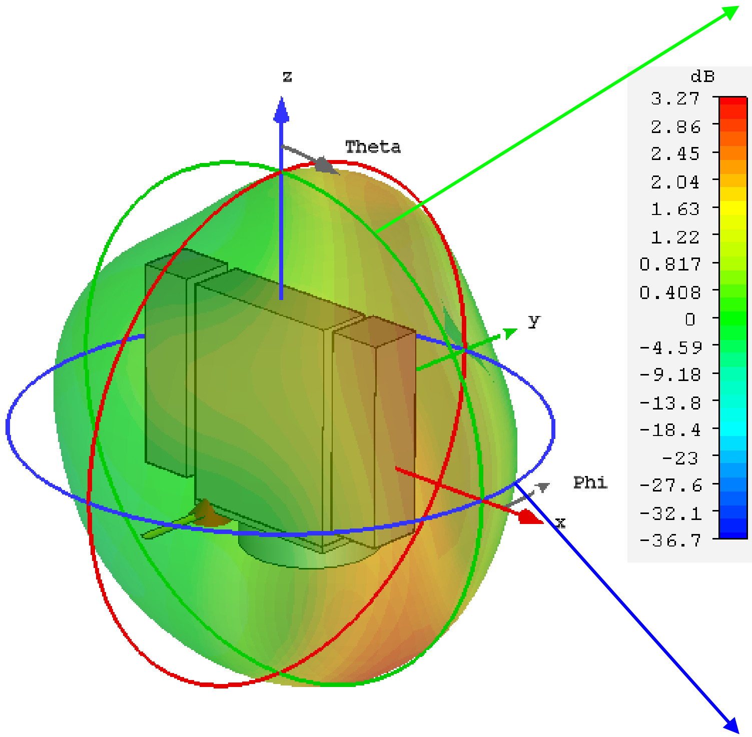
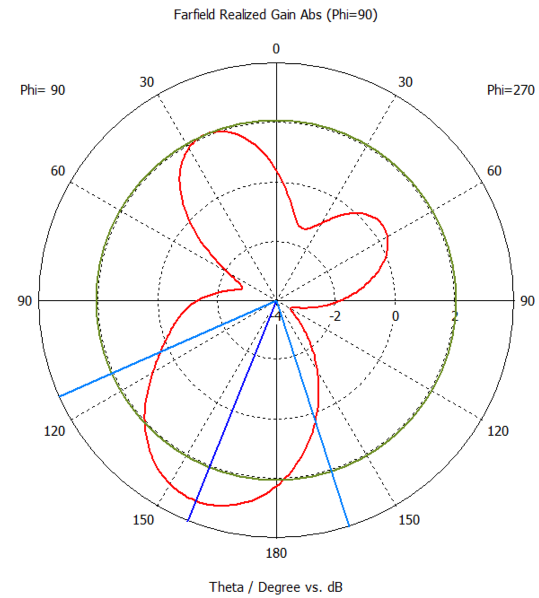
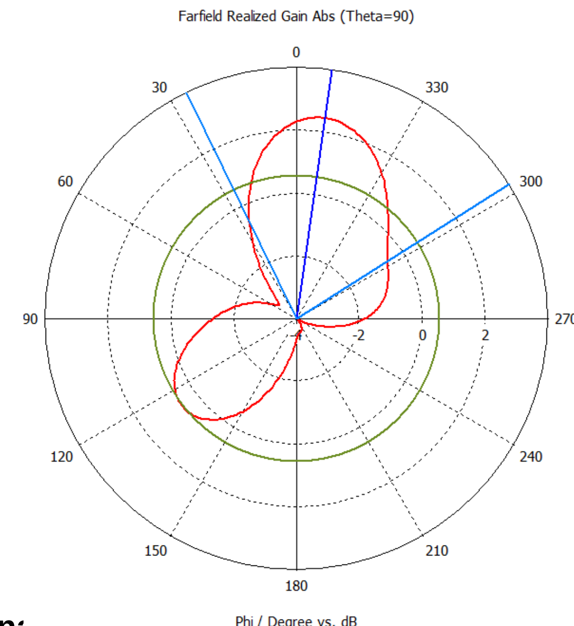
UHF antenna, wide, α = 90º, L = 16 cm (437.5 MHz)





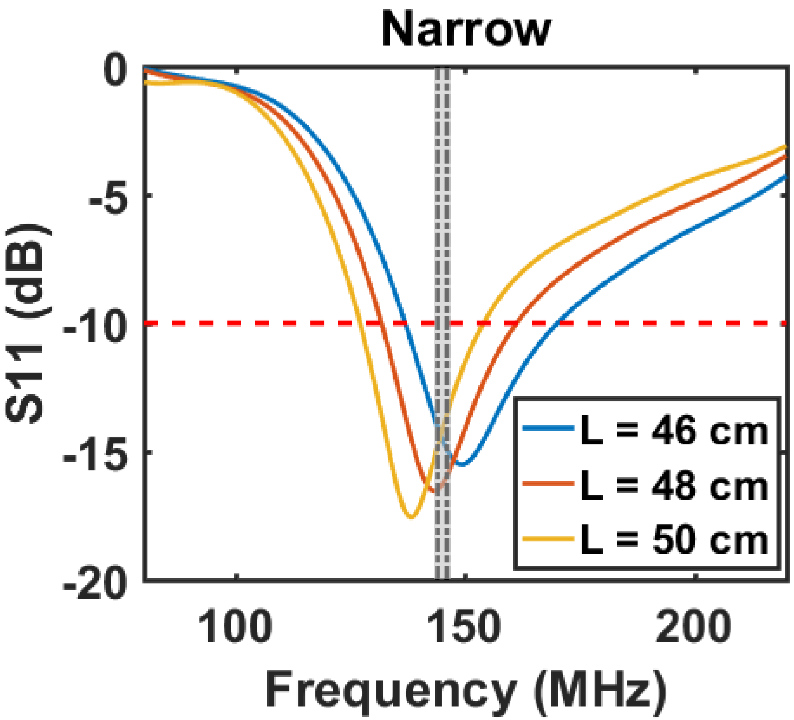
Frequency = 437.5
Main lobe magnitude = 3.26 dB
Main lobe direction = 158.0 deg.
Angular width (3 dB) = 84.1 deg.
Side lobe level = -1.2 dB

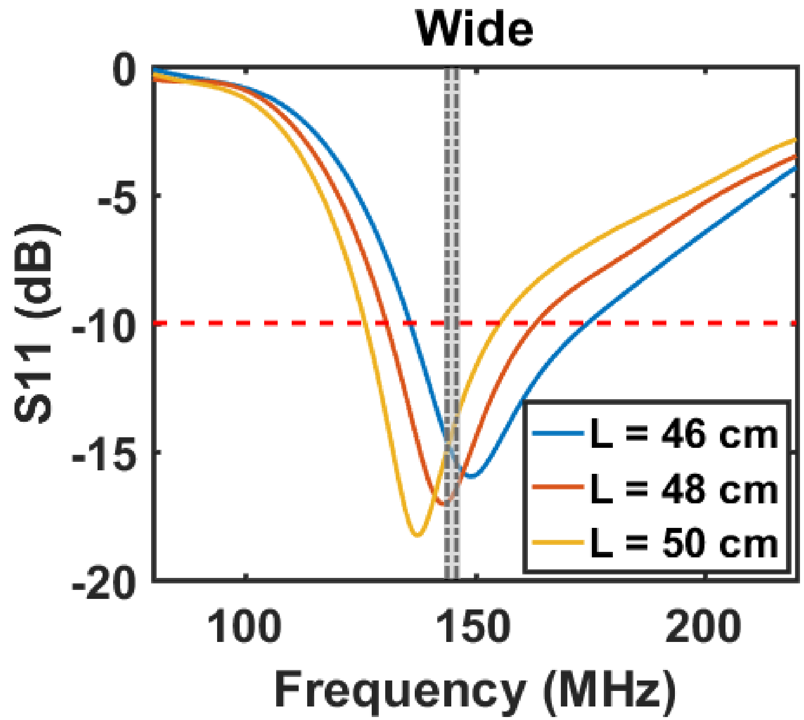


Frequency = 437.5
Main lobe magnitude = 2.44 dB
Main lobe direction = 352.0 deg.
Angular width (3 dB) = 83.5 deg.
Side lobe level = -1.9 dB

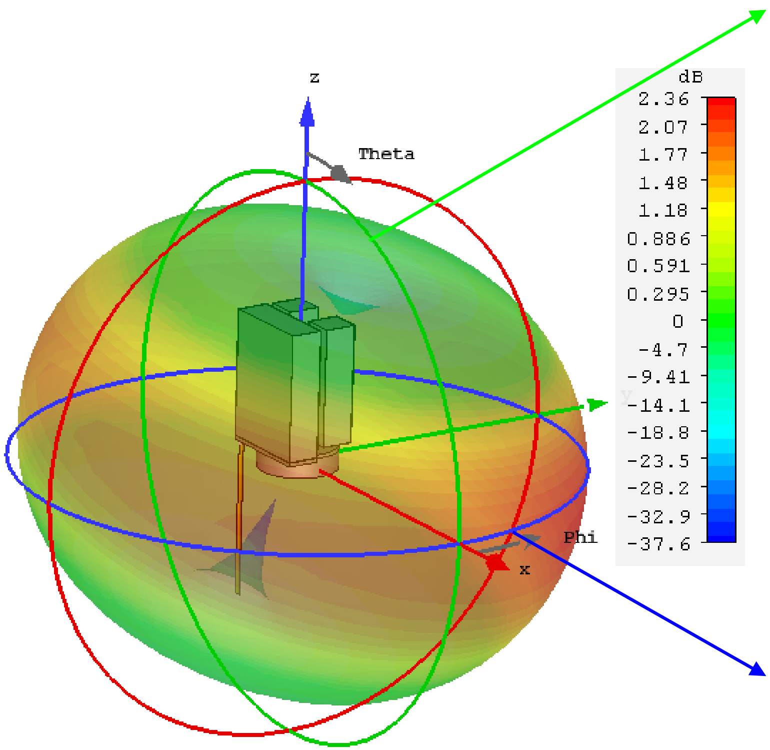
VHF antenna, α = 0º – Reflection Coefficient

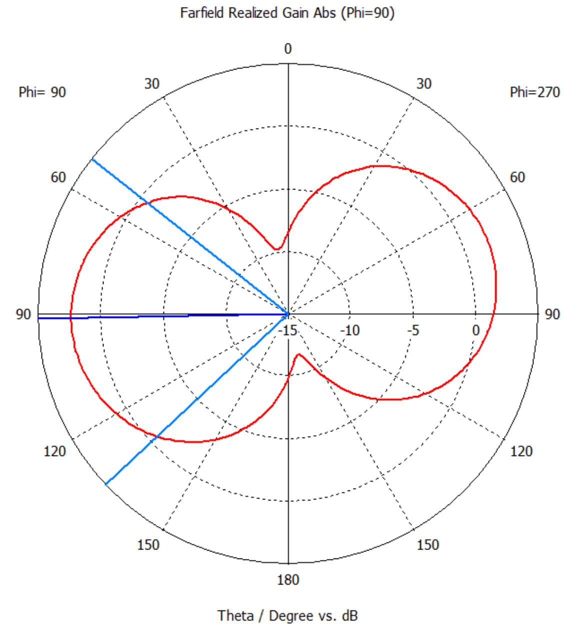
- **Antenna operating frequencies unaffected by changing configurations**
- **L = 48 cm for operation in amateur band (close to expected $\frac{\lambda}{4}$)**



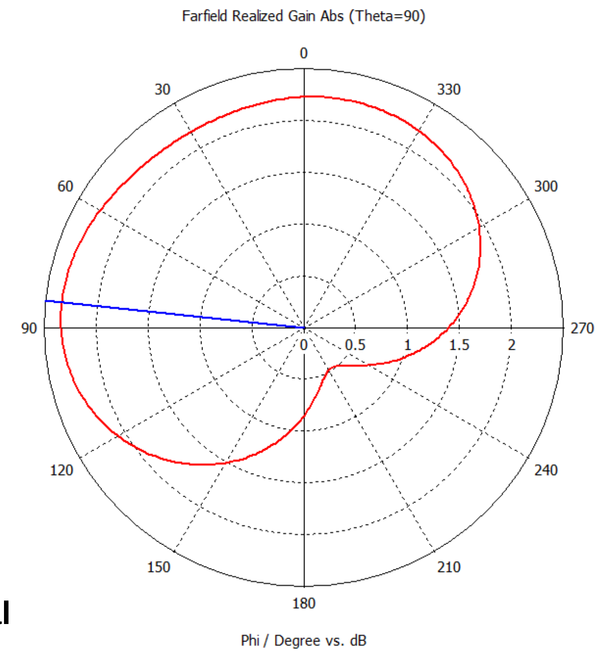


VHF antenna, narrow, α = 0º, L = 48 cm (145 MHz)





Frequency = 145
Main lobe magnitude = 2.34 dB
Main lobe direction = 91.0 deg.
Angular width (3 dB) = 81.2 deg.



Frequency = 145
Main lobe magnitude = 2.34 dB
Main lobe direction = 84.0 deg.

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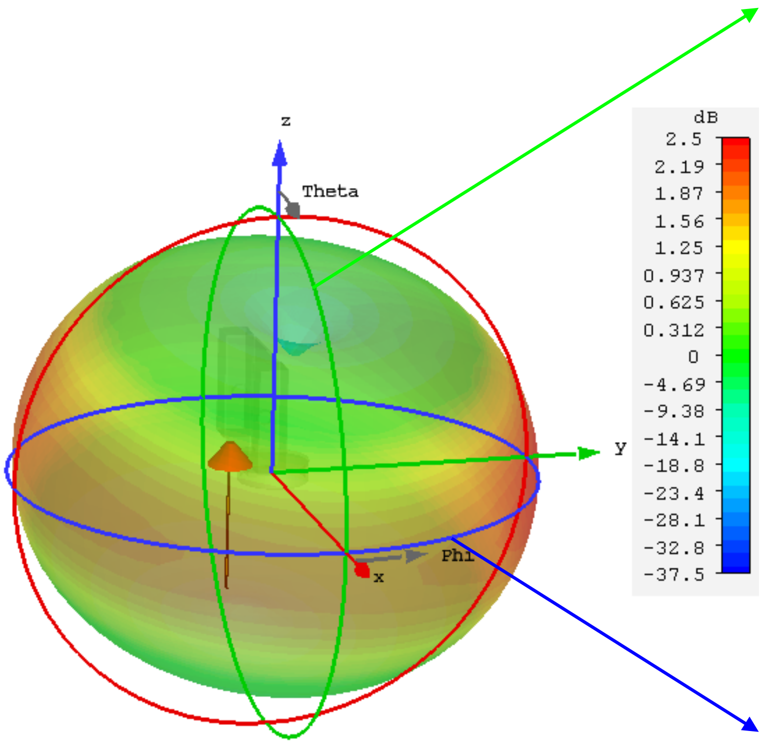
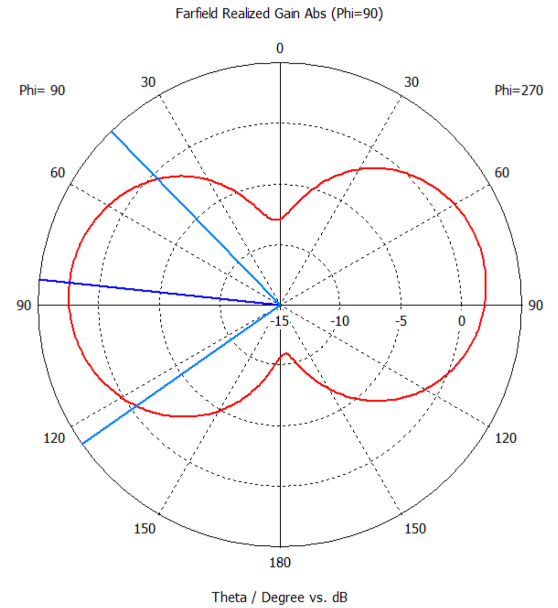
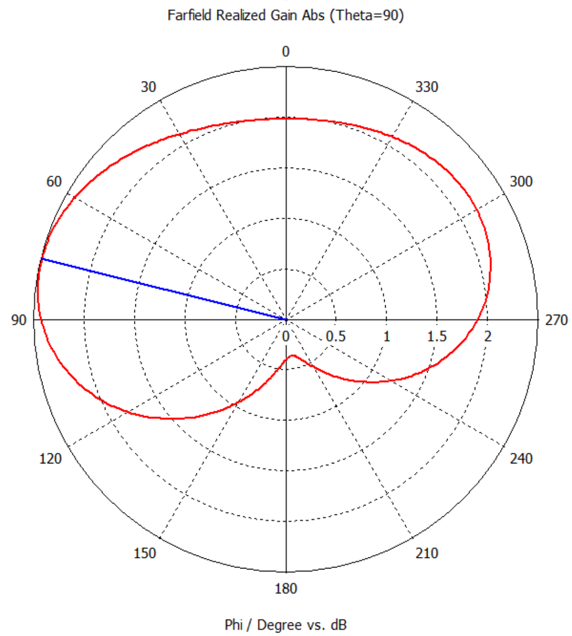
VHF antenna, wide, α = 0º, L = 48 cm (145 MHz)





Frequency = 145
Main lobe magnitude = 2.48 dB
Main lobe direction = 84.0 deg.
Angular width (3 dB) = 80.9 deg.



Frequency = 145
Main lobe magnitude = 2.49 dB
Main lobe direction = 76.0 deg.

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Conclusions

- **VHF operation acceptable with antenna at 0º in both configurations**
  - S11 ~ -17 dB (VSWR ~ 1.35) at 48 cm length, 145 MHz
  - Expected monopole radiation pattern
  - Narrow: 2.34 dB; Wide: 2.48 dB
- **UHF operation affected by LVI ring but still acceptable at 0º in both configurations**
  - S11 ~ -20-30 dB (VSWR ~ 1.0 – 1.1) at 15 cm length, 437.5 MHz
  - Radiation pattern highly affected, non-isotropic, expecially in wide configuration
    - 3dB beamwidths of 80 deg

space structures laboratory

AAReST CoreSat OBSW

Thibaud Talon

Antonio Pedivellano

Caltech

Outline

- **Requirements**
- **Design / Architecture**
  - Hardware abstraction layer
  - TCT handler / queue
  - Modules / Tasks
- **State of the OBSW**
  - Currently implemented code
  - Software to write
- **Communications protocols**
  - TCTM protocol
  - File Transfer protocol
- **Example**
- **Future Work**
- **Questions**

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Requirements

Requirements

Needs	Requirement
Communicate with the ground	Receiving data from ground should be interrupt-driven
Communication protocol for large data transmission	TCTM protocol must have limited overhead
	File transfer protocol must allow transmission of files over multiple passes
	Protocols must include error-detecting code
	Must send beacon message with critical data
Obtain live telemetry for docking	Must be able to downlink live telemetry data during separation and docking: a) ADCS parameters b) MirrorSat and CoreSat critical health data
Control each subsystem from the on-board computer	Architecture must enable interfaces (I2C, UART, etc.) specified by each subsystem
	Must provide interface code between ground messages and subsystems
Automatically control subsystems	Software must be real time
	Software must be able to read scripts of commands
Ensure safety of spacecraft	Must monitor safety of satellite periodically
	Must manage safe mode by only preserving critical systems
	Must save critical data to non-volatile memory
Reprogram in-flight	Must include Bootloader to self program the OBC

Design / Architecture

Design / Architecture

- **Microcontroller**
  - EFM32 on CubeComputer (CubeSpace)
  - Interfaces available: I2C (x2), UART (x2), CAN, SPI

- **Real Time Software**
  - FreeRTOS
  - *Wide user base, flown on previous missions* [1], available on EFM32 programming software

- **Software Architecture**
  - Generously given by Surrey
  - Based on tasks for each subsystem and critical functions
  - Contains TCT handler / queue for message transfer between tasks
  - Interface with Hardware via a Hardware Abstraction Layer

(1) Duke, R., Bridges, C., Stewart, B., Taylor, B., Massimiani, C., Forshaw, J.L. and Aglietti, G., 2016, September. Integrated Flight & Ground Software Framework for Fast Mission Timelines. In *Proceedings of 67th International Astronautical Congress 2016*.

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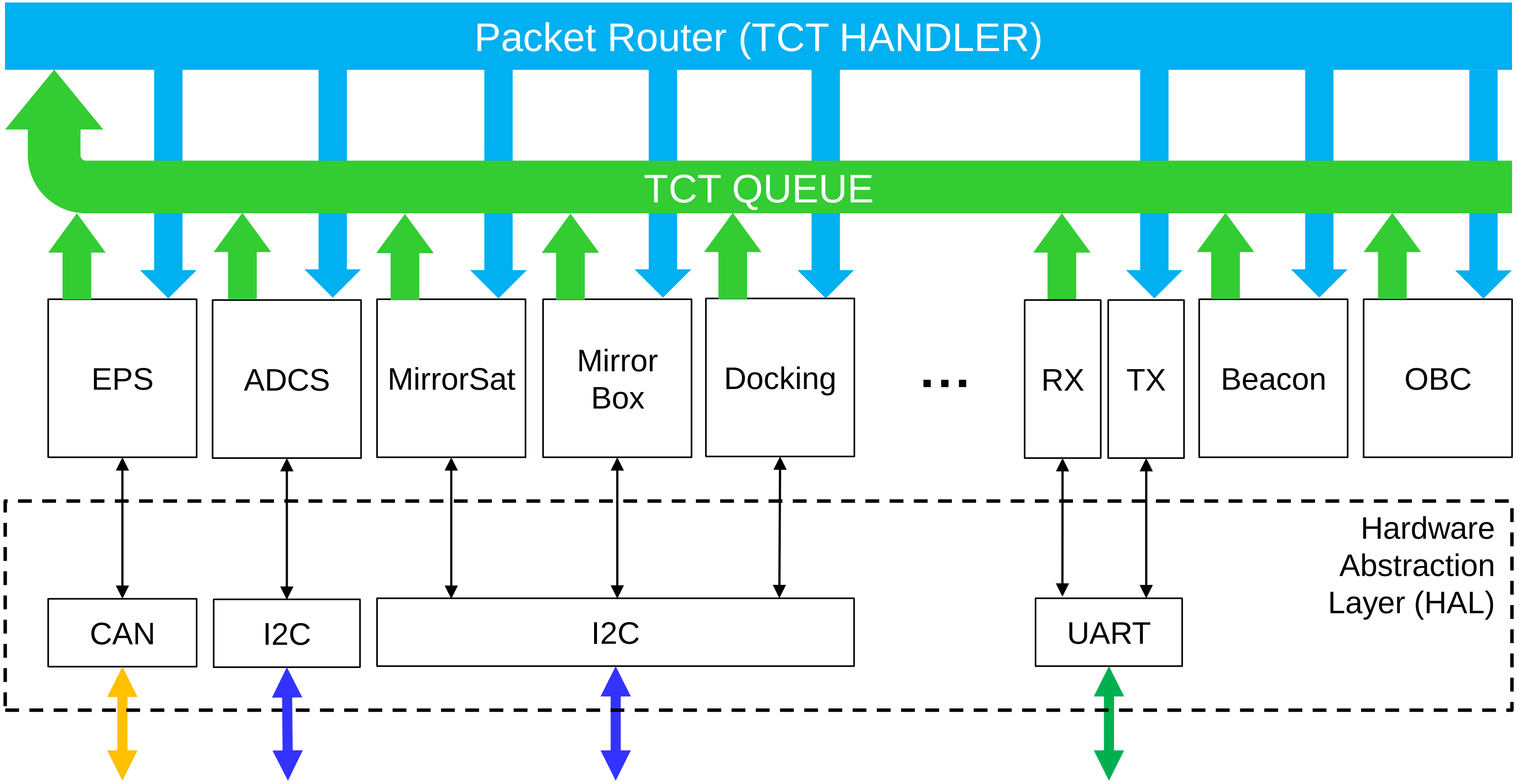
Design / Architecture



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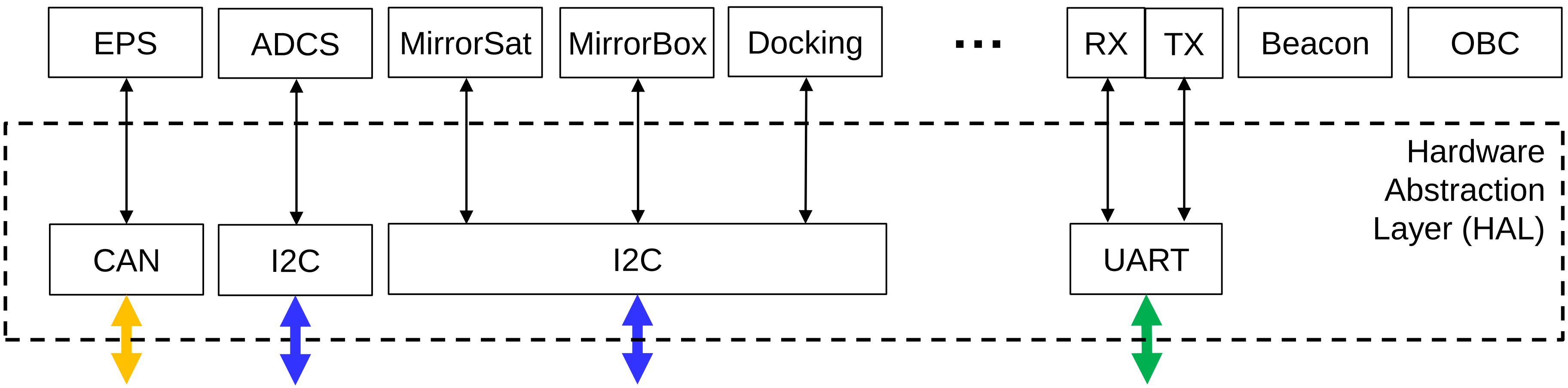
Hardware Abstraction Layer



- **List of functions for each interface**
  - Transfer message over each interface

- **Functions directly implemented in each task**
  - No specific task for each interface
  - Except UART which is interrupt driven (used for Ground comms)

- **Functions include Semaphore Mutex to prevent two tasks to access the same interface at the same time**

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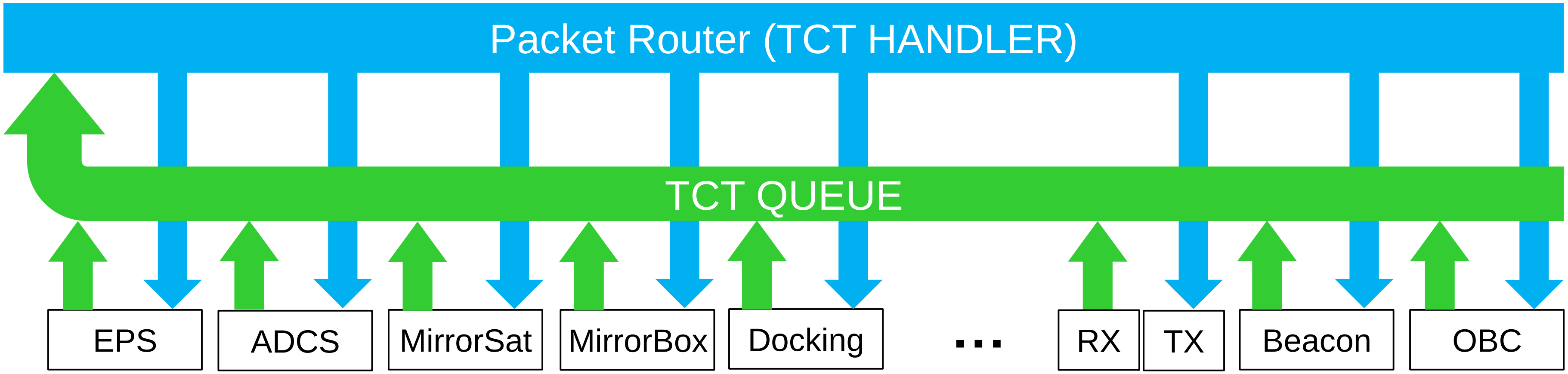
TCT Handler / Queue



- **Manages transfer of information between Tasks**
- **Messages are structures**
  - Source ID
  - Reply ID
  - Return value
  - Destination ID
  - Message ID
  - Message type
  - Packet length
  - Packet (array)

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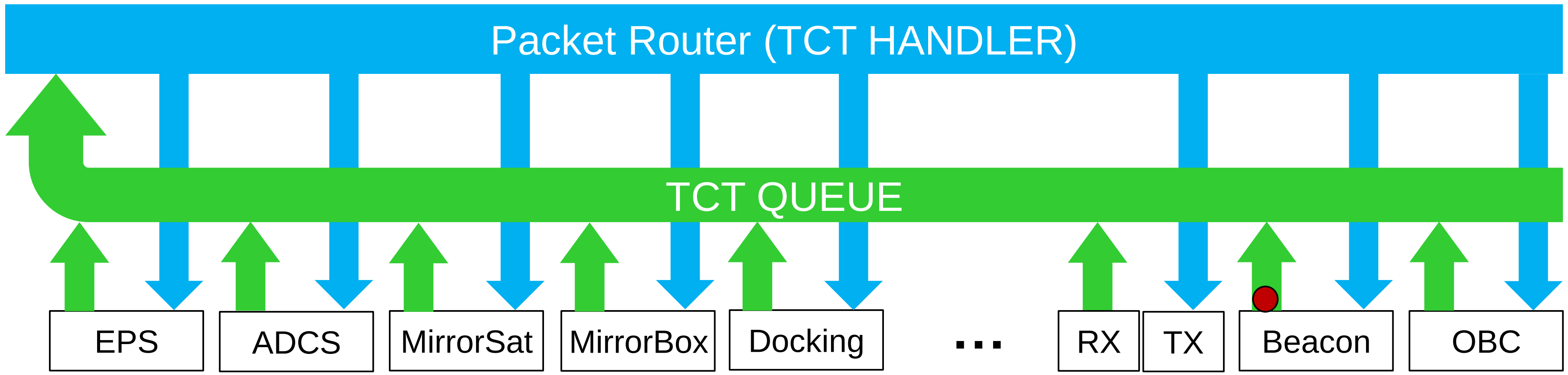
TCT Handler / Queue



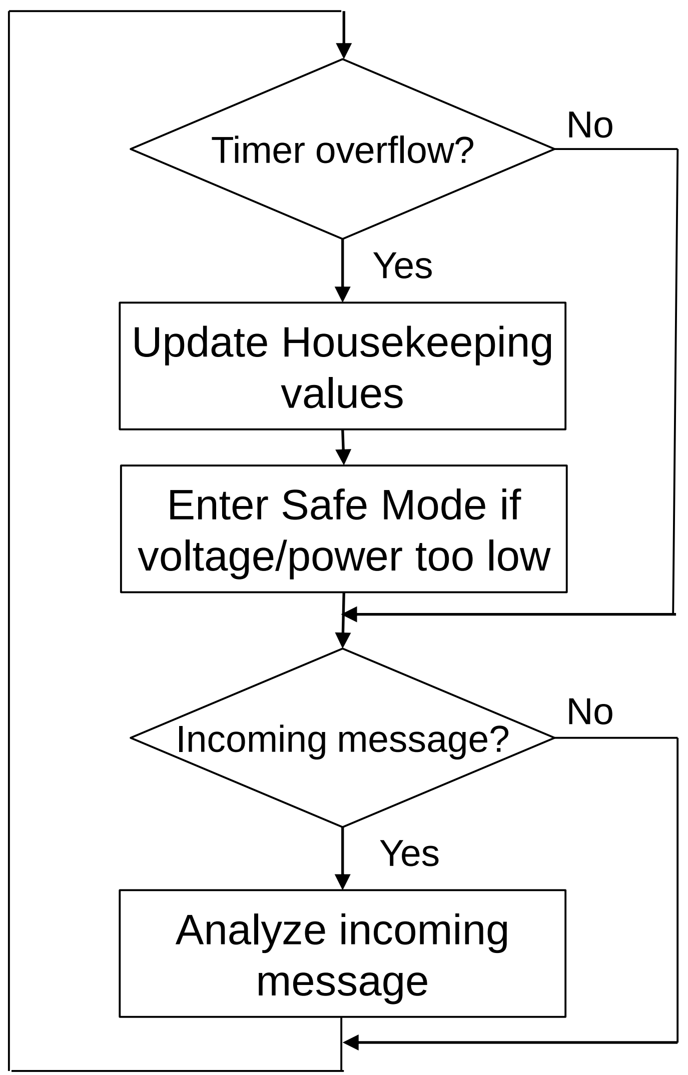
- **Example: Beacon sending voltages and currents from EPS**

Source ID	UART TX (38)
Reply ID	
Return value	
Destination ID	GomspaceEPS (41)
Message ID	81
Message type	request
Packet length	4 (default)
Packet (array)	

Source ID	GomspaceEPS (41)
Reply ID	
Return value	Result (from I2C communication)
Destination ID	UART TX (38)
Message ID	81
Message type	ack
Packet length	21
Packet (array)	(Voltages and currents)

EPS task

Task infinite loop:



List of Housekeeping values:

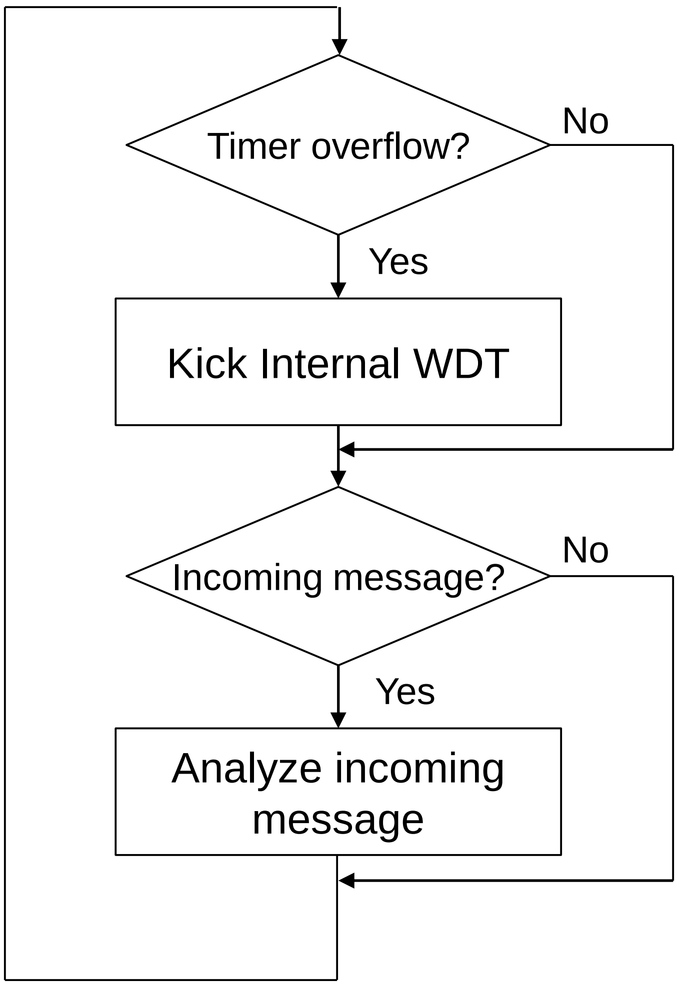
- Voltages
- Currents (In and Out)
- Temperatures (including battery)
- Battery modes
- Latch-ups
- Watchdog timers state
- Errors
- Etc.

List of commands / messages

- Read housekeeping values
- Set outputs
- Read/Set configuration
- Reset
- Etc.

OBC task

Task infinite loop:



List of commands / messages

- Check health (safe mode)
- Trigger safe mode, reset, etc.
- Set/Read unix time
- Test I2C, CAN lines
- Suspend/Resume tasks
- Change flight code (through bootloader)
- Manage watchdog timers

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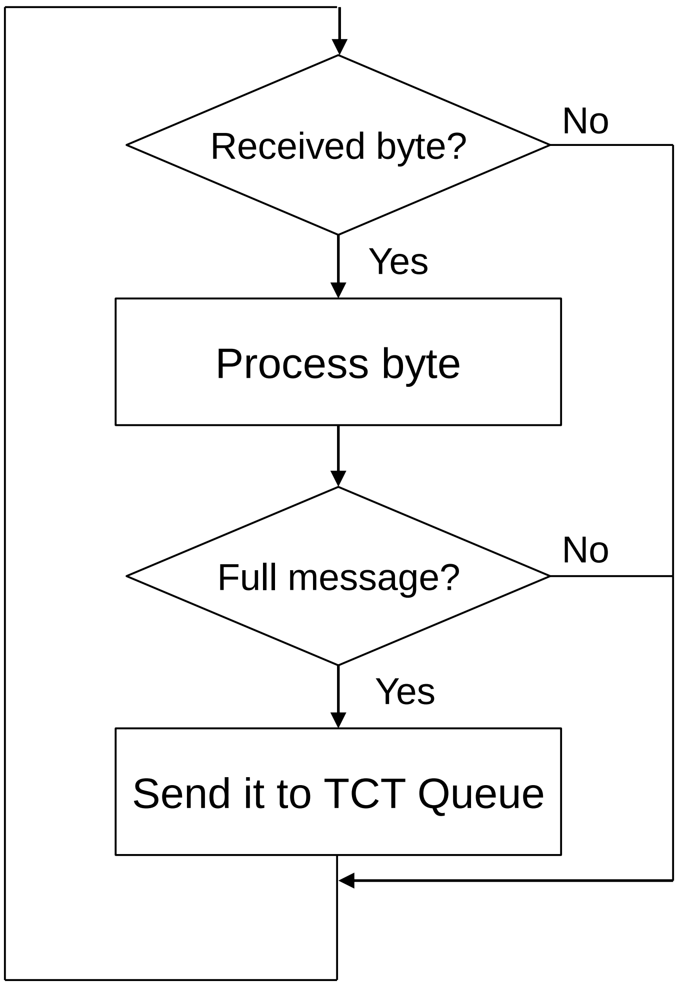
UART tasks

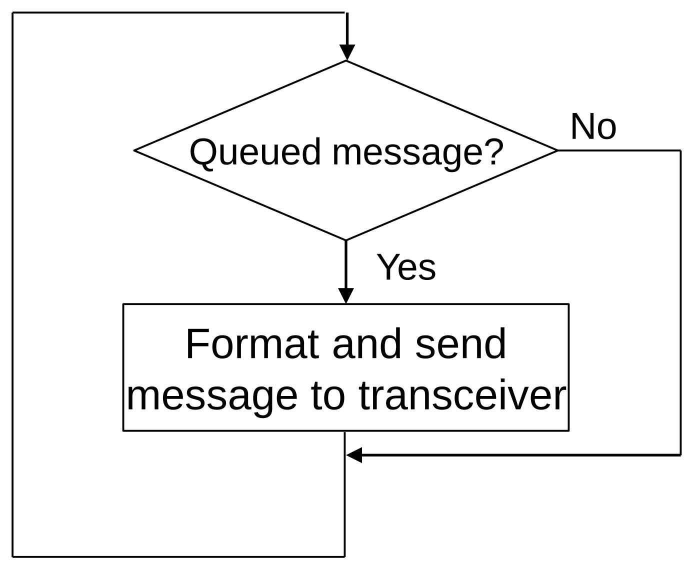
RX task infinite loop:



Process byte:

- Look for Start of Message
- Look for End of Message
- Add byte to correct structure field
  - Destination ID
  - Message ID
  - Packet

TX task infinite loop:



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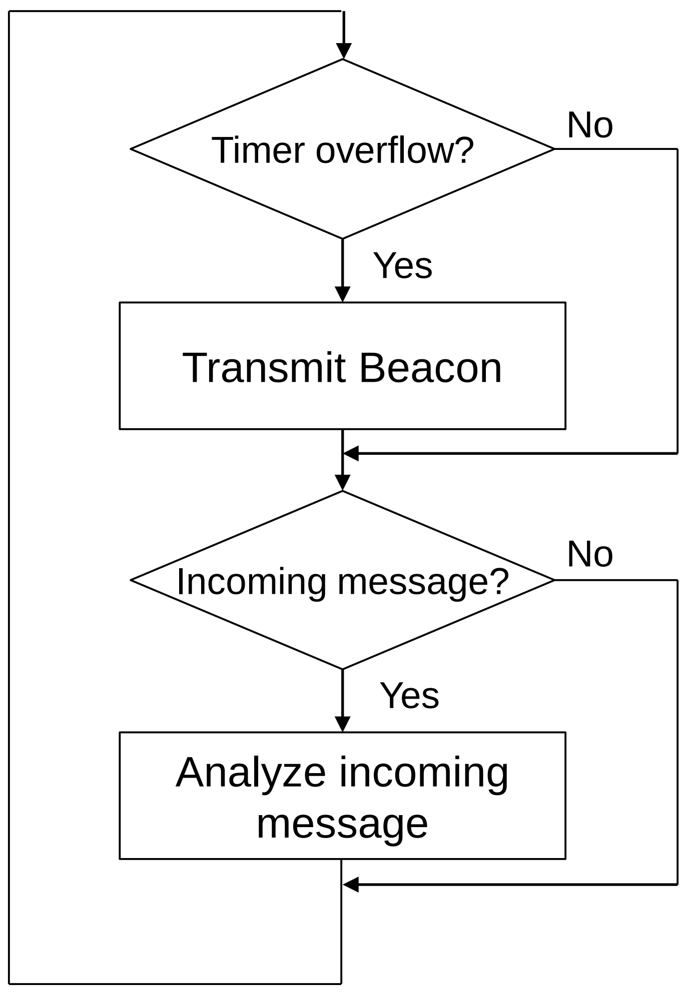
Beacon task

Task infinite loop:



List of Beacon values:

- **ADCS** (position and rates)
- **OBC** (safe mode, battery, power, reboot counts, AMRAD message)
- **EPS** (Voltages, currents, WDT info, temperatures)
- **Transceiver/Receiver** (Voltage, currents, temperatures, reception times, message counts, transfer times
- **Payload** values

List of commands / messages

- Change beacon parameters

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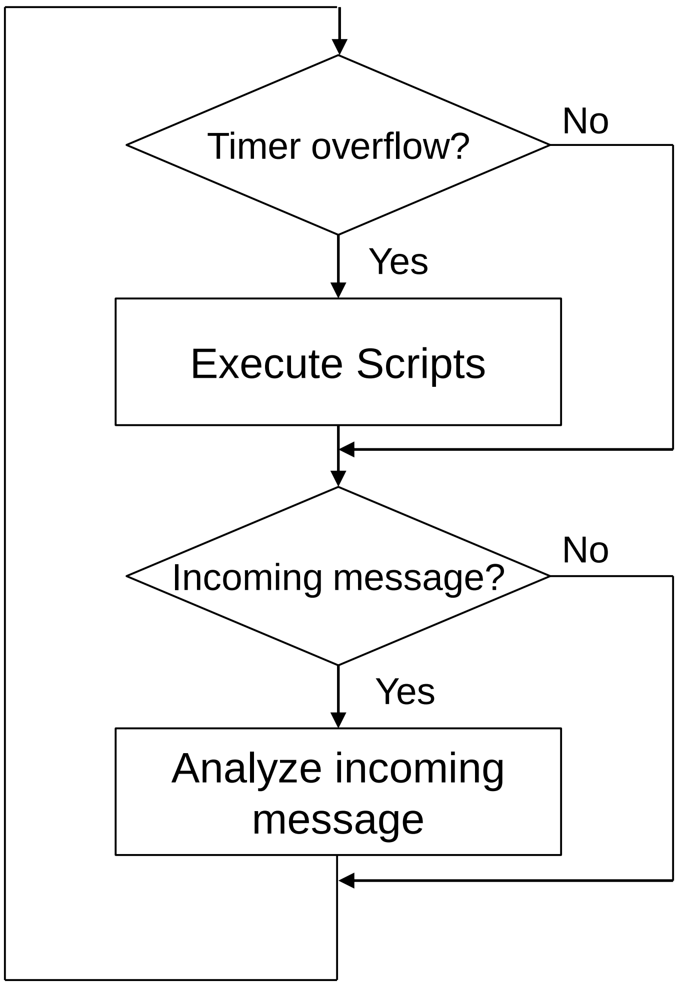
Automation task

Task infinite loop:



Scripts:

Automated list of commands

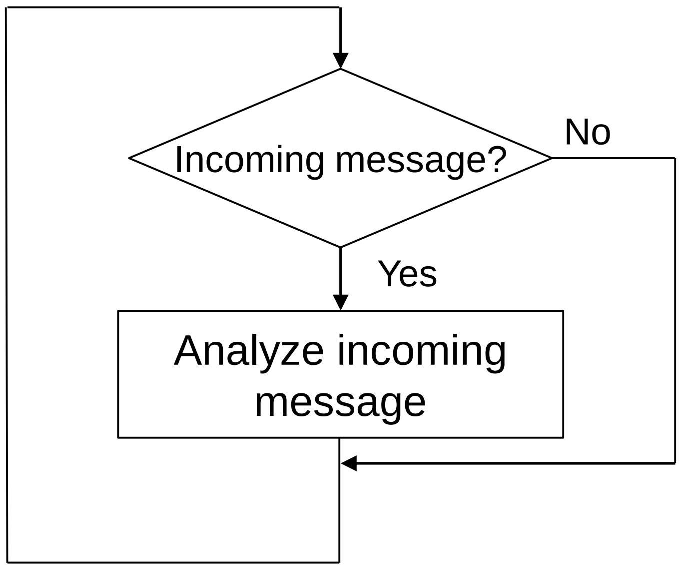
- Saved in SD card
- Each command has a start time, etc.
- Many scripts can be executed in parallel

List of commands / messages

- Schedule scripts
- Stop/Restart scripts
- Get status of scripts
- Write scripts

Mirror Box

Task infinite loop:



- Mirror Boxes are mainly controlled by the Telescope Camera
- The CoreSat only needs to interface with Box if Camera link is lost

List of commands / messages

- Read housekeeping values (register values)
- Set picomotor position
- Debug commands
- Etc.

State of OBSW

State of OBSW

- **Hardware Abstraction Layer (from Surrey)**
  - I2C
  - CAN
  - UART
  - Flash
  - GPIO
  - SD card
  - MCU
  - Time
  - Watchdog
- **Fully implemented**

State of OBSW

- **Tasks (from Surrey)**
  - File Transfer
  - OBC
  - UART comms
  - Beacon
  - Automation
- **Fully implemented / minor updates**

- **Tasks (to implement)**
  - EPS
  - ADCS
  - Transceiver/Receiver
  - Antenna deployment
  - MirrorSat
  - Docking/Undocking
  - Mirror boxes
  - Camera
  - Boom Delpoyement
  - Frangiblot

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Communications protocols

TCTM Protocol (Jorge Llop)

- **HDCL protocol**
  - Less overhead on each message
  - Robust (flown before)
- **TCTM Protocol**

2 Bytes	5 Bytes		3 Bytes	1 Byte	1 Byte	Variable Length	1 Byte
Decoder Flag	**Callsign (AAReST)**	**Length of Message**	**Number of Increments**	**Group ID**	**Message ID**	**Payload Channels**	**Decoder Flag**

- **Example:**
  - ADCS Telemetry, spacecraft velocity (v_x, v_y, v_z).

C010	**27FB281A20**	**000e**	**52**	**41**	**81**	**0x3e9ff4a3**	**0x4090874a**	**0x4090f47a**	**C0**

Length of message in Bytes

Number of increments in sequence

Group ID: ADCS

Message ID: Read ADCS state

V_x, V_y, V_z

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File Transfer Protocol

- **Saratoga protocol**
  - Fast, scalable, simple, and robust
  - Has heritage from Surrey missions

The image part with relationship ID rId2 was not found in the file.

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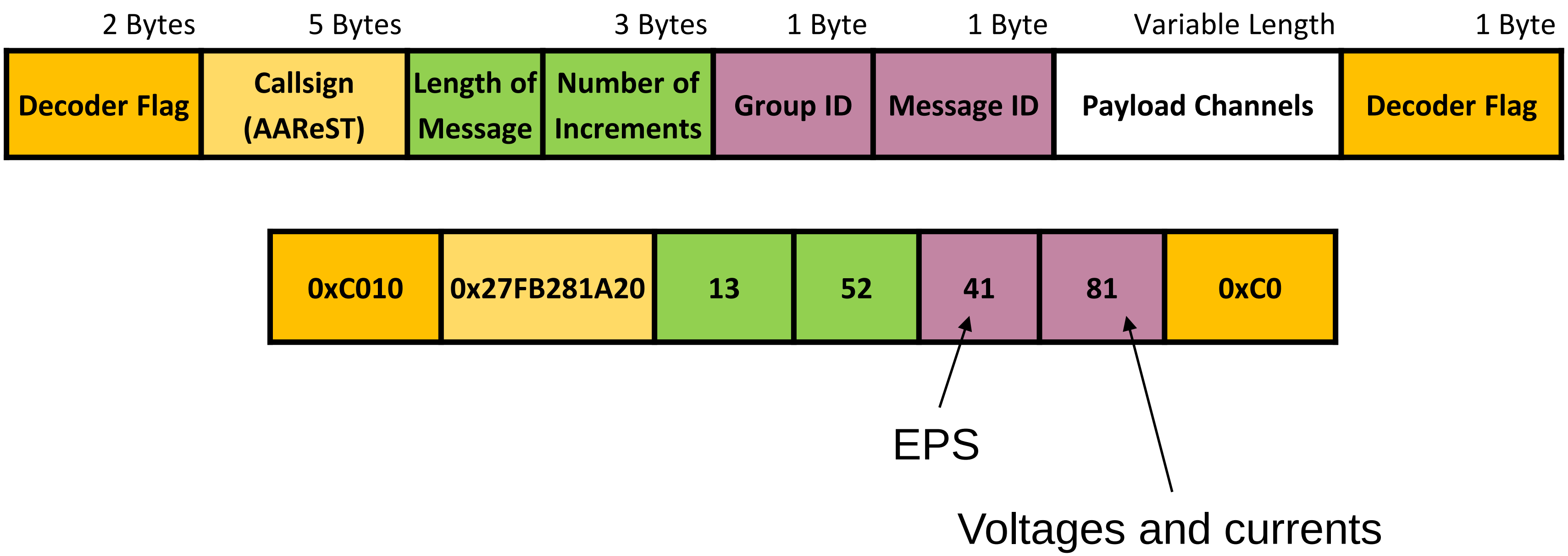
Example

EPS Telemetry request

- Format message on Ground



- And send to spacecraft

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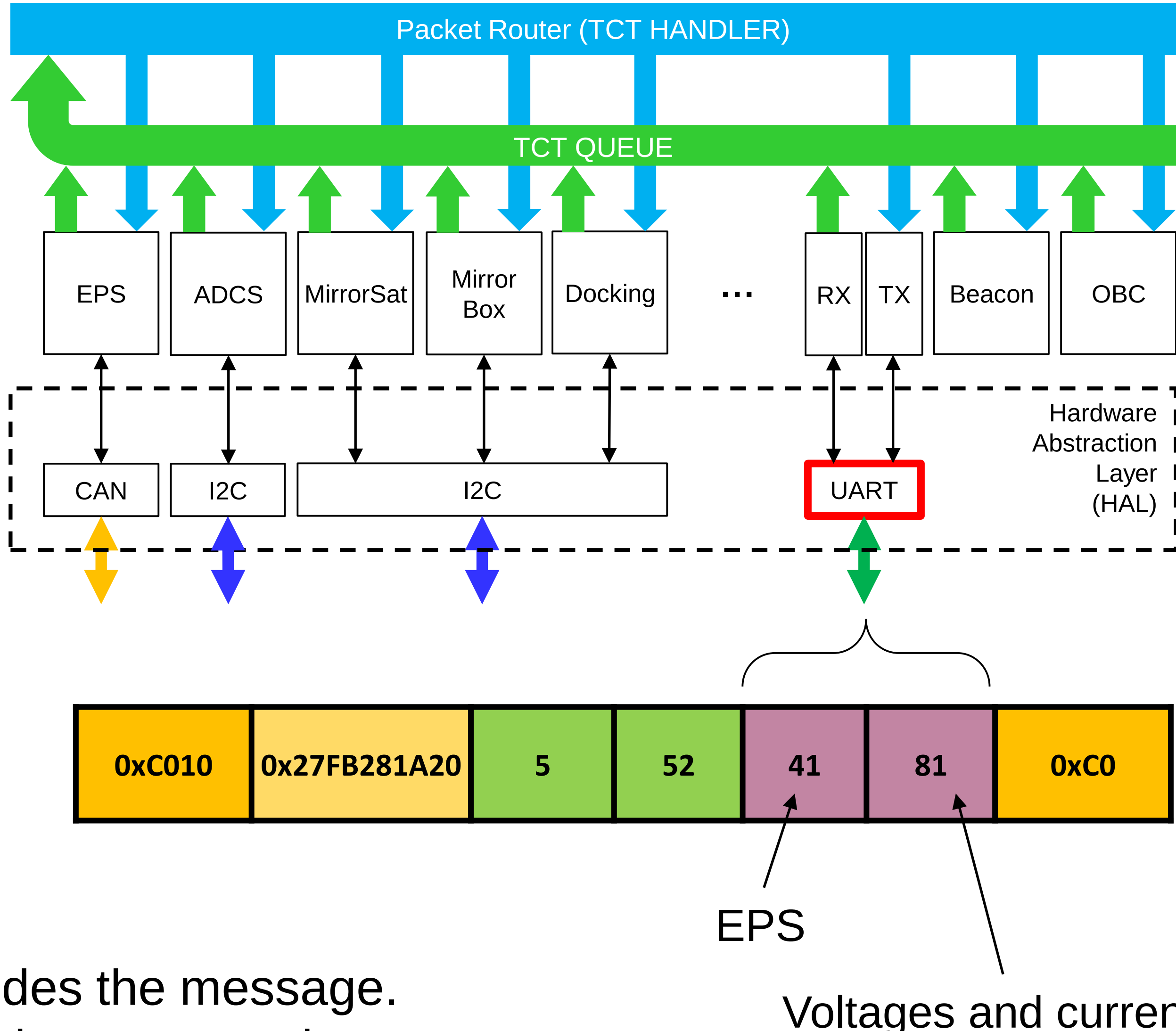
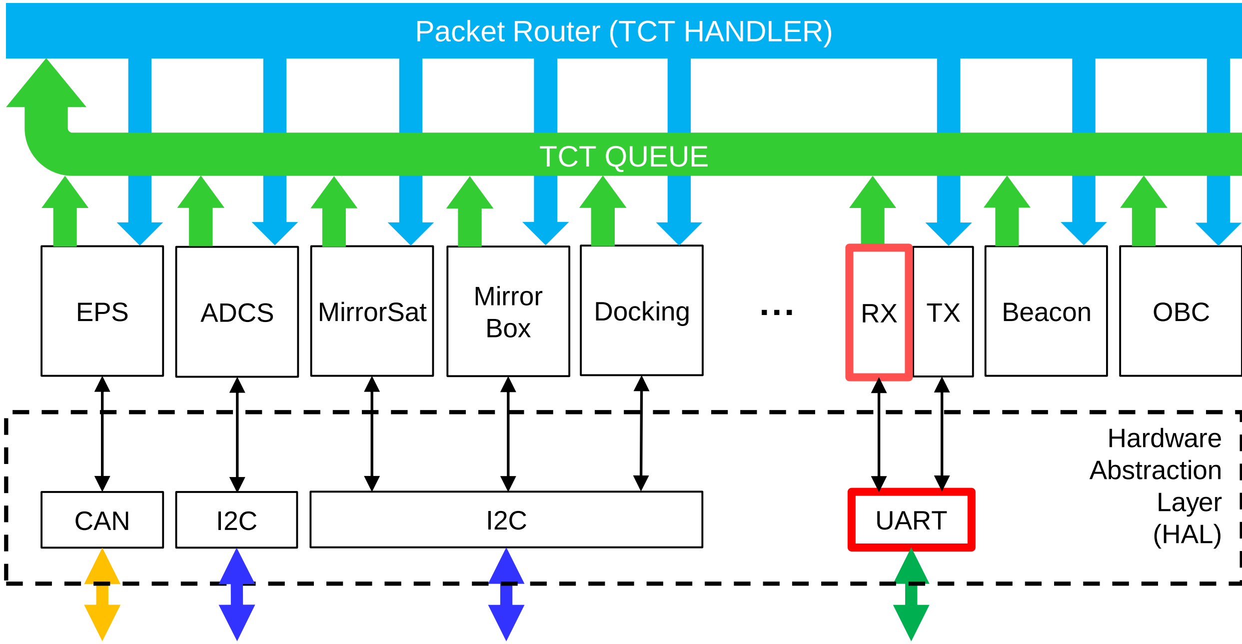
EPS Telemetry request



- The transceiver decodes the message.
- Only the data part of the message is transmitted to the OBC
- The reception of a byte creates an interrupt

EPS Telemetry request



The UART task reads and parses the data and creates a TCT message

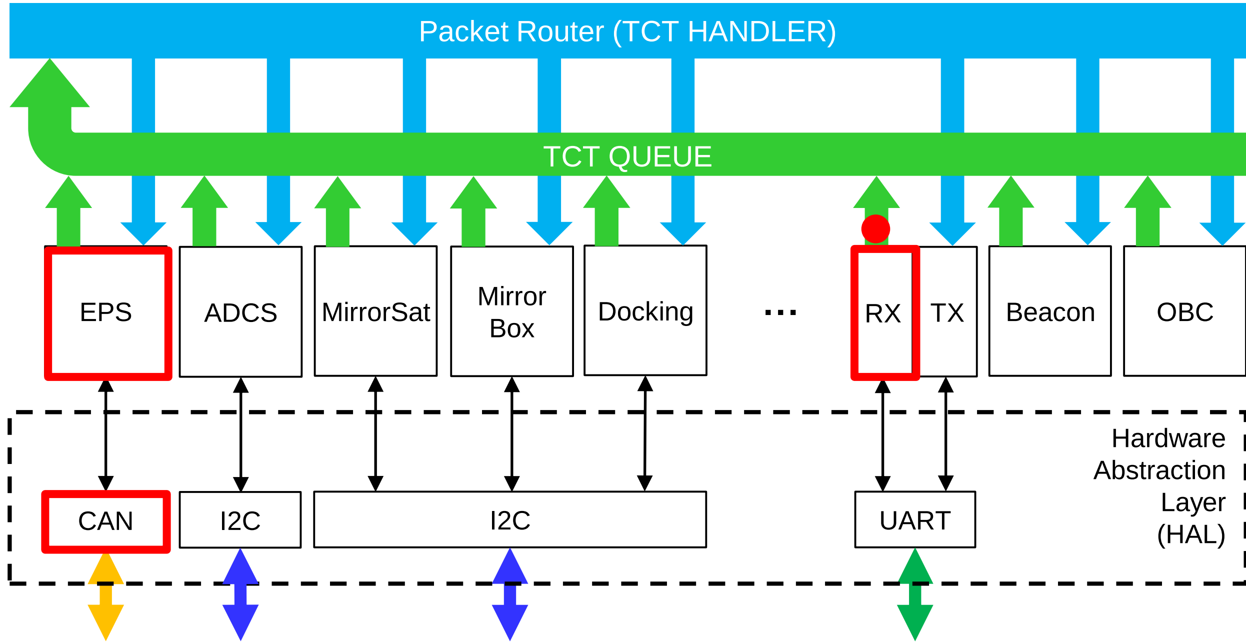
0xC010	0x27FB281A20	5	52	41	81	0xC0

Source ID	UART TX (38)
Reply ID	
Return value	
Destination ID	GomspaceEPS (41)
Message ID	81
Message type	
Packet length	4 (default)
Packet (array)	

EPS

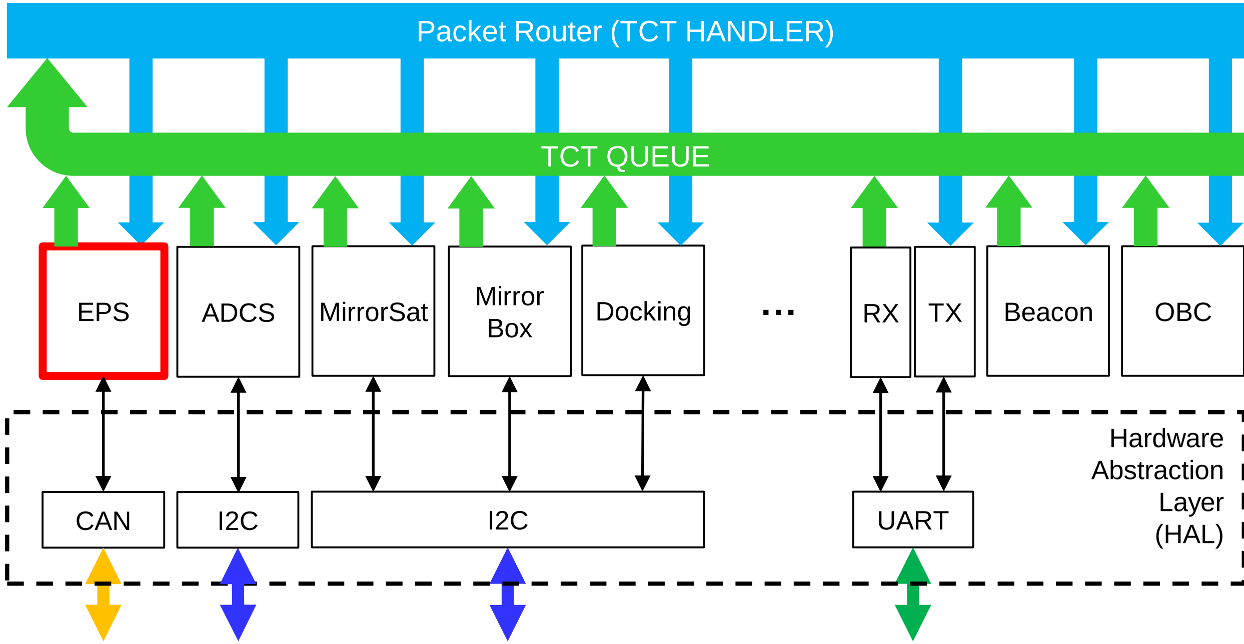
Voltages and currents

EPS Telemetry request



UART parses data → Message sent to EPS → EPS parses the message → EPS requests voltages and currents

EPS Telemetry request



The EPS task creates a TCT message

Source ID	GomspaceEPS (41)
Reply ID	
Return value	Result (from I2C communication)
Destination ID	UART TX (38)
Message ID	81
Message type	ack
Packet length	21
Packet (array)	(Voltages and currents)

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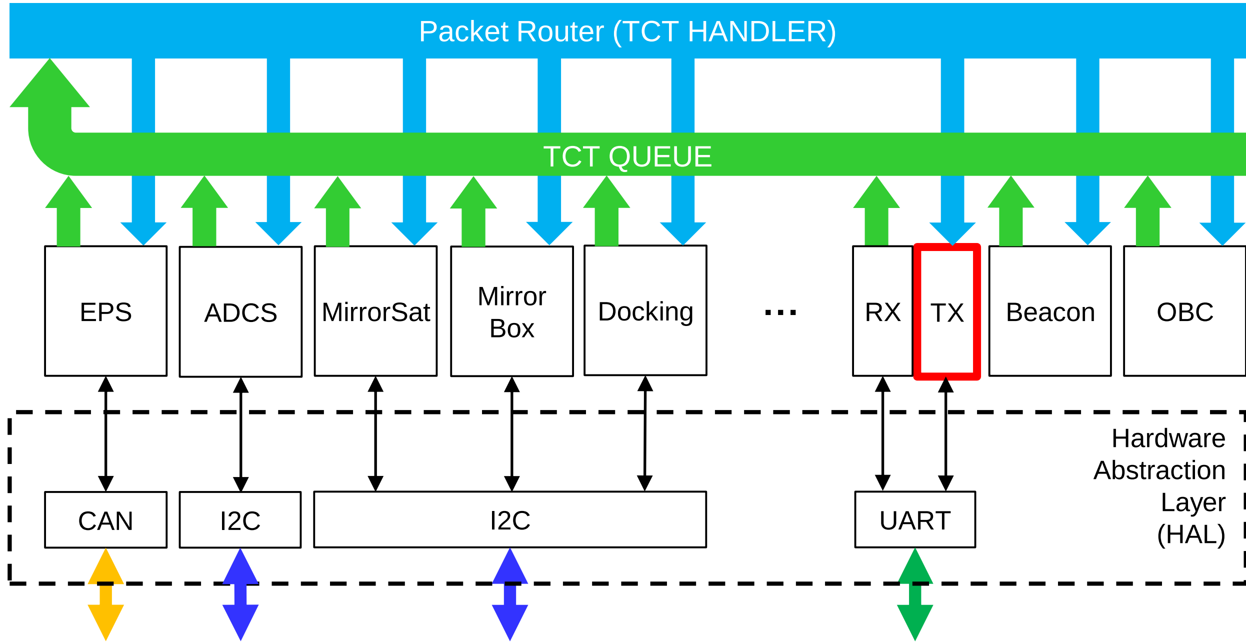
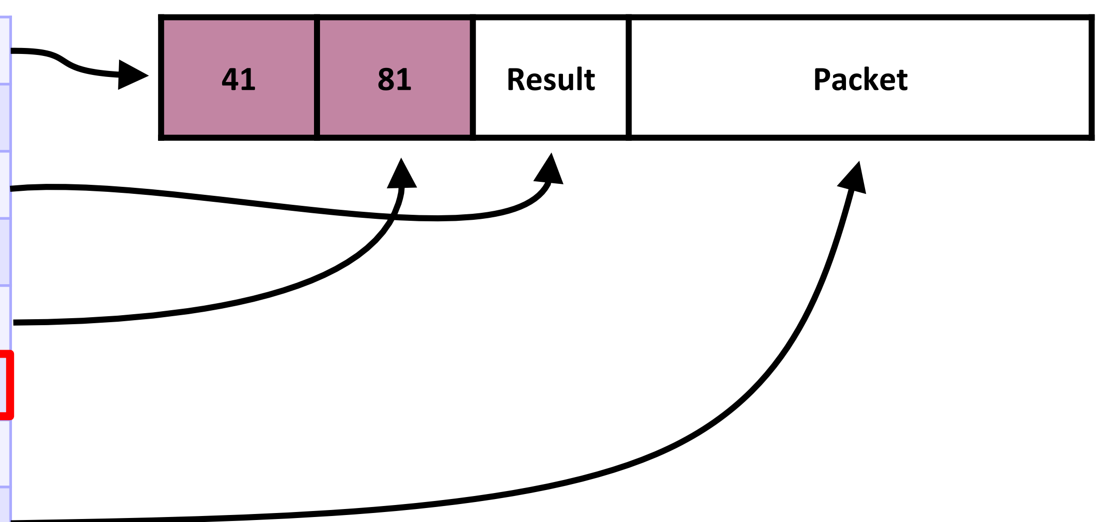
EPS Telemetry request

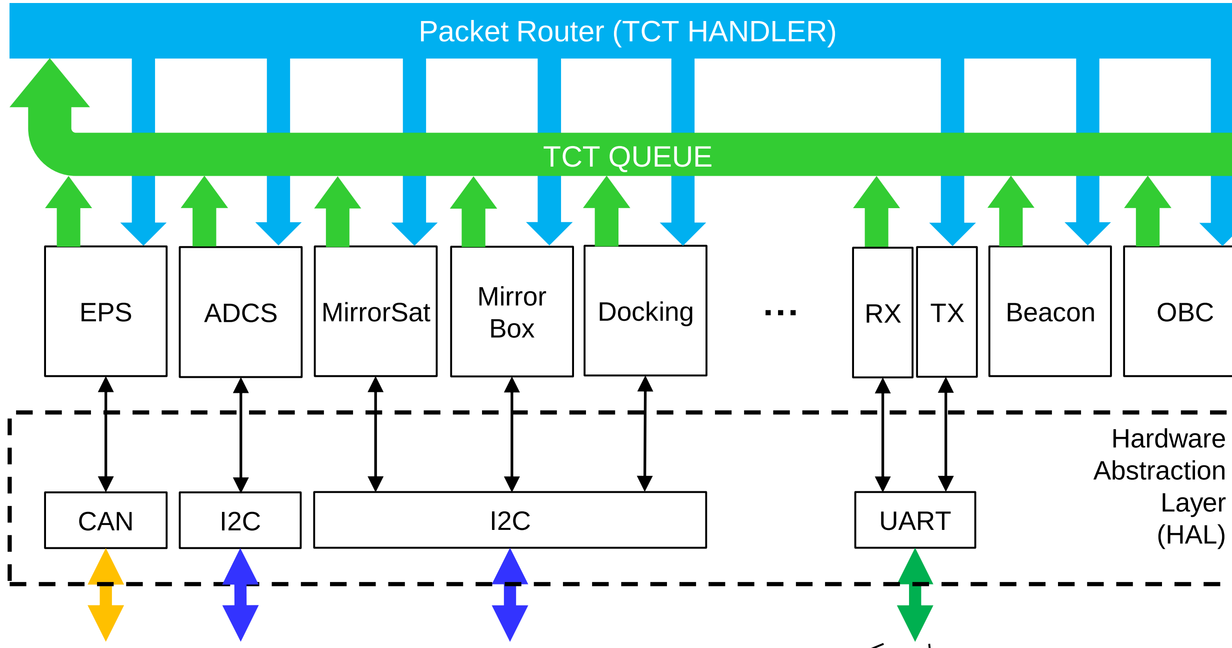


The UART task reads the message and creates the downlink data

Source ID	GomspaceEPS (41)
Reply ID	
Return value	Result
Destination ID	UART TX (38)
Message ID	81
Message type	ack
Packet length	21
Packet (array)	(Voltages and currents)



EPS Telemetry request



The transceiver format the message to the ground

0xC010	0x27FB281A20	34	113	41	81	0x3e 0x9f 0xa3f8 0x1940 0xab47 … 0xee23	C0

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Open Issues

- **Actions during Docking operations?**
  - What data / telemetry is transferred
    - Telemetry to ground
    - Data from CoreSat to Surrey
  - Separate actions from Surrey and CoreSat

- **Automatically generated code?**
  - From Excel sheets
  - Creates code and documentation
  - How expensive is your Python Script?

Future Work

- **Define lists of updates**
- **Progressively compile the code**
  - Hardware Abstraction Layer
  - Tasks that don’t require hardware communication
- **Write task code and test as hardware is available**

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