Final Oral Review

CUBE^3

Customer:
Professor Robert Marshall
Advisor:
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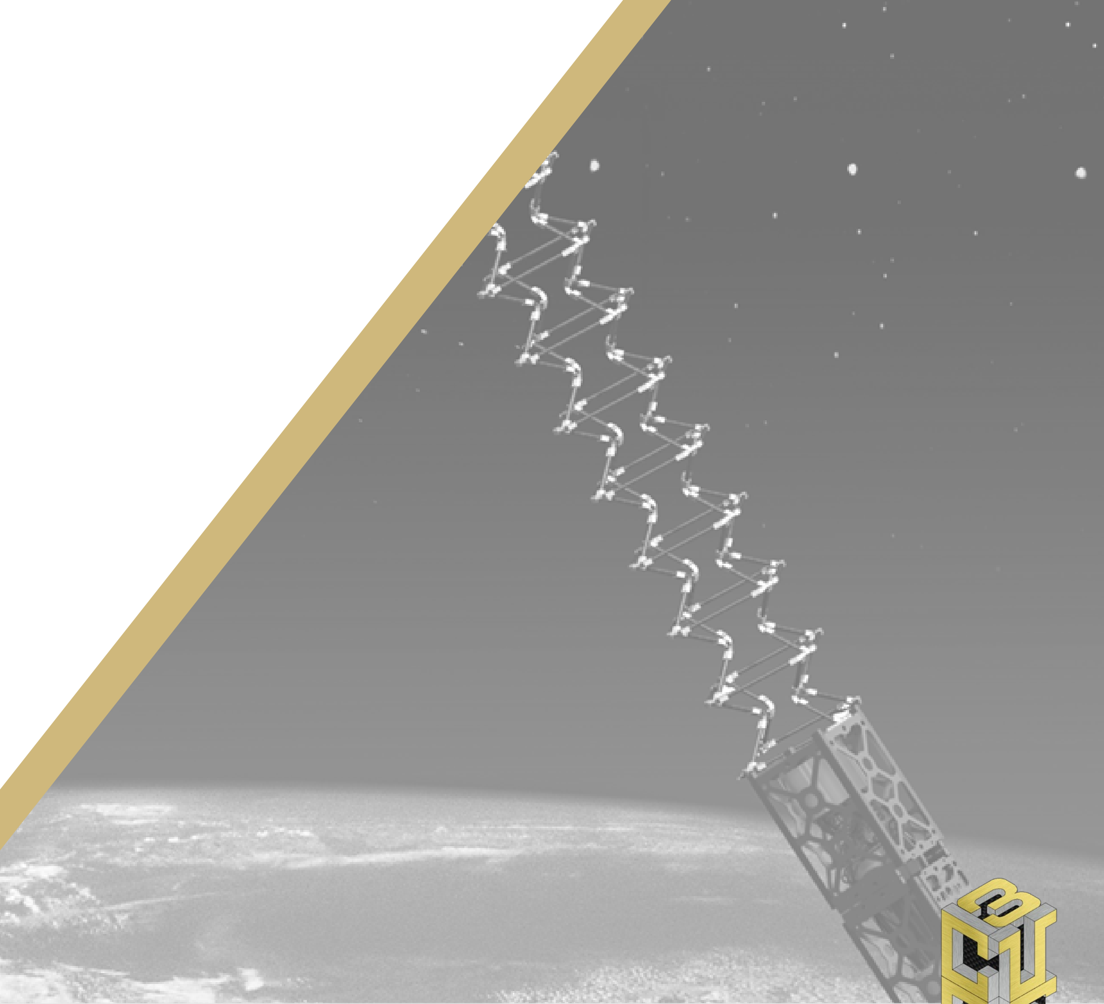
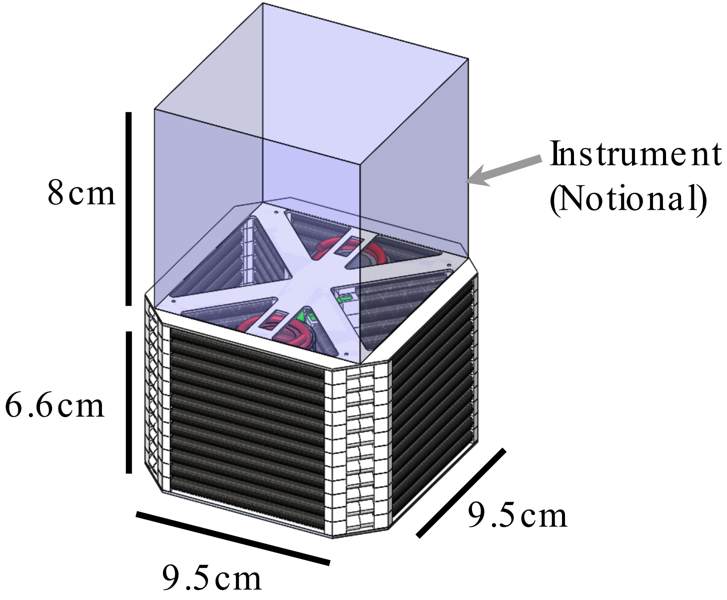


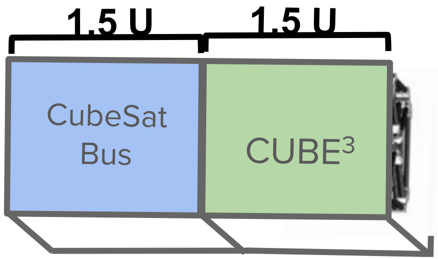
CU Boulder Engineers Creating Universal Boom Extensions for CUBEsats

Purpose & Objectives

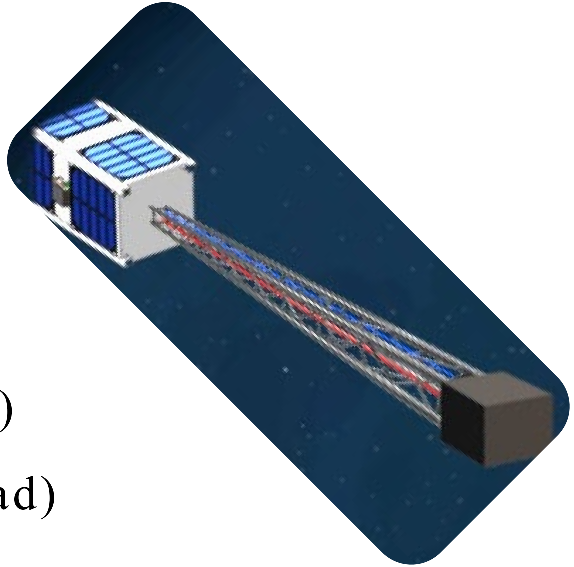
Project Overview

The purpose of this project is to create an ***extendable CubeSat boom*** *to separate a* ***sensitive instrument*** *from the cubesat bus*





Project Objectives

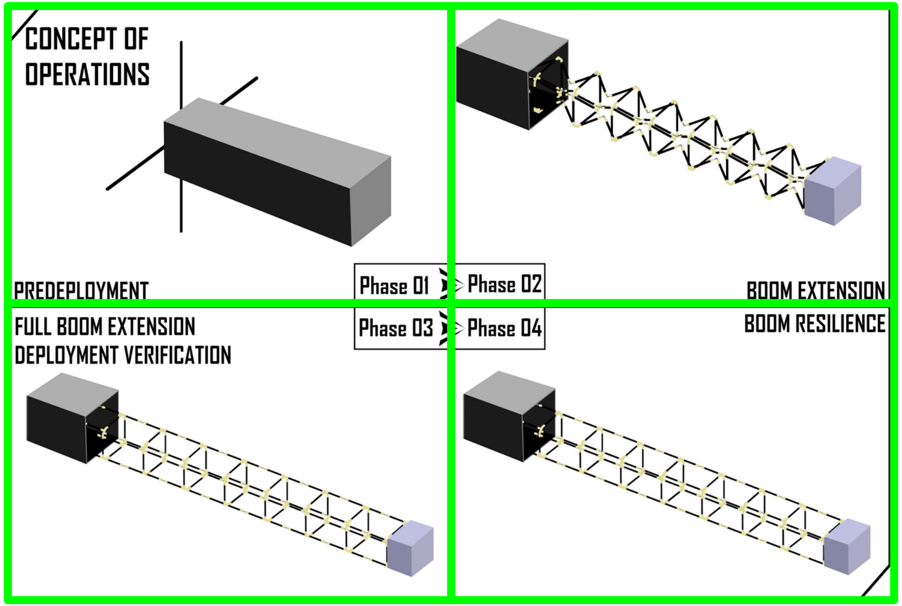


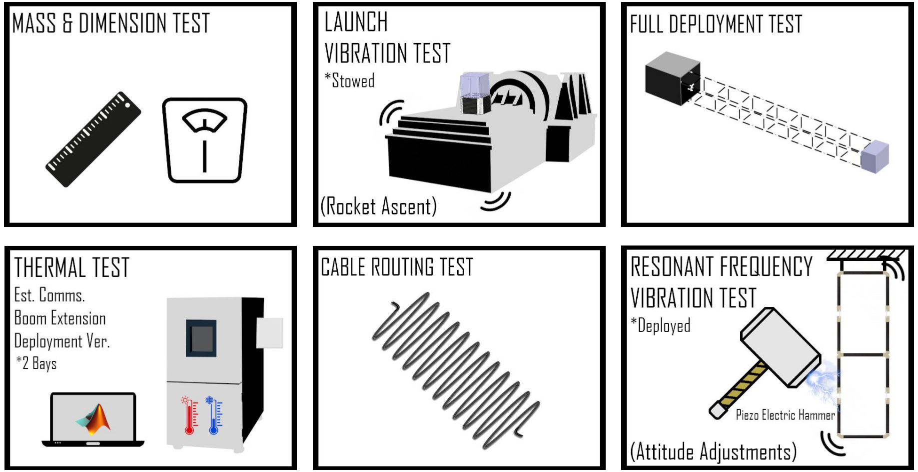
- Support a **500 g payload** at the end of the boom
- Extend a **minimum distance of 60 cm**
- Fit within **1.5 U** when undeployed (including payload)
- Have a mass of less than **1.5 kg** (not including payload)
- Have a first resonant frequency over **2.5 Hz**
- Deploy on command in **under 2 minutes**
- Provide routing for **power and data cabling** to/from payload

Select Levels of Success

Project Element	Level 1	Level 2	Level 3
Boom Structure: Deployment Length	The boom can be extended to 60 cm past the spacecraft body.		The boom can be extended to 1 m past the spacecraft body.
Boom Structure: Resonant Frequency	The boom has a first resonant frequency mode of greater than 2.5 Hz when analytically modelled.		The boom demonstrates a first frequency mode over 2.5 Hz in a vibe table test environment.
Boom Structure: Total Mass & Size	The deployable boom system and the 1.5 U containment structure have a mass of less than 1.5 kg.		
Environmental Resilience	Analysis indicates probably 1 year lifespan on orbit.	Vacuum testing indicates probably 1 year lifespan on orbit.	TVac testing indicates probable 1 year lifespan on orbit.
Software Interface	The external C2 computer is able to send commands to the boom electronics.	The external C2 computer is able to receive telemetry from the deployment sensor.	The boom successfully deploys when commanded.
Payload Connectivity	The system is able to deploy power and data cables to the sensor payload at the end of the boom.		

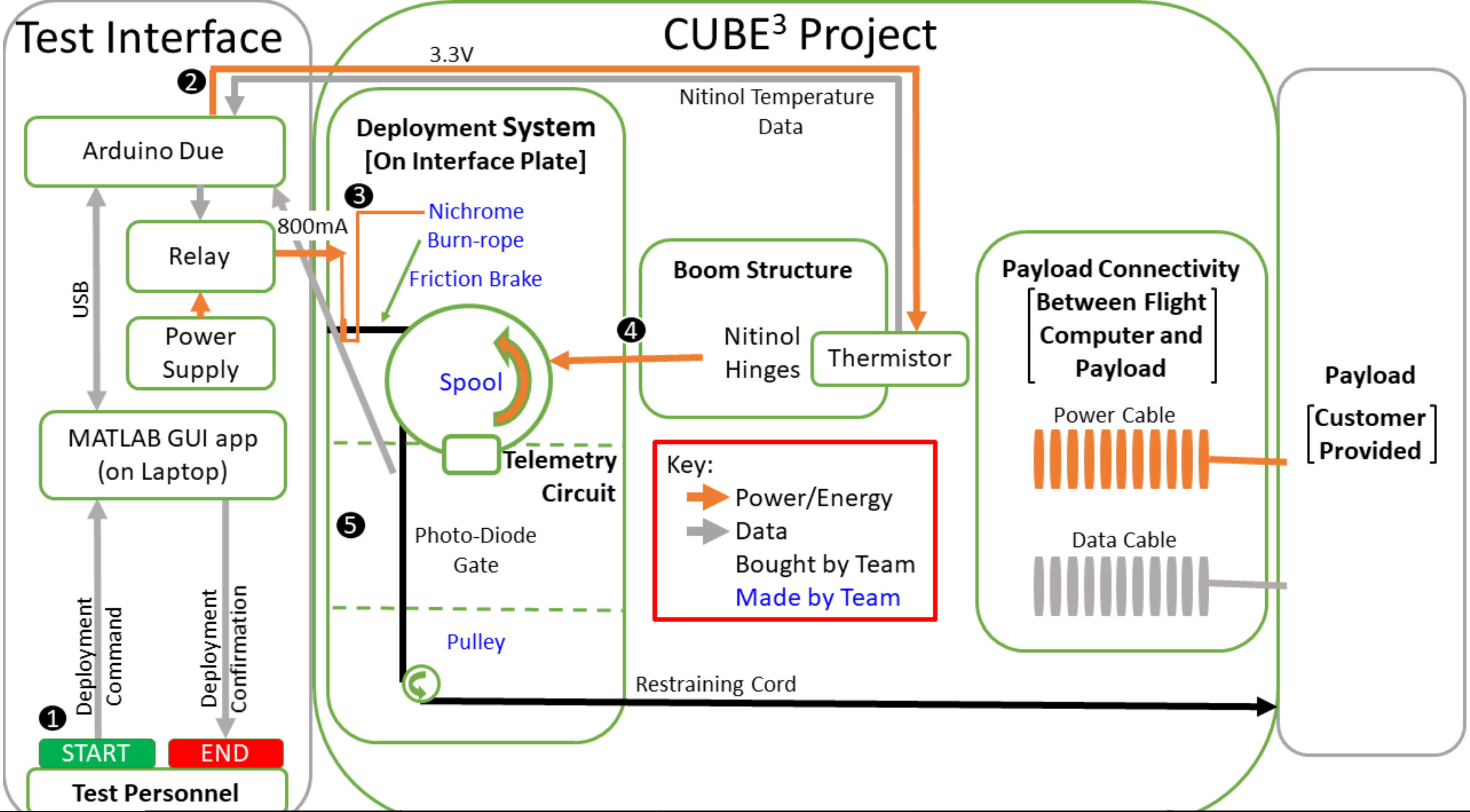
CONOPS


CONCEPT OF OPERATIONS
PREDEPLOYMENT
Phase 01
Phase 02
BOOM EXTENSION
FULL BOOM EXTENSION
DEPLOYMENT VERIFICATION
Phase 03
Phase 04
BOOM RESILIENCE


MASS & DIMENSION TEST
LAUNCH
VIBRATION TEST
*Stowed
(Rocket Ascent)
FULL DEPLOYMENT TEST
THERMAL TEST
Est. Comms.
Boom Extension
Deployment Ver.
*2 Bays
CABLE ROUTING TEST
RESONANT FREQUENCY
VIBRATION TEST
*Deployed
Piezo Electric Hammer
(Attitude Adjustments)

Design Description

F
B
D

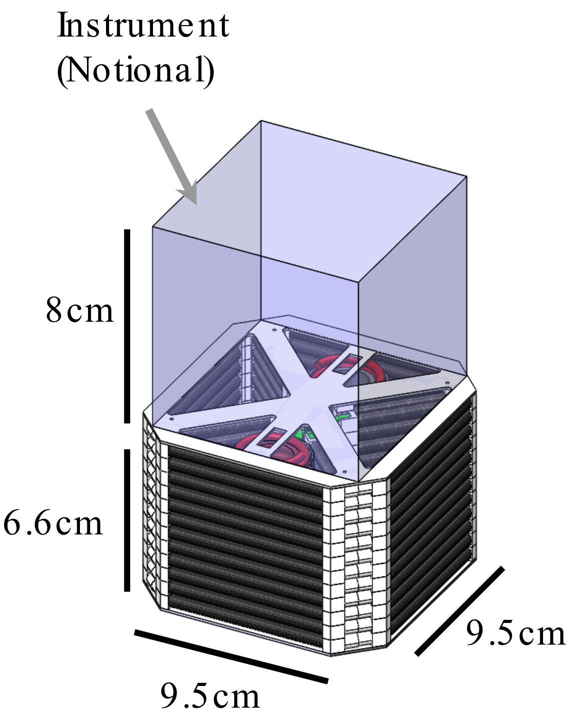


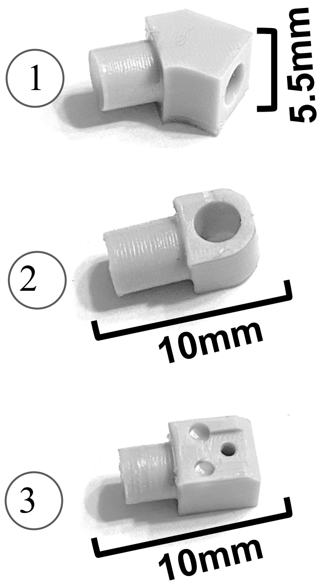
Design Description

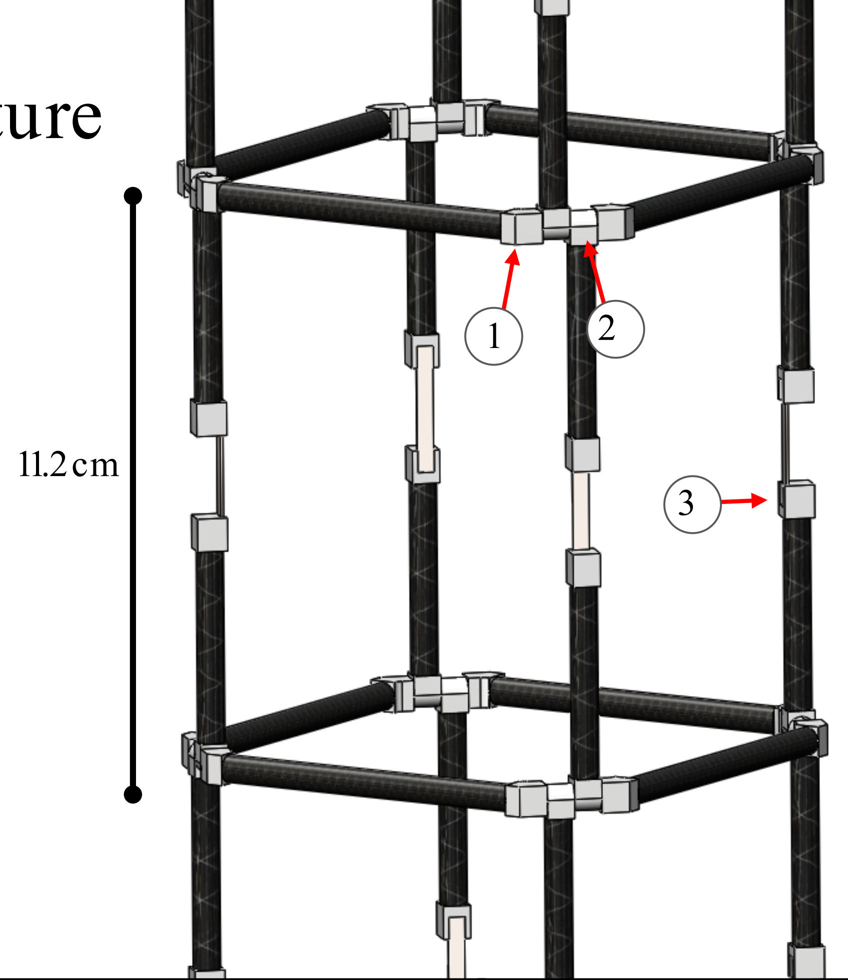
Critical Project Elements

1. **Deployable Boom Structure**
   - Stow in 1.5U with an 8x8x8 cm, 500 g payload
   - First resonant frequency ≥ 2.5 Hz
2. **Payload Connectivity**
   - Power/data cable provisions
3. **Software Interface**
   - Command and telemetry
4. **Deployment System**
   - Deploy on command
   - Confirm deployment via telemetry
5. **Environmental Resilience**
   - LEO radiation/thermal environment
   - Vibrational launch environment

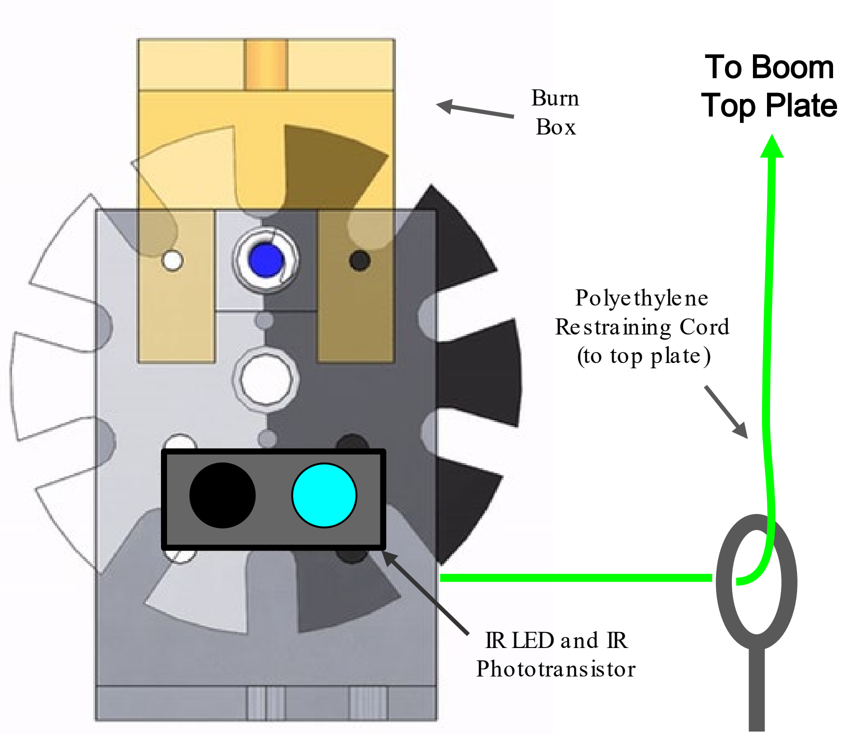
Baseline Design - Boom Structure

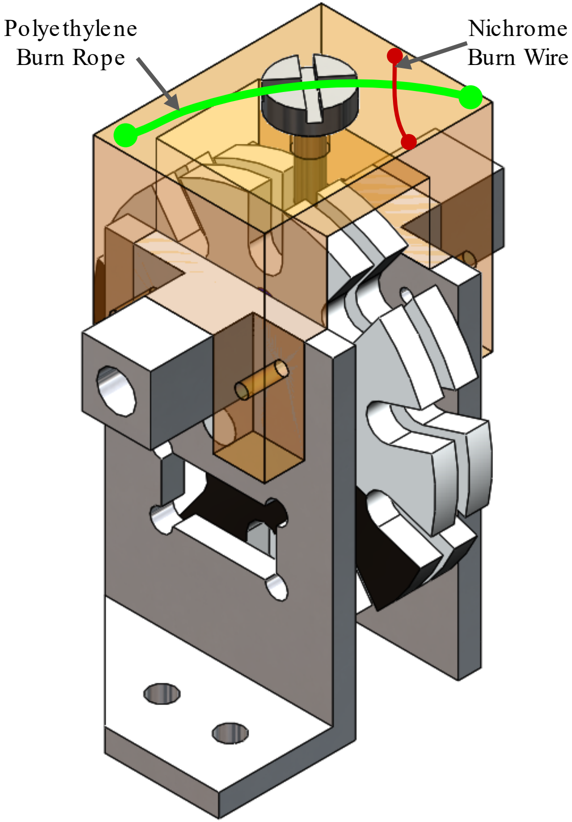


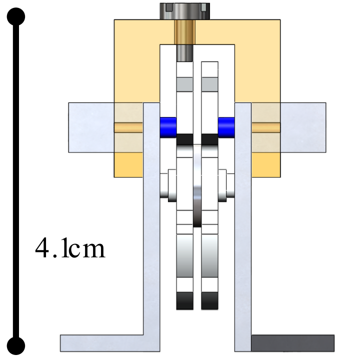




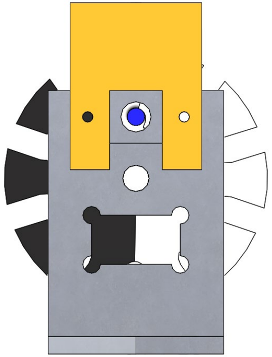
Baseline Design - Deployment Mechanism



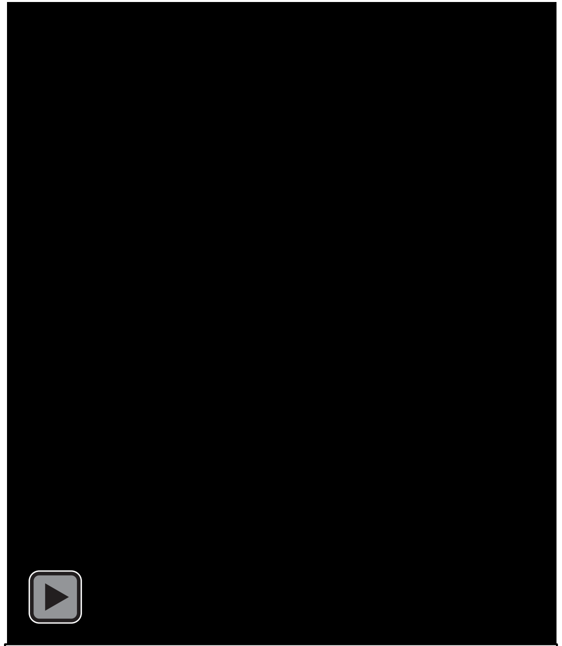




IR LED and IR
Phototransistor



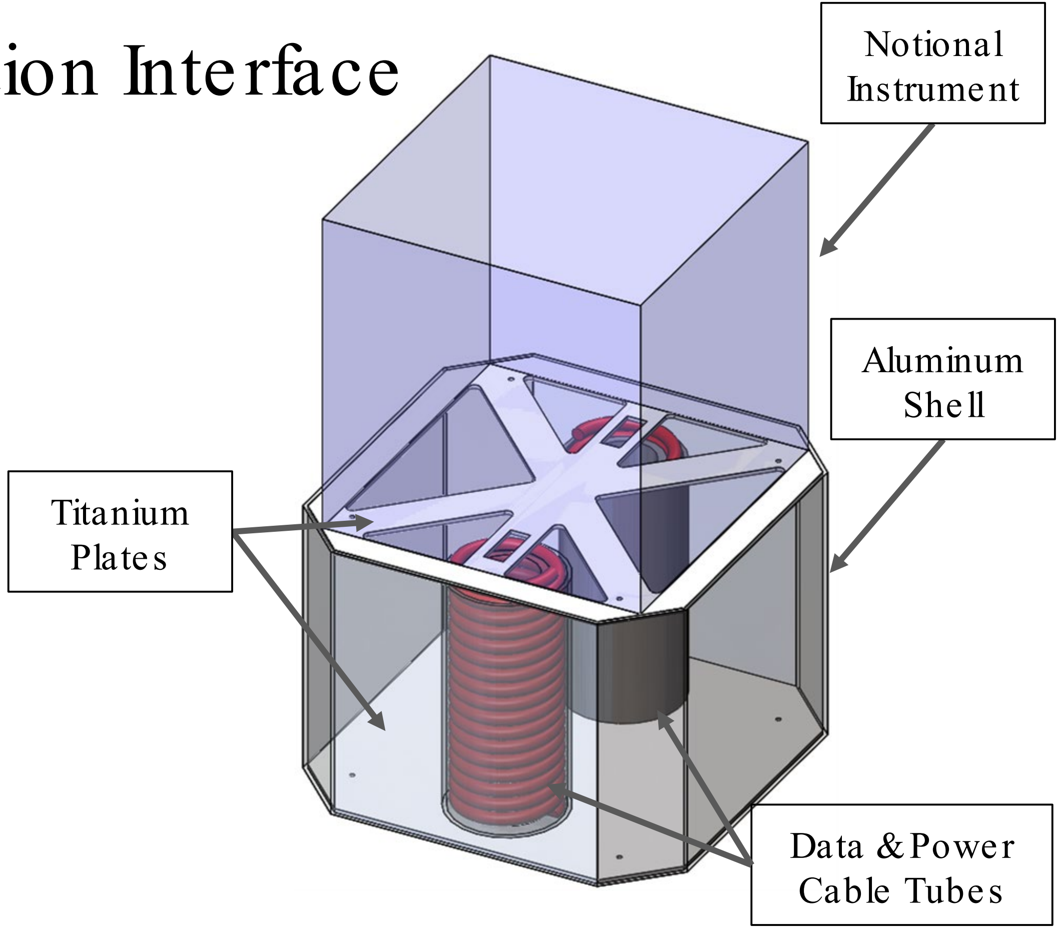
Release Pin Stand Alone Testing



Polyethylene Burn Rope and Pin Movement (Nichrome Current = 800 mA)

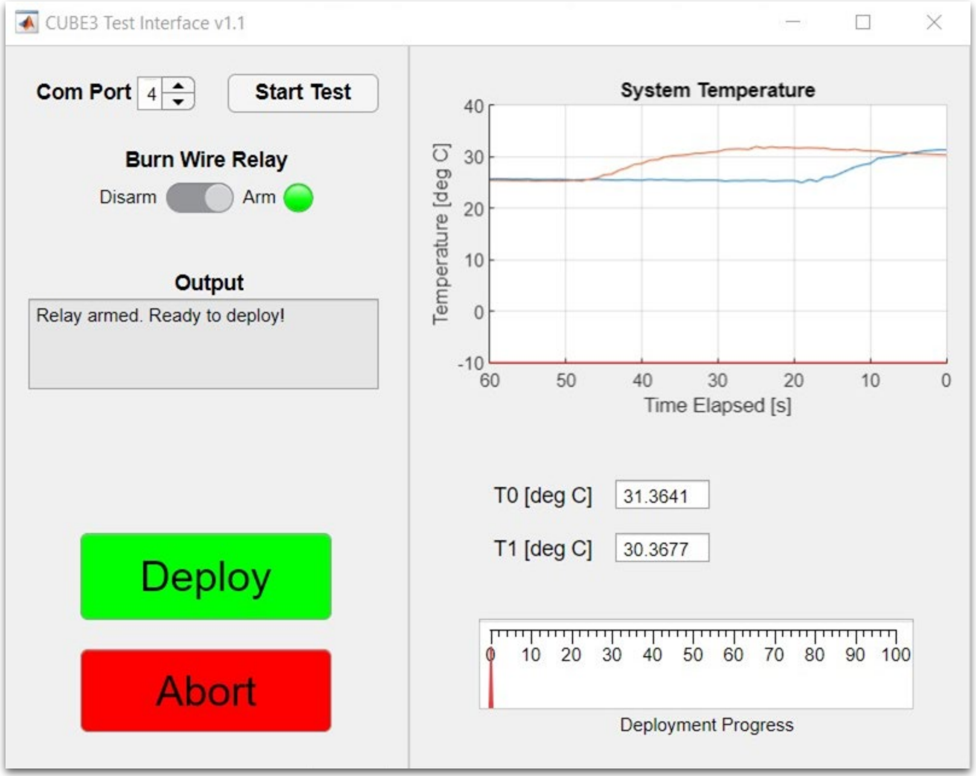
CubeSat & Instrumentation Interface

- Top and bottom plates designed to secure boom to cubesat and instrument to boom
- Coils carrying all power & data wires extend with minimal impact to deployment



Baseline Design - Software

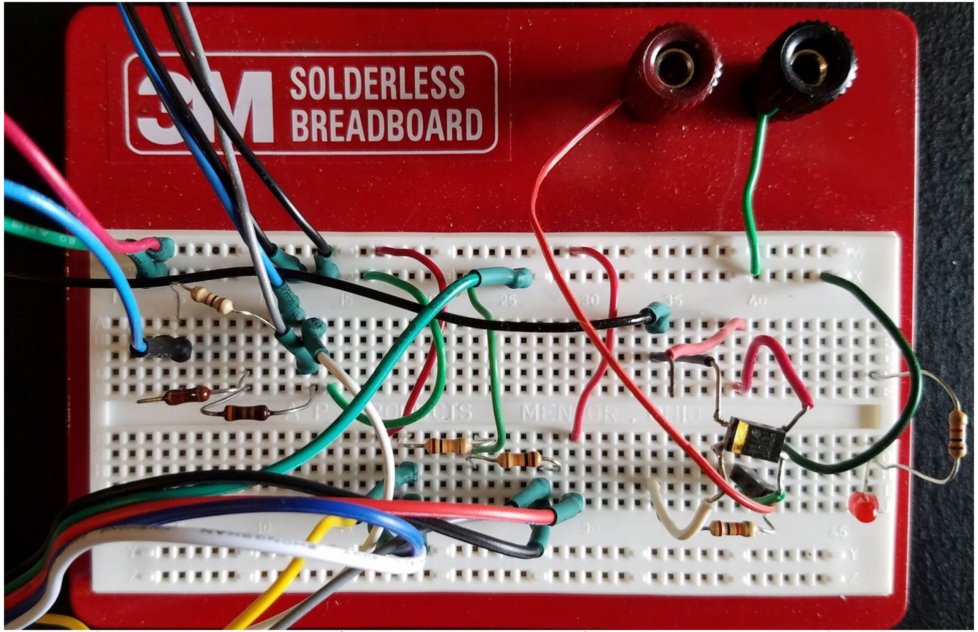
- Not for delivery
- MATLAB GUI
  - Built in App Designer
  - Uses Arduino Hardware Support Package
- v1.1 is released for use
  - Temperature display
  - Burn wire relay arm/control
  - IR spool revolution sensor telemetry



Design Description

Baseline Design - Test Electronics

- Not for delivery
- 3 separate circuits
    - IR LED and phototransistor voltage divider
    - Thermistor voltage divider
    - Burn wire relay



IR LED Phototransitor	Thermistors	Burn Wire Relay

Test Overview

Test Results

Cable Routing

Planned
Scheduled
Preliminary
Completed
Processed

Launch Environment

Planned
Scheduled
Preliminary
Completed
Processed

Resonant Frequency

Planned
Scheduled
Preliminary
Completed
Processed

Full Deployment

Planned
Scheduled
Preliminary
Completed
Processed

Mass / Dimension

Planned
Scheduled
Preliminary
Completed
Processed

LASP Thermal Chamber

Planned
Scheduled
Preliminary
Completed
Processed

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Test Overview

Cable Routing Test

Motivation - Verify that the cable routing design allows for full deployment of the boom and cables are still functioning after deployment

Facilities:

- Electronics Lab, Pilot Room

Equipment:

- Arduino Due microcontroller (as mock flight computer)
- Keysight 34461A Digital Multimeter
- Sorensen XPH 35-4D Power Supply set as Current Supply
- Keysight 33220A Function/Arbitrary Waveform Generator*
- Oscilloscope*

General Procedure:

- Attach deployment equipment to the undeployed boom
- Send deployment command from mock flight computer.
- Check for physical damage to boom and/or cables
- Check for cable functionality with a continuity test and successfully send and receive a differential signal*
- Restow boom

*Unavailable due to current circumstances

Requirements Under Test	
DR_2.1	Boom shall have capability of routing three-wire power setup
DR_2.2	Boom shall have capability of routing 3 separate differential cables
FR_2	Boom shall provide routing for power and signal cabling

Cable Routing Test

Preliminary Testing:

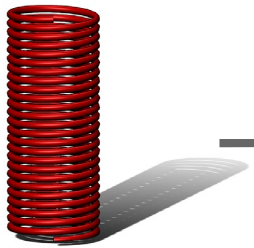
- Continuity Check performed successfully

Analytical Model:

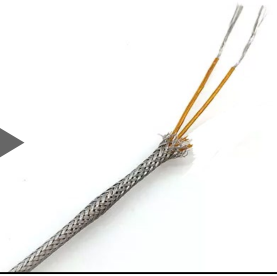
Goal: Estimate maximum data rate in kb/s

Steps:

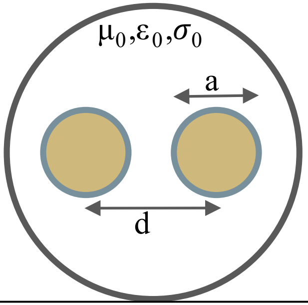
1. Circuit Equivalent Model
2. Attenuation generated by circuit
3. Estimate fastest rise time limited by cable attenuation
4. Estimate maximum data rate from fastest rise time



Data Coil Containing Two Twisted Pair Cables



Single Twisted Pair Cable

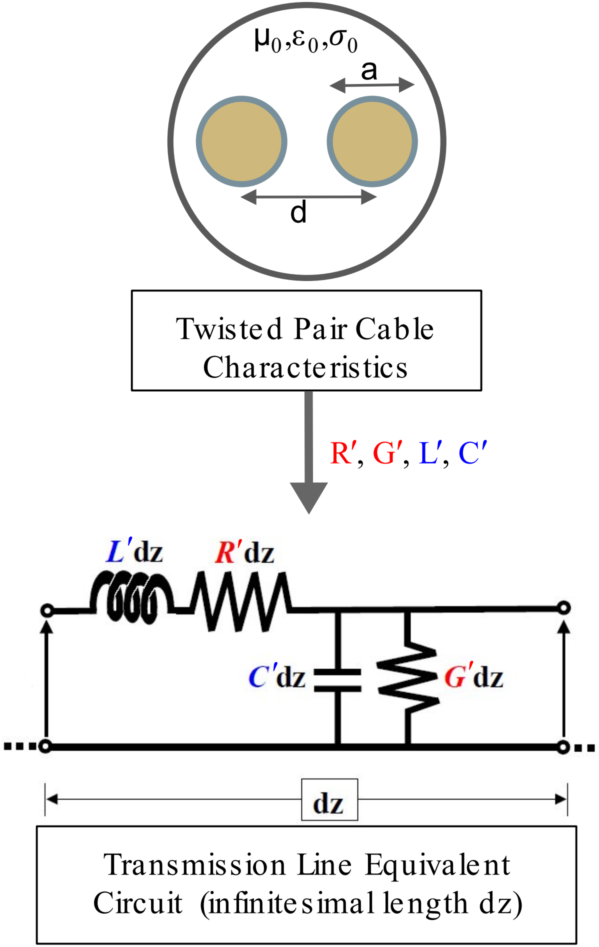


Twisted Pair Cable Characteristics

Cable Routing Test, Steps 1 and 2

Analytical Model:

Goal: Estimate maximum data rate in kb/s



Step 1: Equivalent Circuit

- 2 models used to estimate circuit's R, G, L, and C per unit length based on line characteristics
  - Two wire line model (d >> a) [1]
  - Twisted pair model [2]
- Resistance per unit length, R′, is heavily dependant on frequency, f
  - High f causes R′ to depend on a surface resistance - $R'(R_S(f))$
  - $R_S = \sqrt{(2\pi f/\sigma_c)}$

Step 2: Attenuation of Circuit

- Solution to the voltage along circuit given by sine wave:
  $V(z) = V_+ e^{-i\gamma(f)z} + V_- e^{+i\gamma(f)z}$ [V]
- Propagation coef = $\gamma(f) = \sqrt{[(R(f)' + i\omega L')(G' + i\omega C')]}$
  - Attenuation(f) = Real{$\gamma(f)$} [Np/m]

[1] \ vww}p´ Zoya B., and \ vww}p´ Branko D. *Introductory Electromagnetics.* Prentice Hall, 2000.
[2] Christopoulos, Christos. *The Transmission-Line Modeling Method: TLM* Oxford, Angleterre, 1995.

Cable Routing Test, Steps 3 and 4

Analytical Model

Goal: Estimate maximum data rate in kb/s

From steps 1 and 2: Attenuation(f) = Real{√[(R(f)′+iωL′)(G′+iωC′)]}

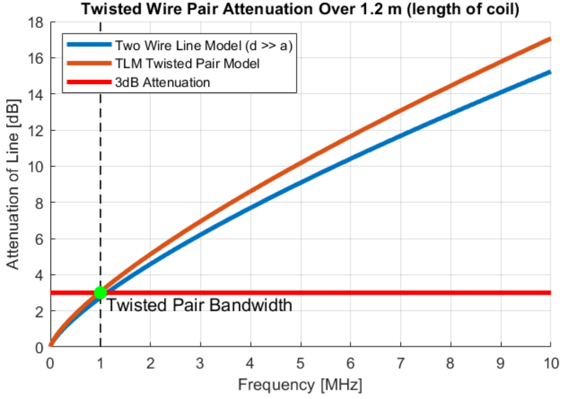
Step 3: Rise Time Defined by Bandwidth

- Digital signals can be characterized by a Rise Time, $RT_{10\text{-}90}$
  - $RT_{10\text{-}90}$: time for signal to go from 10% to 90% of final voltage
- Maximum $RT_{10\text{-}90} = 0.35/BW$ [3]
  - Defining bandwidth, BW, as a 3dB attenuation off of the amplitude of the harmonics of an ideal square wave: $RT_{10\text{-}90} = 0.35\,\mu s$

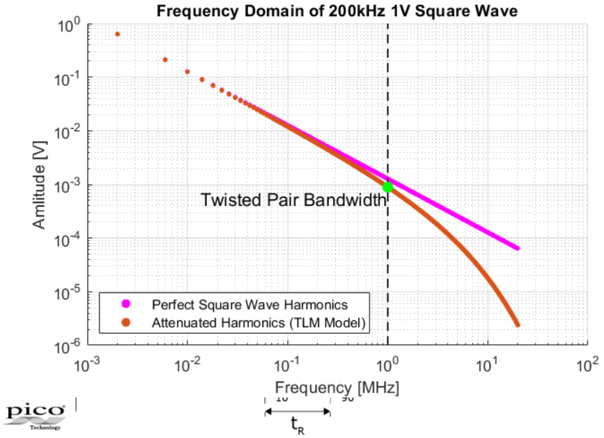
Step 4: Data Rate Limitation

- Estimating $RT_{10\text{-}90}$ as 7% of the digital signal period
  - period = 0.35 µs/7% = 5 µs
  - f = 1/period = 200 kHz
- **Predicted: 200 kb/s data rate**

*Note: analysis does not take into account impedance mismatches, coupling to other line pairs, radiative loss or em interference



Attenuation(f) = Real{√[(R(f)′+iωL′)(G′+iωC′)]}



Effect of Attenuation on Ideal Square Wave Harmonics

[3] Bogatin, Eric. *Signal and Power Integrity, Simplified* Prentice Hall, 2018.

Test Results

Cable Routing	Launch Environment	Resonant Frequency	Full Deployment	Mass / Dimension	LASP Thermal Chamber
Planned	Planned	Planned	Planned	Planned	Planned
Scheduled	Scheduled	Scheduled	Scheduled	Scheduled	Scheduled
Preliminary	Preliminary	Preliminary	Preliminary	Preliminary	Preliminary
Completed	Completed	Completed	Completed	Completed	Completed
Processed	Processed	Processed	Processed	Processed	Processed

Launch Environment Test

Motivation - **Verify that the boom assembly components can survive the vibrational loads experienced during launch.**

Facilities:

- Vibe room

Equipment:

- UD shaker table
- 8-Bay Structure

General Procedure:

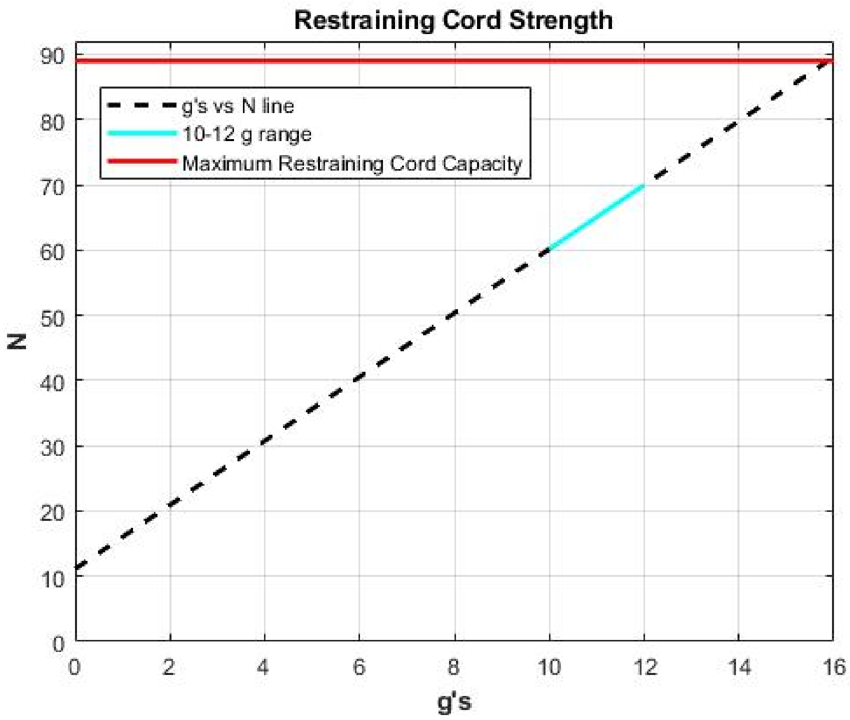
- Setup undeployed boom on shaker table
- Qualification test
  - General Environmental Verification Standard
- Remove boom from shaker table
- Deploy boom structure

Requirements Under Test	
FR_7	Survive 10 G vibrations in the undeployed state.
DR_7.1	Survive under the conditions of the launch environment in the undeployed state.

Risk Reduction:

- Ensure that the boom will survive the launch environment and function as expected afterwards

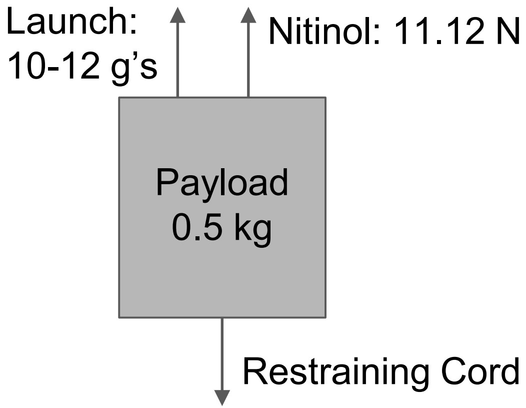
Launch Environment- Restraining Cord



Goal: Determine if restraining cord can survive launch

Max load (12g's): **70 N**

Absolute Max: **15.87 g's**



Test
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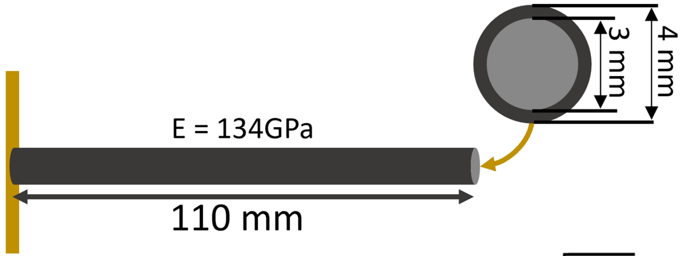
Test Overview

Resonant Frequency Tests

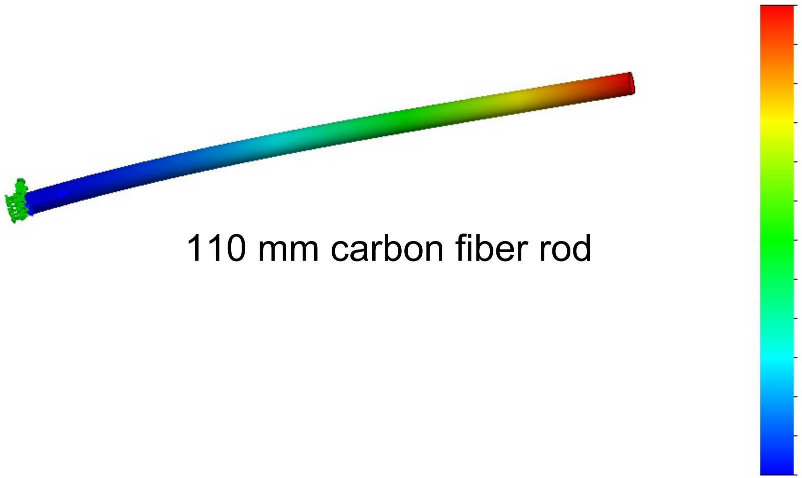
Single Rod Verification

Analytical Method

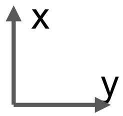


$$I = \frac{\pi}{4}\left(R_0^4 - R_i^4\right) \qquad f = 0.56\sqrt{\frac{EI}{qL^4}}$$

Solidworks Method



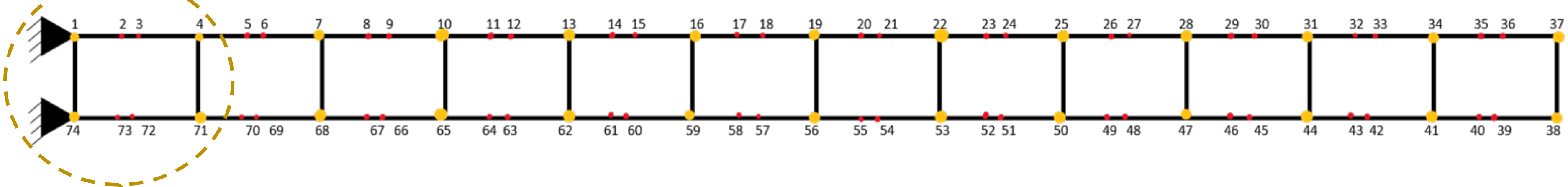
110 mm carbon fiber rod

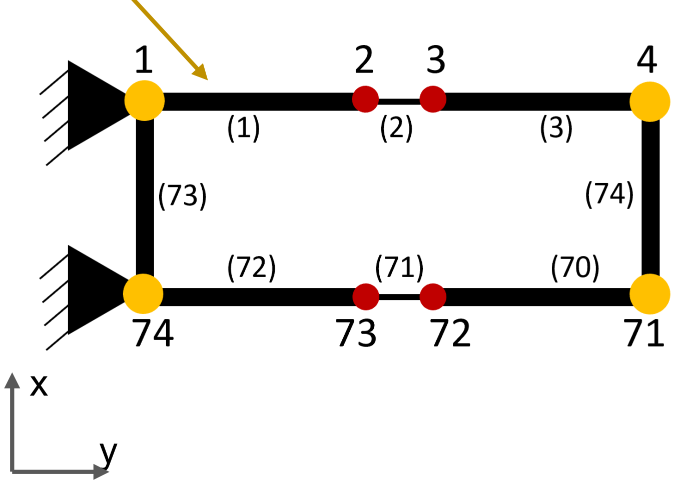


Analytic Result	Solidworks Result	Percent Difference
452.2 Hz	452.6 Hz	0.0885%

Resonant Frequency Tests

12 Bay Truss Verification - Direct Stiffness Method (DSM)





Frequency: $[\mathbf{K} - \omega^2 \boldsymbol{M}] = \mathbf{0}$

Global Master Stiffness Matrix (**K**):

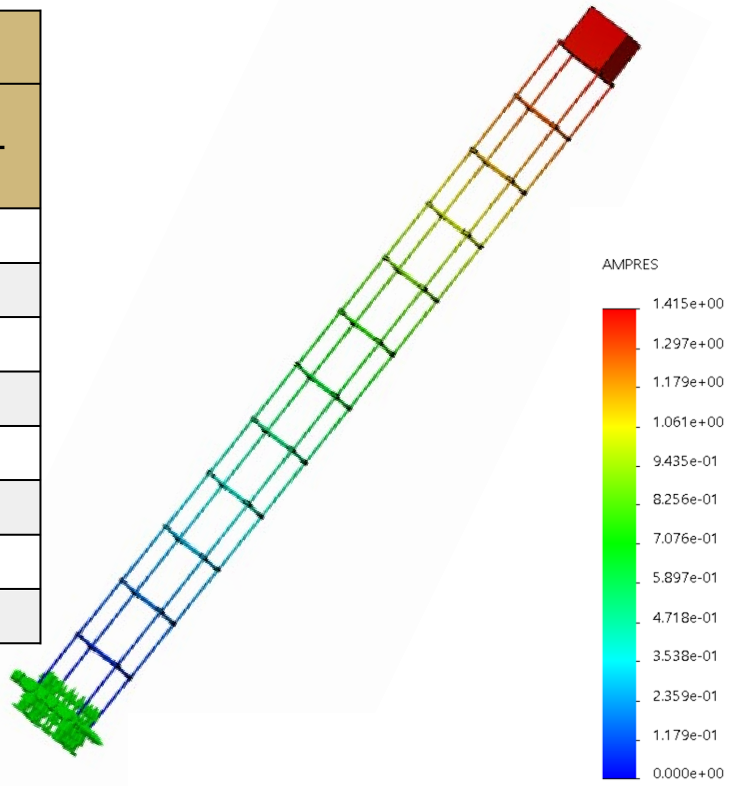
- Populated by DSM and Fixed Pointer Method[4]

Mass Matrix (**M**):

- Populated by Node by Node Lumping Method[5]

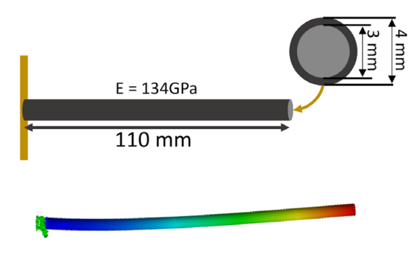
Resonant Frequency Tests

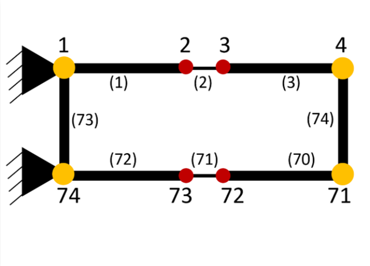
Vibration Analysis with Payload using Solidworks				
Number of Bays	No Instrument [Hz]	No Instrument - Error [Hz]	500 gram Instrument [Hz]	500 gram Instrument - Error [Hz]
1	236.1	2.25	35.0	0.3
2	111.0	4.59	19.8	0.5
3	76.2	6.75	14.7	0.7
4	56.8	9.00	12.1	1.0
5	46.0	11.25	10.3	1.3
6	38.3	13.50	9.0	1.5
7	31.7	15.75	8.1	1.8
8	27.9	18.00	7.2	2.0

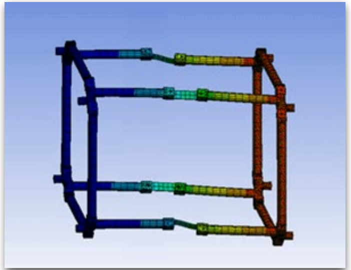


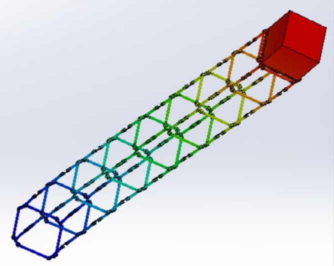
Resonant Frequency Tests

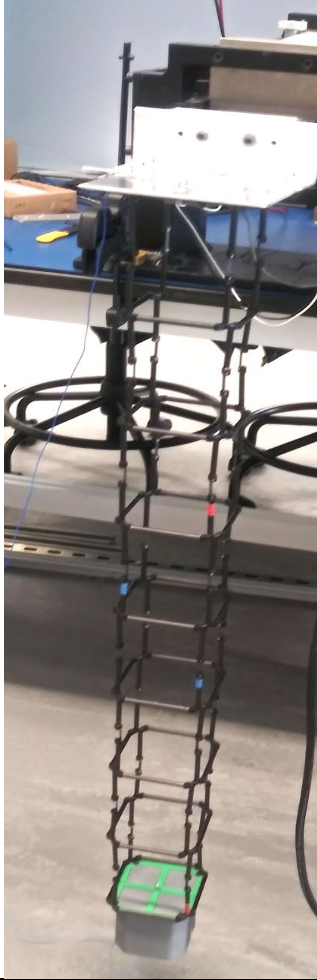
	Single Rod	Single Bay	Full Boom	+ Instrument
Analytical	452.2 Hz	401.5 Hz	71.6 Hz	-
SOLIDWORKS	452.6 Hz	371.24 Hz	31.1 Hz	**7.22 Hz ± 2 Hz**
Ansys	-	302.5 Hz	-	-
Testing	-	Inconclusive	-	**2.6 Hz / 0.5Hz**











Resonant Frequency Tests

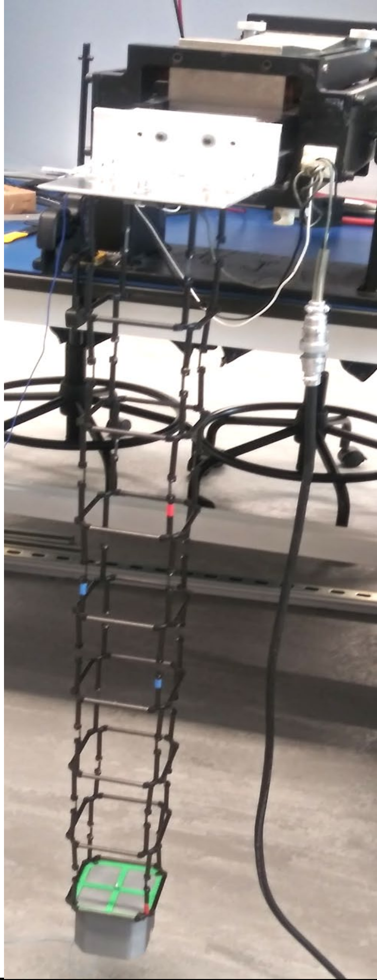
Motivation - Verify that the boom assembly resonant frequency falls within acceptable ranges

Facilities:
- Electronics shop

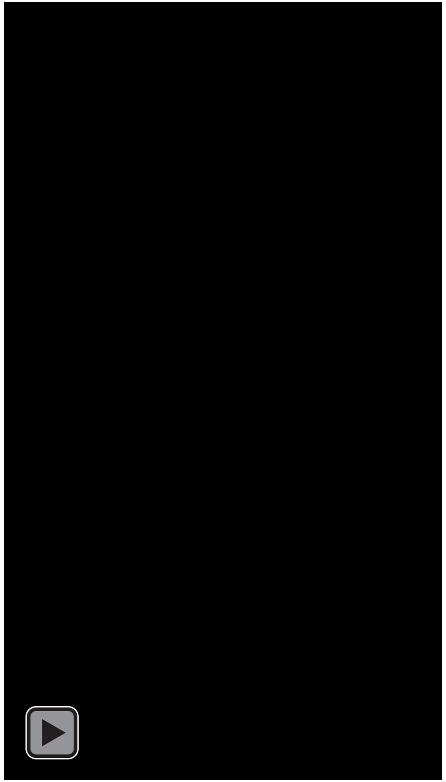
Equipment:
- Mallet
- 2 Teardrop accelerometers
- Horizontal Shaker Table
- 8-Bay Structure

General Procedure:
- Setup deployed boom on shaker table with accelerometers
- Sweep through low frequencies and measure the driven response
    - Data has been processed
- Hit the boom with a mallet and measure the impulse response
    - Data not yet processed

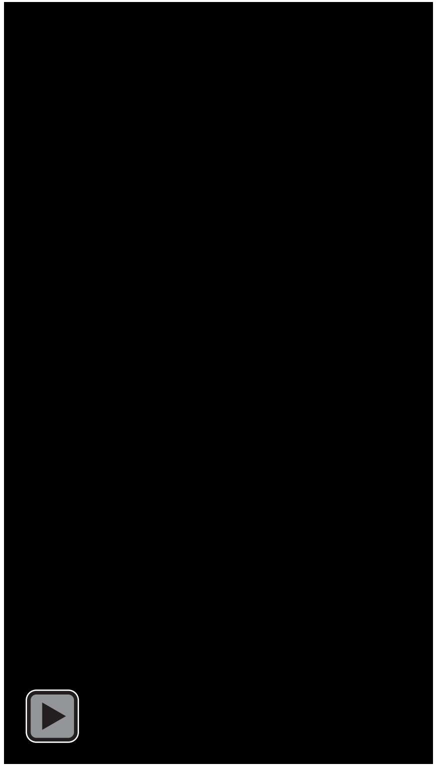
Requirements Under Test	
FR_6	Demonstrate a resonant frequency greater than 2.5 Hz when fully deployed.



Resonant Frequency Tests (Driven vs Hammer tests)



Hammer Test

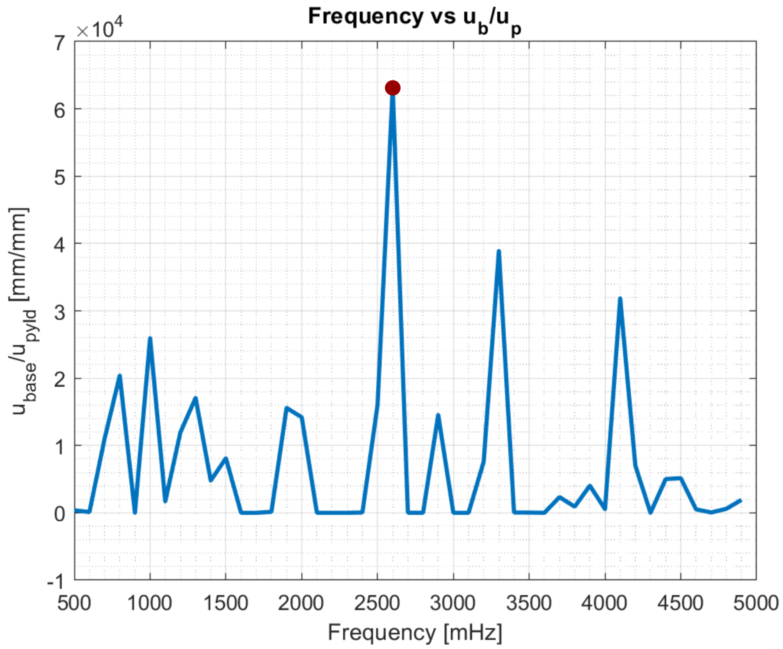


Driven

Resonant Frequency Test Driven Tests

Goal: Determine resonant frequency from driven frequency

- Driven results verify 2.5 Hz requirement
  - First resonant mode **2.6 Hz**
- Acceleration of top and bottom plate were measured until steady state was reached at each frequency
- Displacement was normalized and peaks were found



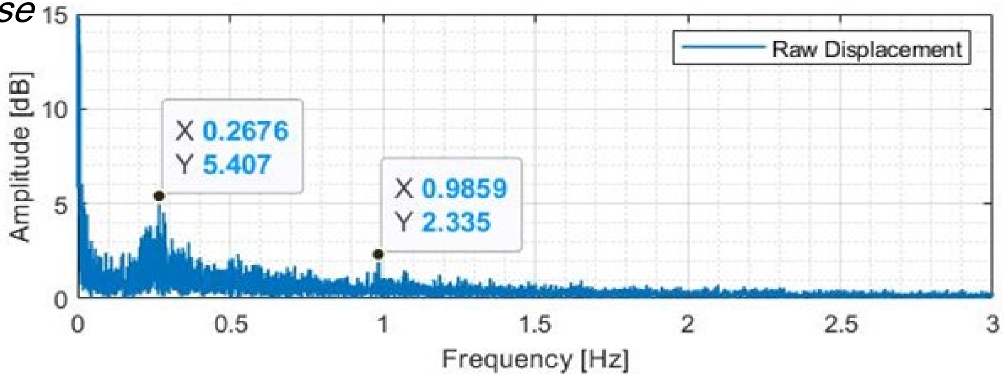
Driven

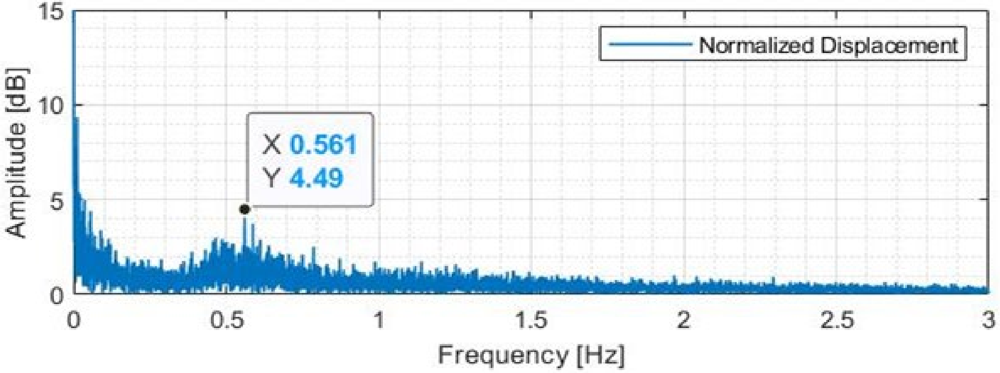
Test Results

Resonant Frequency Test- Hammer Tests

Goal: Determine resonant frequency from an impulse

- Impulse results do not verify 2.5 Hz requirement
  - First resonant mode 0.27 Hz
- Analysis based on MATLAB *fft()*
  - Raw data converted to dB scale
    - Ref. displacement 1mm
  - Fast Fourier Transform
    - Results in frequency domain
  - Null out “negative” frequencies
  - Double “positive” frequencies
  - Peaks are resonances





Resonant Frequency Test- Hammer Tests

Goal: Determine resonant frequency from an impulse

- Resonant frequency below requirement
  - Displacement only 0.27 Hz
  - Normalized displacement 0.56 Hz
- Contributing factors
  - Impulse not representative of operations
  - Possible structural damage
  - Baseplate moved during test (micron scale)
    - Still on shaker (restrained)
- Root cause
  - Test execution

Possible fixes

- Secure baseplate
  - Baseplate moved during test
- Pretest structural inspection
  - Possible epoxy failure before/during test
- Perform smaller test on single carbon fiber longeron to verify analysis results
- Apply impulse at multiple locations

Cable Routing

Planned

Scheduled

Preliminary

Completed

Processed

Launch Environment

Planned

Scheduled

Preliminary

Completed

Processed

Resonant Frequency

Planned

Scheduled

Preliminary

Completed

Processed

Full Deployment

Planned

Scheduled

Preliminary

Completed

Processed

Mass / Dimension

Planned

Scheduled

Preliminary

Completed

Processed

LASP Thermal Chamber

Planned

Scheduled

Preliminary

Completed

Processed

Full Deployment Test

Motivation - Verify the deployment capabilities of the fully assembled boom through a commanded deployment and verify restow capability.

Facilities:

- Electronics Lab, Pilot Room

Equipment:

- Sorensen XPH 35-4D Power Supply set as Current Supply
- Arduino Due microcontroller (as mock flight computer)
- Westward Tape Measure, +/- 1cm
- Teardrop Accelerometer
- Timer
- Roller

General Procedure:

- Attach the various equipment to the undeployed boom assembly such that gravity does not affect deployment
- Send deployment command from mock flight computer
- Confirm deployment telemetry is being received
- Restow boom assembly

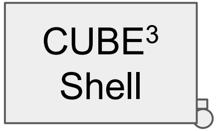
Requirements Under Test	
FR_1	Deploy an instrument of up to 500 g, with 8 x 8 x 8 cm dimensions
FR_4	The boom assembly can communicate with the flight computer
FR_5	Provide ability to re-stow for redeployment
Additionally: DR_1.1, DR_1.2, DR_1.4, SR_1.4.1, DR_1 DR_4.1, DR_4.2, SR_4.2.1, DR_4.3, DR_5.1	

Risk Reduction:

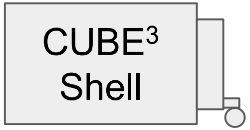
- Proves that the boom assembly fully deploys as intended and demonstrates designed capabilities

Full Deployment Test

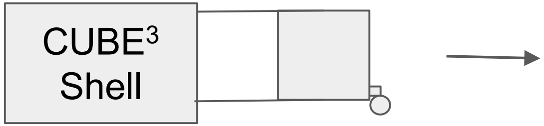
1. STOWED



1. DEPLOYMENT COMMANDED



1. DEPLOYMENT IN PROGRESS



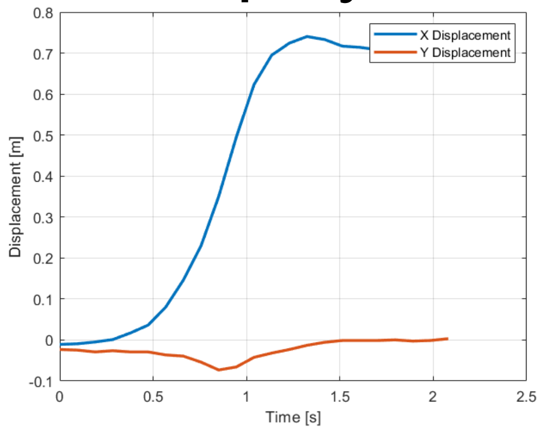
1. DEPLOYMENT COMPLETE

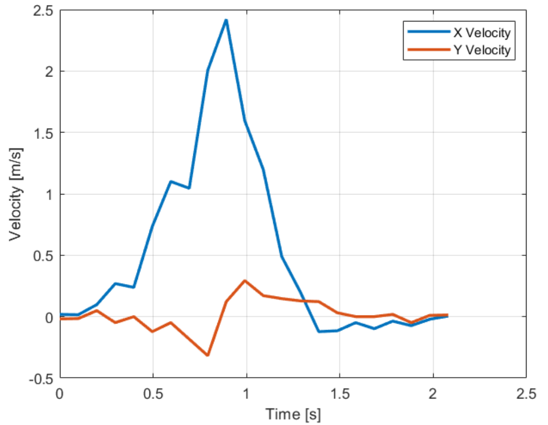
Full Deployment Test - Video Analysis

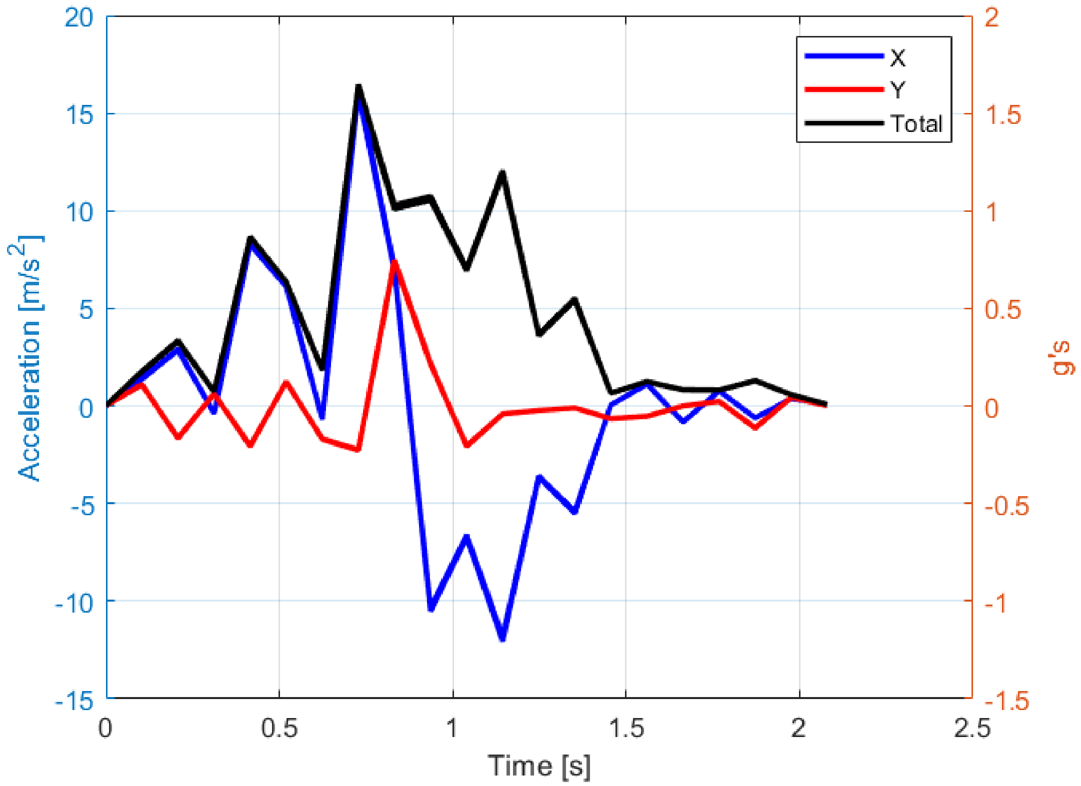
Goal: Determine maximum acceleration on payload during deployment

- Used Video Tracker
  - From 2003 lab
- Analyzed data with MatLab
  - Built in diff function
- Results (shown on next slide)
  - Max 1.65 at 0.728 seconds
    - Consistent with accelerometer data
  - Occurs as payload begins to turn

Full Deployment Test - Video Analysis





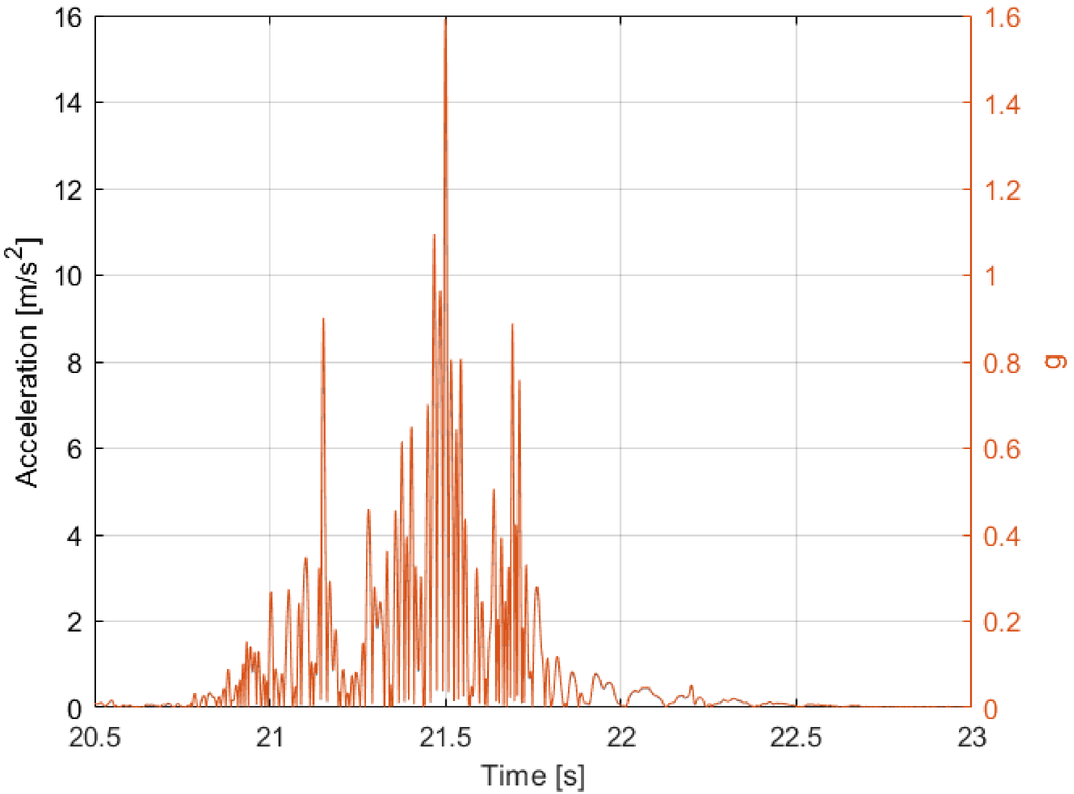


Test Results

Full Deployment Test - Accelerometer Analysis

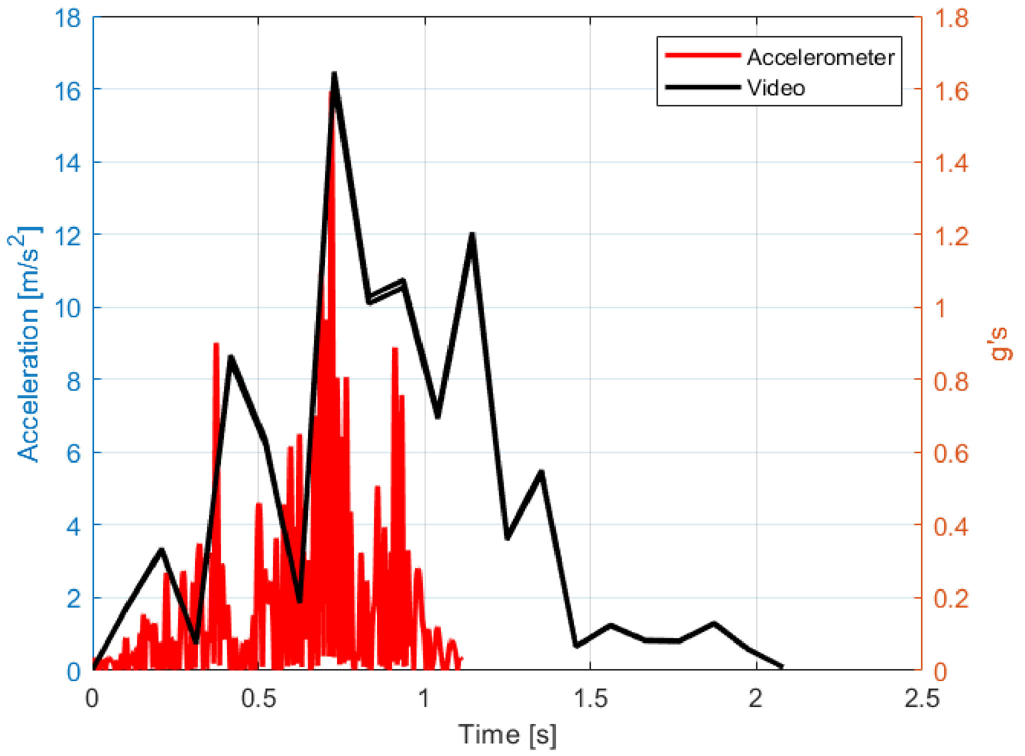
Goal: Determine maximum acceleration on payload during deployment

- Data captured with teardrop accelerometer and beam airplane lab VI
- Spike at 15.6 m/s
- g load of 1.59 g's
  - Matches with Video Analysis



Full Deployment Test - Result Comparison

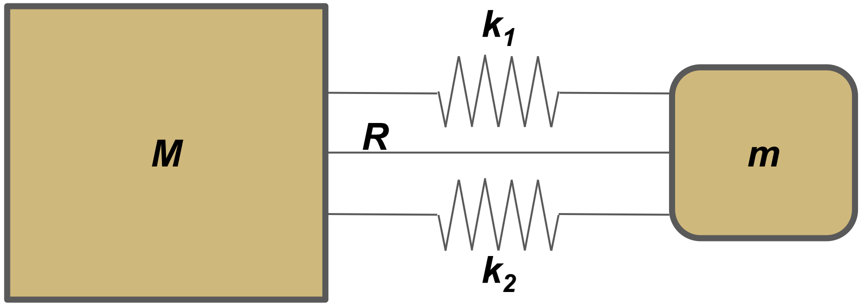
- Accelerometer and Total Video Analysis
- Both predict about 1.6 g's at around 0.7 seconds

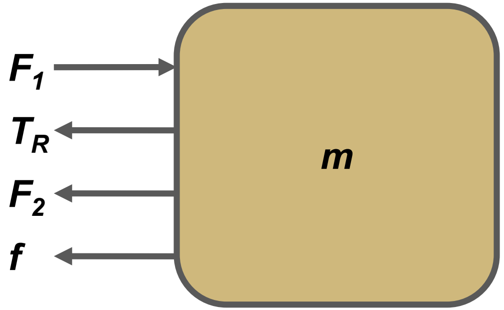


Full Deployment Test - Model Correlation

Goal: Compare original model to test results

- Acceleration
  - Model: 1.12 g
  - Video: 1.65 g
  - Accelerometer: 1.59 g
- Time
  - Model: 0.4 s
  - Experimental: 2 s
- Conclusions
  - Initial acceleration 32% faster than expected
    - Nitinol nonlinearity
  - No useful comparison in time since test went sideways

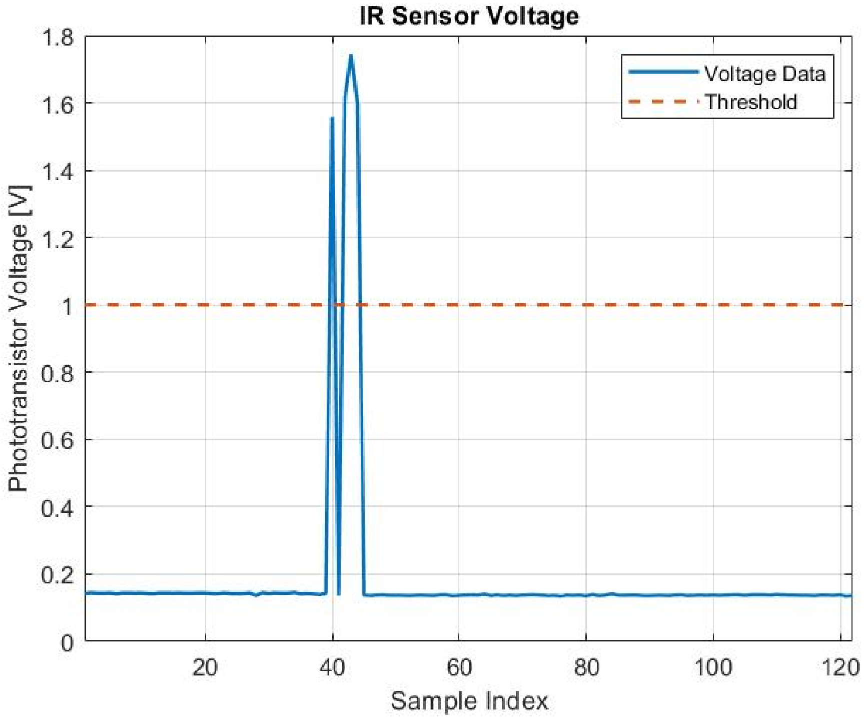




Full Deployment Test - IR Sensor

Goal: Determine if telemetry circuit worked as expected

- Failed to detect deployment
  - Sampling rate 10-12 Hz
  - Spool deployed 15-20 Hz
- Contributing factors
  - Brake tuning
  - Nitinol temperature
  - Arduino Due sampling rate
- Root cause
  - Reliance on Due ADC
- Possible fixes
  - Different microcontroller
  - External ADC



Cable Routing

Planned
Scheduled
Preliminary
Completed
Processed

Launch Environment

Planned
Scheduled
Preliminary
Completed
Processed

Resonant Frequency

Planned
Scheduled
Preliminary
Completed
Processed

Full Deployment

Planned
Scheduled
Preliminary
Completed
Processed

Mass / Dimension

Planned
Scheduled
Preliminary
Completed
Processed

LASP Thermal Chamber

Planned
Scheduled
Preliminary
Completed
Processed

Mass/Dimension Test

Motivation - Verify that the physical characteristics of the undeployed boom assembly fit within the given requirements .

Facilities:

- Electronics Lab

Equipment:

- Shars Aventor Calipers, +/- 0.01 mm
- Acculab SV-50 Scale, +/- 10 g

General Procedure:

- Measure the dimensions of the x-y-z axes
- Measure the accommodation space for the guide rails
- Weigh the full boom assembly

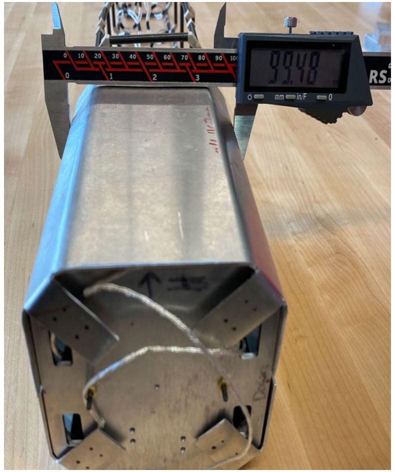
Risk Reduction:

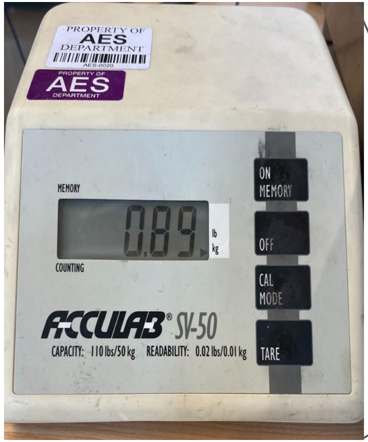
- Confirms that the manufactured boom assembly fits within the sizing and weight constraints set at the start of the project

Requirements Under Test	
DR_3.1	Stow with a length less than or equal to 15 cm, including instrument
DR_3.2	Stow with a height less than or equal to 10 cm, including instrument
DR_3.3	Stow with a width less than or equal to 10 cm, including instrument
DR_3.4	Provide 6 mm by 6 mm accommodation space at each corner for NanoRacks guide rails
FR_9	The whole system, including instrument, will have a maximum total mass of 2kg

Mass/Dimension Test

Test Results		
Req. ID	**Expected Result**	**Result**
DR_3.1	Length = 15 cm	Length = 14.99 cm
DR_3.2	Height = 10 cm	Height = 9.95 cm
DR_3.3	Width = 10 cm	Width = 9.95 cm
DR_3.4	Guide Rail Space = 6 mm x 6 mm	Guide Rail Space = 6 mm x 6 mm
FR_9	Mass $\leqslant$ 2 kg	Mass = 0.89 kg





Cable Routing	Launch Environment	Resonant Frequency	Full Deployment	Mass / Dimension	LASP Thermal Chamber
Planned	Planned	Planned	Planned	Planned	Planned
Scheduled	**Scheduled**	Scheduled	Scheduled	Scheduled	**Scheduled**
Preliminary	Preliminary	Preliminary	**Preliminary**	Preliminary	Preliminary
Completed	Completed	Completed	Completed	Completed	Completed
Processed	Processed	**Processed**	Processed	**Processed**	**Processed**

LASP Thermal Chamber Test

Motivation - **Verify that the boom assembly components can survive the thermal fluctuations experienced in space and establish a deployment temperature.**

Facilities:
- LASP Thermal Chamber Room

Equipment:
- Big White Thermal Chamber
- Thermocouples
- 2-Bay Structure

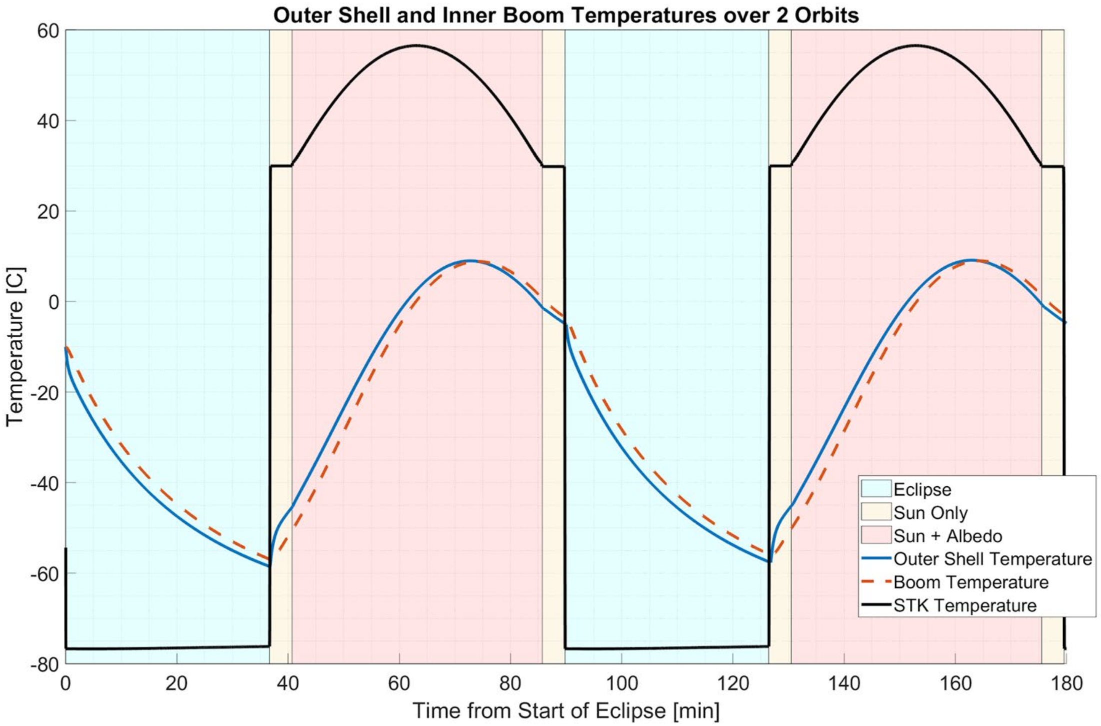
General Procedure:
- Setup undeployed boom in thermal chamber
- Ramp down to -60 ℃
- Ramp up to 10 ℃
- Deploy Boom
- Ramp down to -60 ℃
- Return to ambient and repeat with different deployment temperatures

Requirements Under Test	
DR_8.1	The boom assembly shall survive the thermal fluctuations of the space environment in both the deployed and undeployed configuration.

Risk Reduction:
- Establish feasibility of components not breaking due to extremely low temperatures
- Establish adequate deployment temperatures for the Nitinol hinges

LASP Thermal Chamber- Basis for Temperatures

Goal: Determine maximum and minimum LEO temperatures



Thermal profile used in thermal testing based on rough averaging of MATLAB and STK generated temperature profiles.

	Temp Max	Temp Min
STK	56 °C	-76 °C
MATLAB	10 °C	-60 °C

Manufacturer specifies super elasticity lost at -10 °C

Deployment temperatures tested are: -10 °C, 0 °C, 10 °C

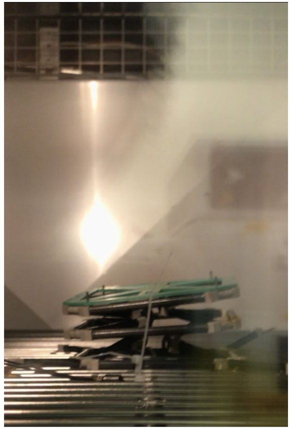
Test Results

LASP Thermal Chamber Test

Temperature	No Deployment	Partial Deployment	Full Deployment
-10 ℃	x		
0 ℃	x		
5 ℃		x	
10 ℃			x

No component damage was observed even after reducing the structure down to the minimum of -60 ℃

← Established Deployment Temperature

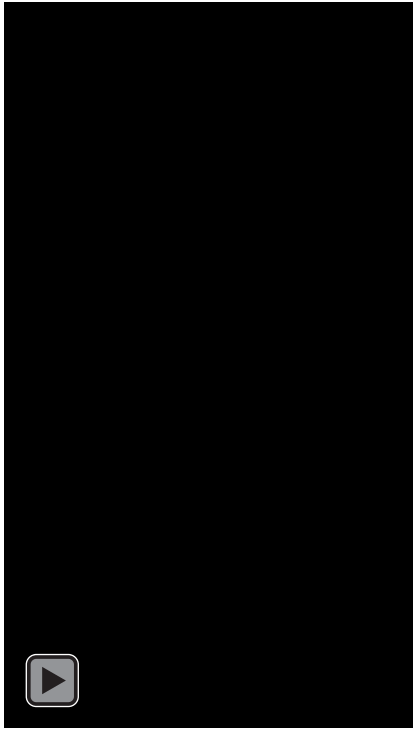


-10 ℃ No Deployment

5 ℃ Partial Deployment

10 ℃ Full Deployment

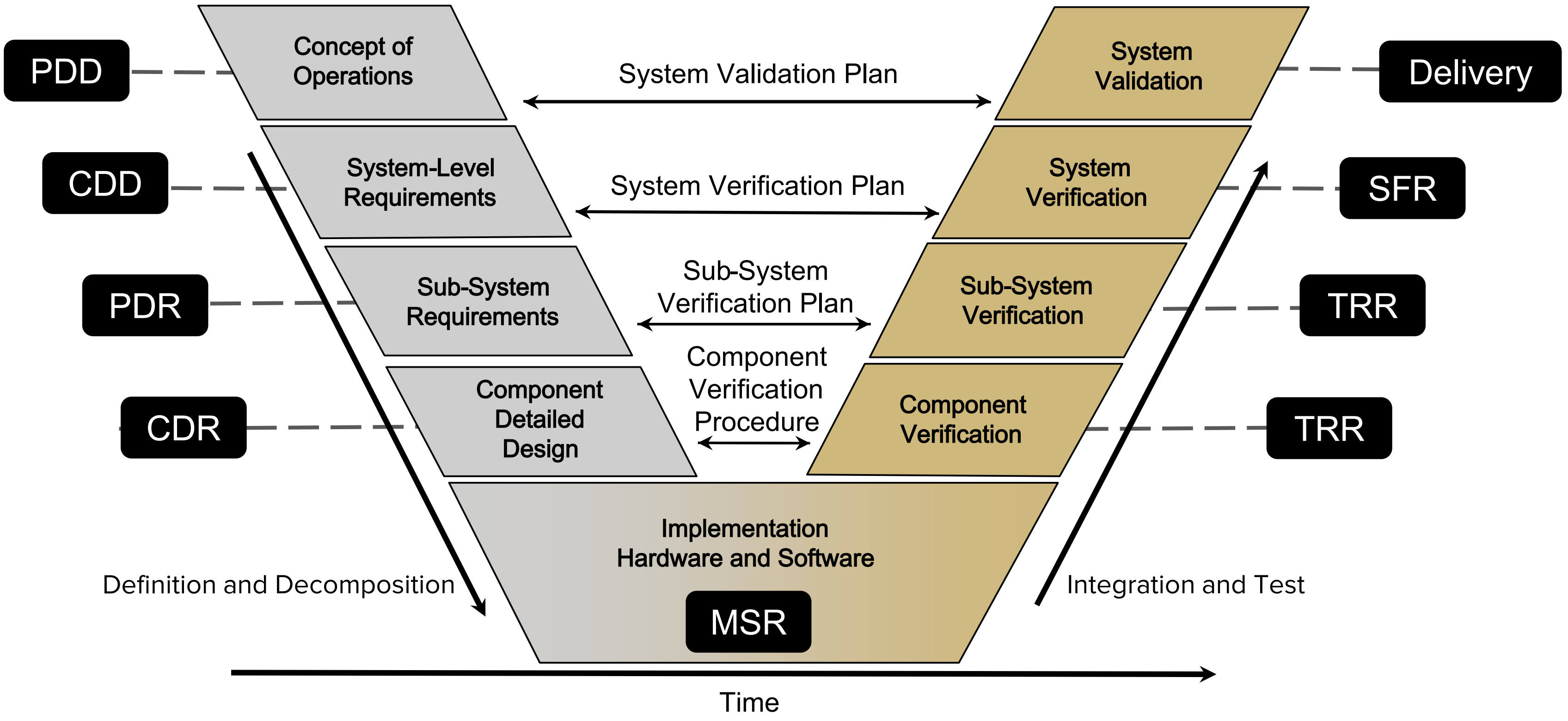
LASP Thermal Chamber Test



Video of Thermal Deployment at 10℃

Systems Engineering

Systems Engineering “V” Guideline



Issues / Challenges Encountered

- Trade Study Completion
  - Not every possible trade study was carried out at the start of the project
  - Lead to problems within design during manufacturing
- Design Changes During Manufacturing
  - To alleviate certain complications design changes were implemented
  - Ended up causing manufacturing to be longer than originally planned ultimately delaying testing

Lessons Learned:

- Fully analyze each aspect of the design and perform all required trade studies early rather than performing a trade study to design a new part when it is determined one is functionally unachievable.
- Keep better track of the division of work between each sub-system group
- Develop more thorough interface documents at the start of the design process
- Try to avoid design changes during manufacturing

Requirement Flow Down

Critical Project Elements

- #1 Deployable Boom Structure
- #2 Payload Connectivity
- #3 Software Interface
- #4 Deployment System
- #5 Environmental Resilience

Customer Requirements

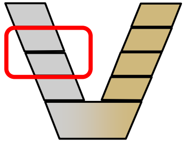
- Extends $\geq$ 60cm, Resonance $\geq$ 2.5Hz, Mass $\leq$ 1.5kg, Volume $\leq$ 1.5U
- The system contains power and data cables for the instrument
- Deployment can be commanded from an external computer.
- Deploys in under 2 minutes with < 10 Gs & can confirm deployment
- Analysis indicates greater than 1 year lifespan on orbit.

Functional Requirements (Short Text)

- **FR_3** Stow in less than 1.5U, including instrument
- **FR_6** Demonstrate a resonant frequency $\geq$ 2.5Hz when fully deployed.
- **FR_1** Deploy an instrument of up to 500g, 8 x 8 x 8 cm
- **FR_2** Accommodate a 12 wire set up
- **FR_4** The boom assembly can communicate with the flight computer
- **FR_8** Survive for one year of deployment in the space environment

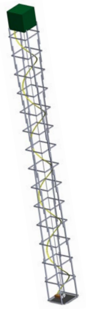
Design Requirements (Short Text)

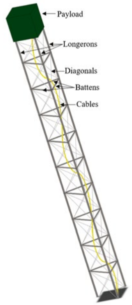
- **DR_3.1** Length $\geq$ 15cm
- **DR_3.2** Height $\geq$ 10cm
- **DR_3.3** Width $\geq$ 15cm
- **DR_1.1** Attach a 500 g or less instrument with dimensions 8x8x8 cm
- **DR_1.2** The boom will deploy a minimum distance of 60 cm
- **DR_1.4** The boom structure will deploy in under 2 minutes
- **SR_1.4.1** Acceleration Limit of the attached instrument will not exceed 10 G's
- **DR_2.1** Accommodate 3x differential signals, 30 AWG or larger
- **DR_2.2** Accommodate three-wire power up to 15 V and 0.5 A
- **DR_4.1** Deploy on command provided by GSE or spacecraft computer
- **DR_4.2** The boom assembly can inform the spacecraft of a successful deployment or not
- **DR_8.1** Survive under the thermal fluctuations of space
- **DR_8.2** Survive under the radiation of space

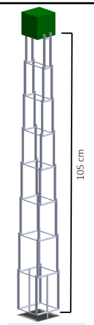


Key Trade Study: Design Baseline Concept

Trade	Weight	ISS-Like	Stackable	Inch Worm	Coilable Truss	Screw
Mass	10%	5	5	5	5	4
Manufacturability	20%	4	4	4	4	4
Complexity	20%	4	4	3	4	3
Heritage	15%	5	3	3	5	4
Rigidity	15%	5	5	5	5	4
Team Knowledge	20	5	5	4	4	4
Total	100%	4.6	4.3	3.9	4.4	3.8

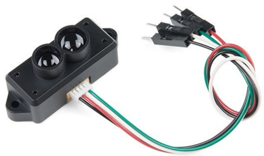



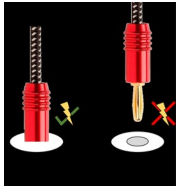


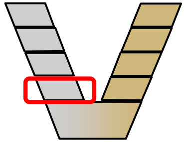


Key Trade Studies: Deployment Telemetry

Trade	Weight	LiDAR Module	Electric Sensor	Camera	Break-Wire
Mass	10%	5	5	1	4
Volume	15%	5	5	2	5
Team Knowledge	20%	4	5	4	5
Risk	20%	2	4	5	5
Accuracy	35%	5	5	2	4
Total	100%	84%	96%	56%	91%







Key Trade Studies: Deployment Progress Sensor

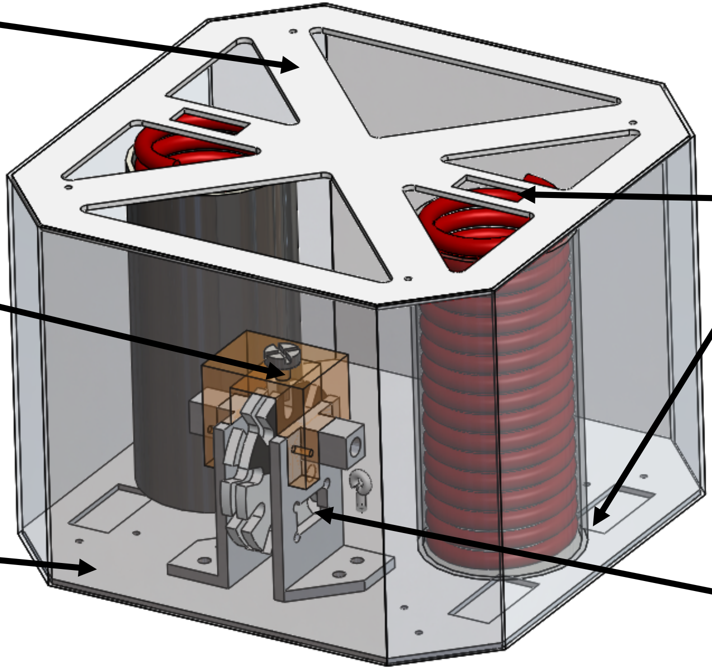
Trade	Weight	Snap Switch	IR Sensor	Optical Encoder
Mechanical Complexity (0-5)	30%	2	5	3
Redundancy Opportunity (0-1)	10%	0	1	1
Software Complexity (0-5)	10%	5	5	3
Power Draw (0-5)	10%	5	3	4
Size (0-5)	40%	1	5	4
Total	100%	40%	96%	74%

Developed Interfaces

Instrument to Boom Assembly Attachment Plate

Electrical Connections for Nichrome Burn Wire

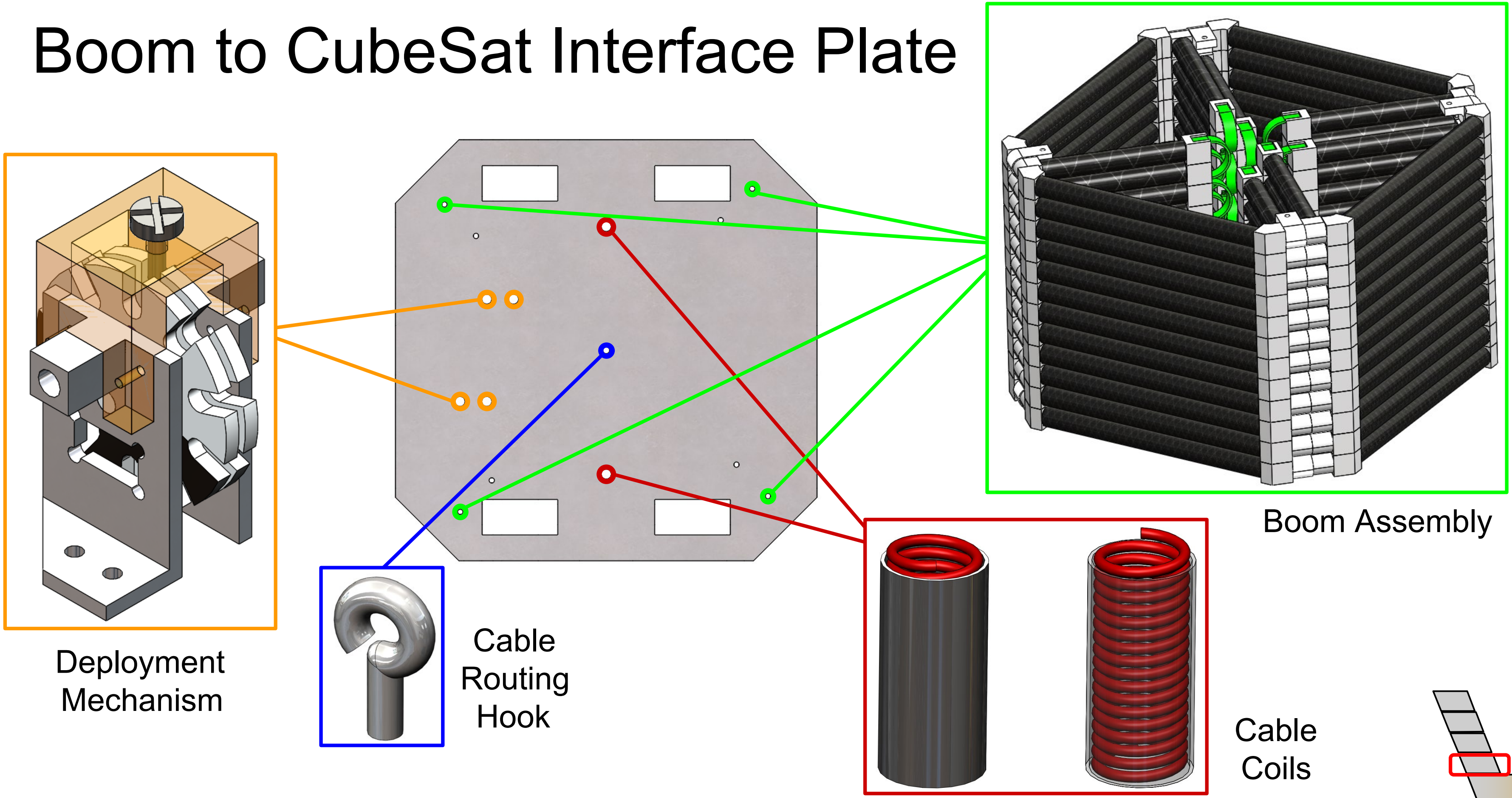
Boom Assembly to CubeSat Bus Attachment Plate



Wire Connections Both to Instrument and Bus

Software / Hardware Interface

Boom to CubeSat Interface Plate



Risk Management Matrix

Probability \ Impact	1	2	3	4	5
5					
4					
3			6. Insufficient Rigidity		
2	9. Test Execution	2. Cold Environment 7. Manufacturing Schedule Slip	3. Nitinol Failure 12. Temperature Flux Induced Failure		
1	4. Radiation/UV 13. Budget Overload	1. Manufacturability 5. Test Unavailability 11. Cold Welding	8. Nitinol Sourcing 10. Deployment Release Failure		

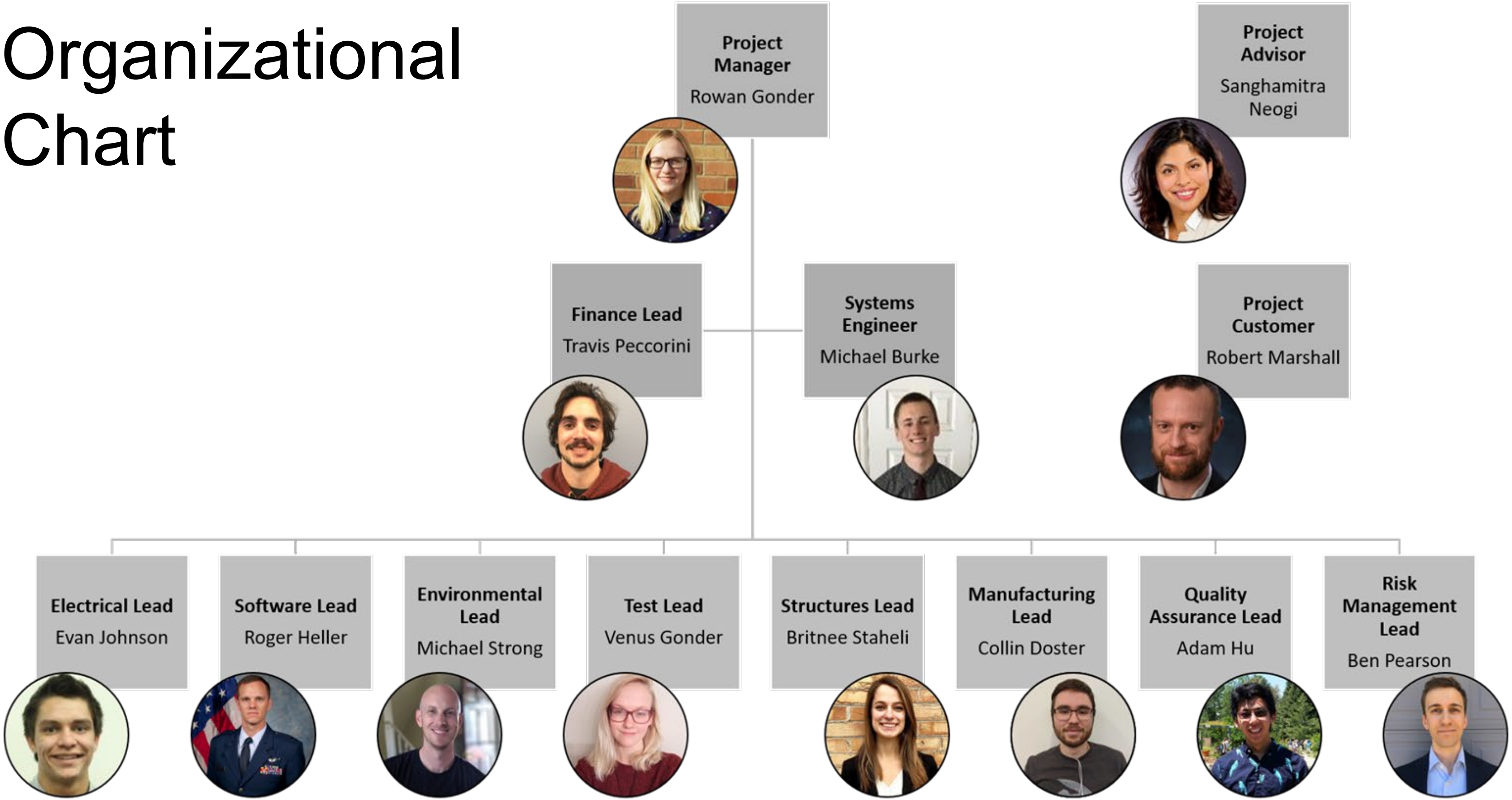
Key Movements:

- Nitinol Failure moved from Probability 3 & Impact 5 to Probability 2 & Impact 3
- Manufacturability moved from Probability 3 & Impact 3 to Probability 1 & impact 2

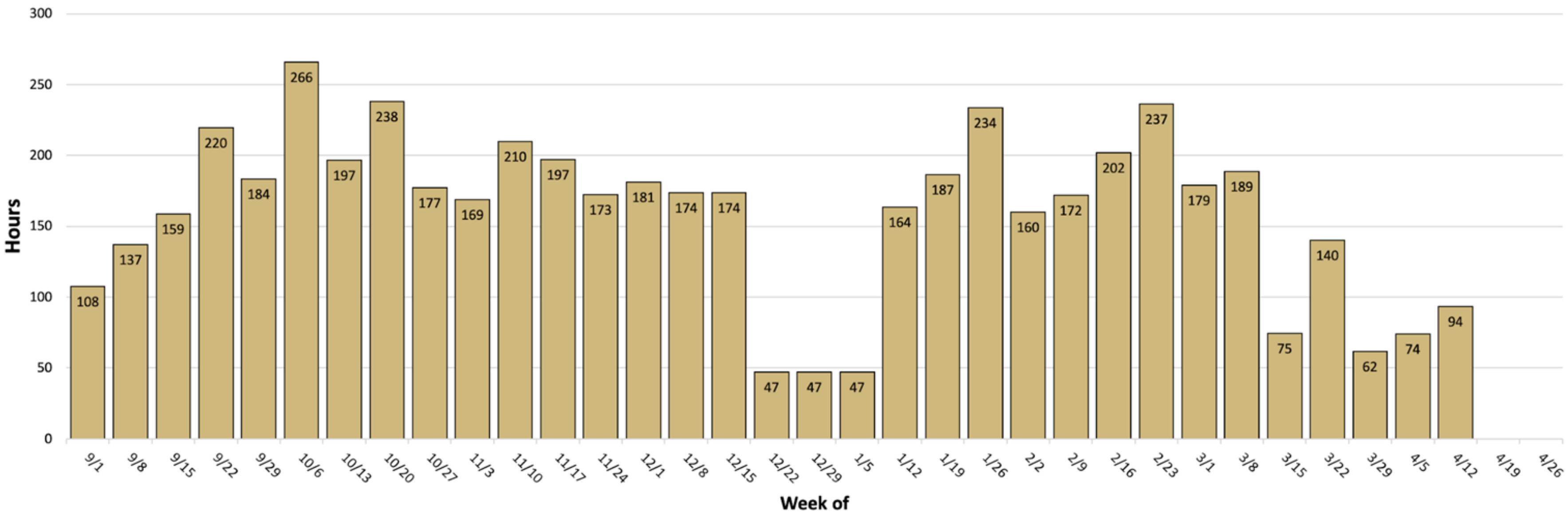
Systems Engineering

Project Management

Organizational Chart



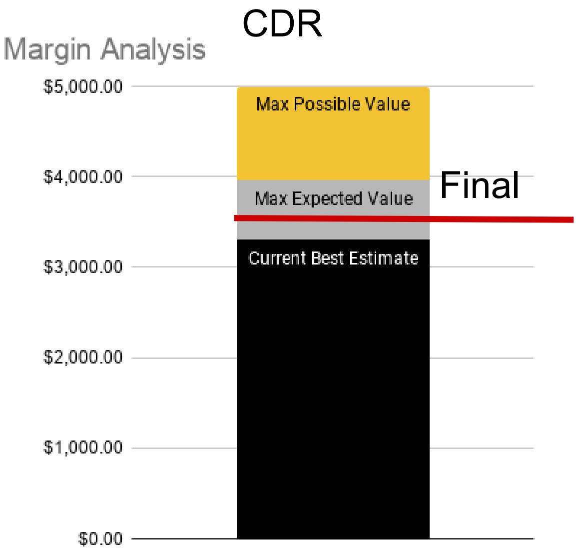
Team Hours Worked



Total: 5267 Hours

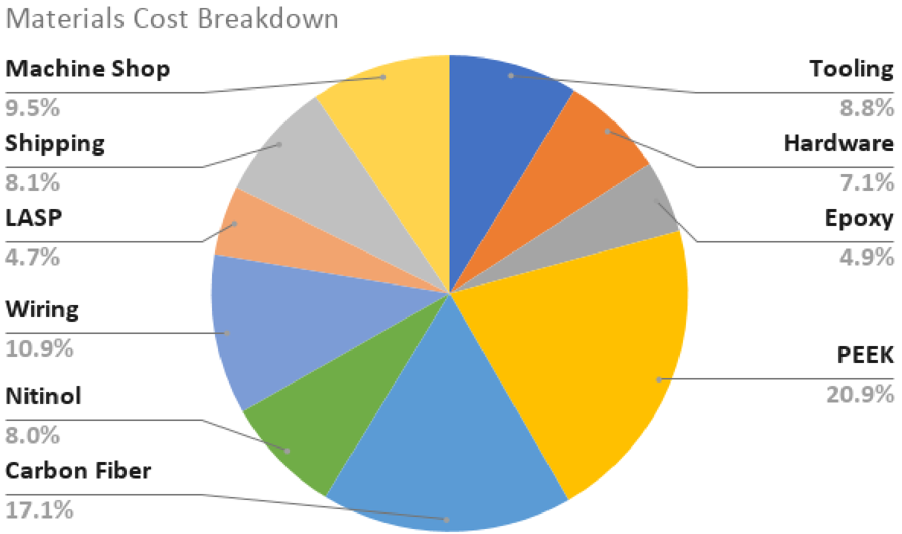
Project Budget Evolution

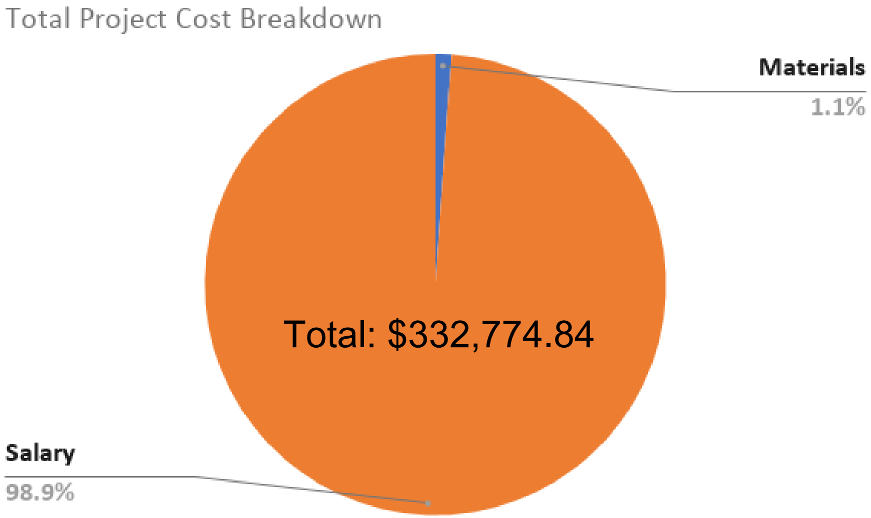
Margin Analysis



Line Item	CDR	+ Contingency	Final	Difference
Tooling	$43.66	$52.39	$272.04	$219.65
Hardware	$410.55	$492.66	$427.93	$64.73
Epoxy	$90.58	$108.70	$90.58	$18.12
PEEK	$540.95	$649.14	$770.66	$121.52
Carbon Fiber	$399.17	$479.00	$627.94	$148.94
Nitinol	$295.80	$354.96	$295.80	$59.16
Wiring	$300.00	$360.00	$338.34	$21.66
LASP	$750.00	$900.00	$175.00	$725.00
Test Equipment	$100.00	$120.00	$140.09	$20.09
Shipping	$300.00	$360.00	$273.46	$86.54
Machine Shop/Classes	$350.00	$75.00	$350.00	$75.00
Total	**$3,297.62**	**$3,887.38**	**$3,586.84**	**$300.54**

Costs Breakdown





Industry Cost = (2*Salary)+Materials
= (2*164,594)+3,586.84
= $329,188 + 3,586.84

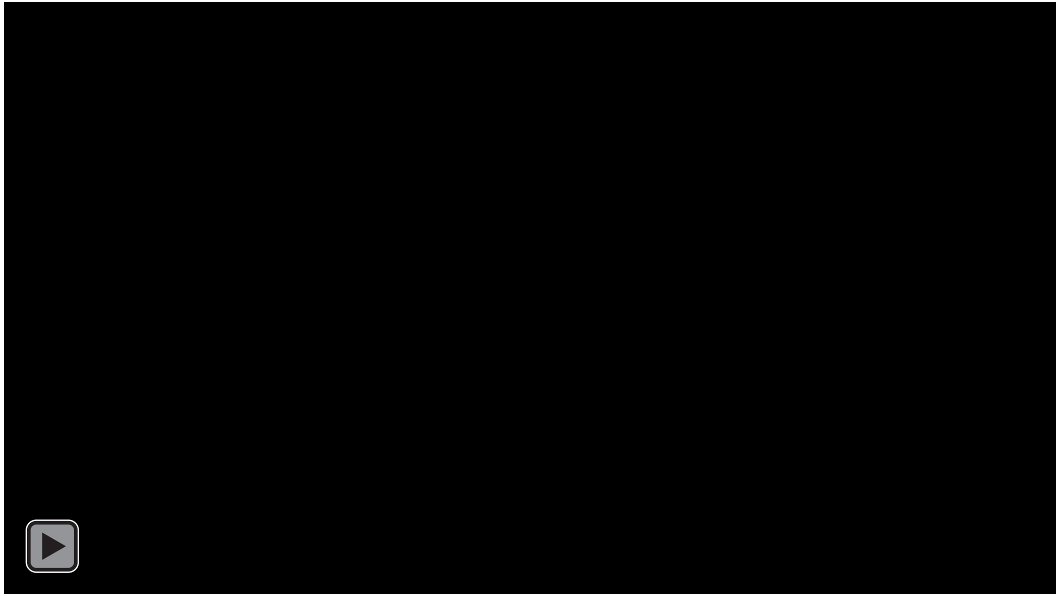
Successes, Challenges & Lessons Learned: Project Management

- Few issues with internal deadlines being met, but with a team calendar/task list and more thorough explanation of expectations, project tasks were kept on track.
- Through the creation of personal slide decks everyone had the opportunity to see what other team members were doing and keep our expectations in line with reality and keep the team accountable.
- Over-all, a lot of hard work and effort went into this project from everyone, and we almost made it to the end of the project even with the reduced schedule.

Lessons Learned:

- Make the schedule early and make sure everyone knows what is expected and agrees to follow it.
- Frequent reviews of each team member's contribution (especially with individual powerpoints) helps keep everyone up to date on the project and reduces surprises.
- There are a lot of experts in the building who are very willing to help us work through engineering design/analysis problems.

Questions?



Backup Slides

Environmental - Structure Material

Material	Temp Range °C	Radiation	Outgassing
Aluminum	Max Temperature: 475 °C Min Temperature: Well below operation range	High UV tolerance	Little to no outgassing
Carbon Fiber	Max Temperature: 70-100 °C depending on type Min Temperature: Well below operation range	Large UV resistance	Low outgassing
Nitinol	Max Temperature: Annealing temperature of the specific Nitinol used Min Temperature: survives, but becomes non-elastic at below 10^{o}C	High UV tolerance	Low outgassing

Cable Routing Test- Step 1

Steps:

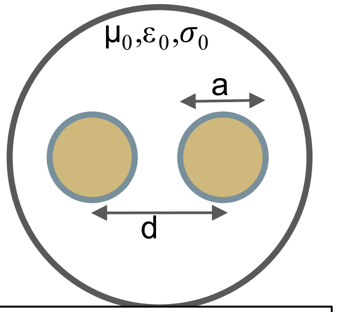
1. Circuit Equivalent Model
   a. Find: R’, G’, C’, L’

$$C' = \frac{\pi\varepsilon_0}{acosh(d/a)}\ [F/m]$$
$$L' = \frac{\mu_0}{\pi} acosh(d/a)\ [H/m]$$
$$R' = \frac{2R_s}{\pi a} \frac{d/a}{\sqrt{(d/a)^2-1}}\ [\Omega/m]$$
$$G' = \frac{\pi\sigma_0}{acosh(d/a)}\ [S/m]$$

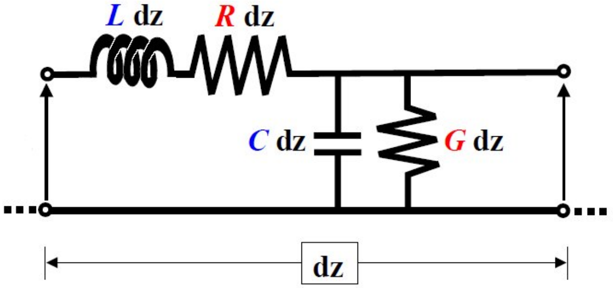
Source [1]

$$C' = \frac{\pi\varepsilon_0}{ln(2d/a)}\ [F/m]$$
$$L' = \frac{\mu_0}{\pi} ln(2d/a)\ [H/m]$$
$$R' = \frac{2R_s}{\pi a}\ [\Omega/m]$$
$$G' = \frac{\sigma_0}{\varepsilon_0} C'\ [S/m]$$

Two Wire Line Approximation [2]



Twisted Line Pair Characteristics



Transmission Line Equivalent Circuit (infinitesimal length dz)

Using KCL and KVL, voltage along transmission line can be found:

$$L'\frac{di_n}{dt} = -\frac{v_{n+1}-v_n}{\Delta z} \rightarrow \frac{\partial v(t,z)}{\partial z} = -L'\frac{\partial i(t,z)}{dt}$$

$$C'\frac{dv_n}{dt} = -\frac{i_n-i_{n-1}}{\Delta z} \rightarrow \frac{\partial i(t,z)}{\partial z} = -C'\frac{\partial v(t,z)}{dt}$$

Combing the two equations:

$$\frac{\partial^2 v(t,z)}{\partial t^2} - \frac{1}{L'C'}\frac{\partial^2 v(t,z)}{\partial z^2} = 0$$

A solution to the differential equation:

$$V(z) = V_+ e^{-j\beta z} + V_- e^{+j\beta z}$$

Test Results

Cable Routing Test- Step 2: Skin Depth Attenuation

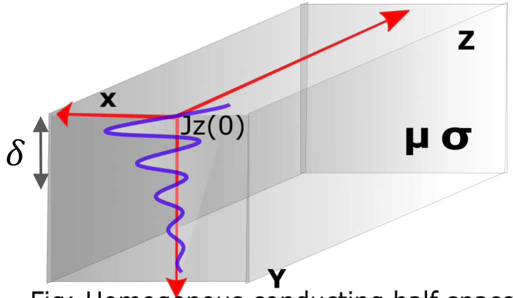
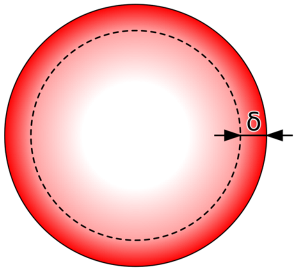
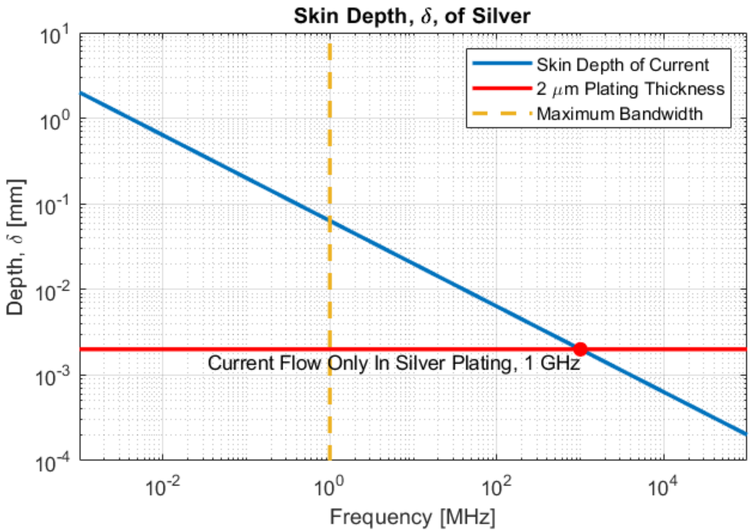


Fig: Homogenous conducting half space with sinusoidal current





As frequency of sinusoidal current increases, current distributes itself towards surface of conductor

Current density vector decreases exponentially with increasing y at a distance:

$$\delta = \sqrt{\frac{2}{2\pi f \mu \sigma}}$$

Majority of current flows through silver after 1 GHz, computations therefore assume a copper conductor

Cable Routing Test- Step 3

Analytical Model:

Goal: Estimate data rate in kB/s

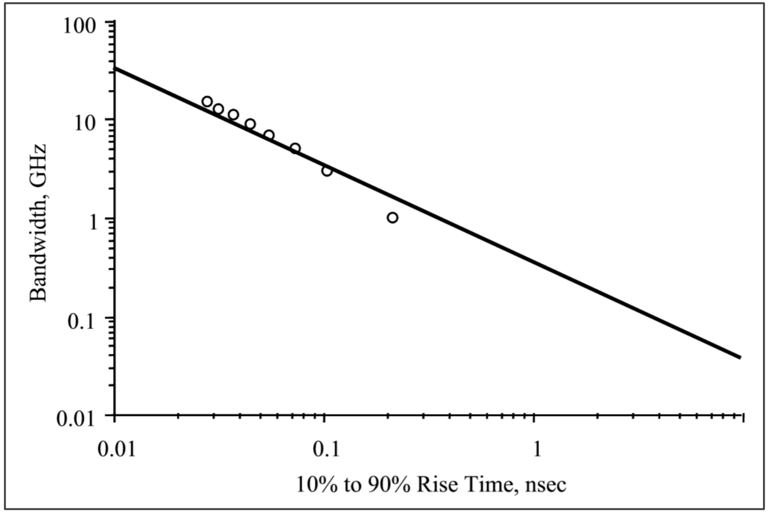
*Note: analysis does not take into account impedance mismatches, coupling to other line pairs, radiative loss or em interference

Steps:

3. Rise time degradation caused by attenuation
   a. Define bandwidth, BW, of transmission line

Defining Bandwidth of the Transmission Line

1. In a realistic time domain waveform, the higher spectral components will drop off faster than an ideal square wave
   a. How many spectral components are deemed significant?
2. Defining significance as keeping at least 50% of an ideal square waves power
   a. Relates to keeping 70% of an ideal square wave's harmonic amplitude
   b. In dB this relates to keeping all amplitudes with less than a 3dB attenuation



Relationship Between Bandwidth of a Square Wave and Its 10-90 Rise Time [3]

BW = 0.35/RT

Cable Routing Test- Step 4

Analytical Model:

Goal: Estimate data rate in kB/s

*Note: analysis does not take into account impedance mismatches, coupling to other line pairs, radiative loss or em interference

Steps:

4. Data rate limitation
   a. Dependent on bandwidth of transmission line

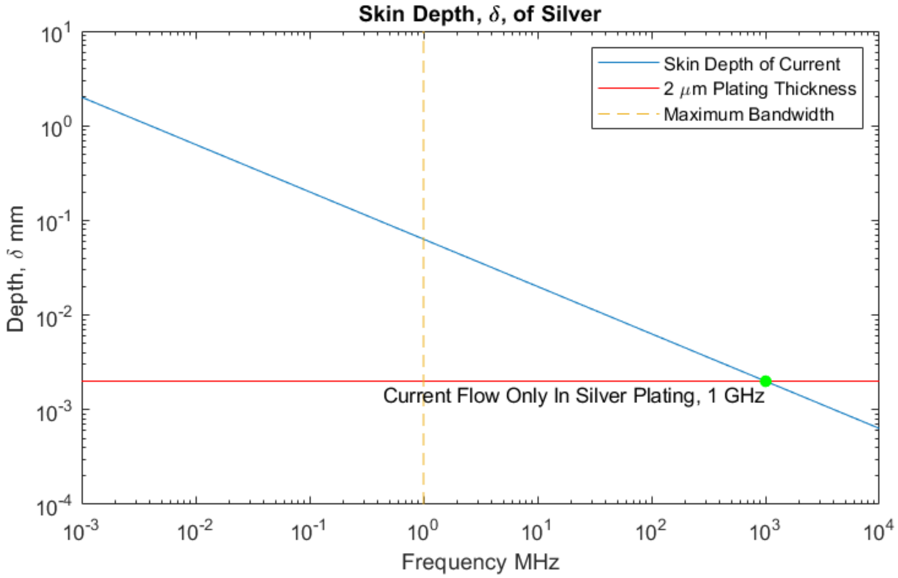
Defining Data Rate Limitation Based on BW

1. Attenuation increases along length of transmission line
   a. Leads to a specific BW for a given length along the line
      i. $\alpha(f) \times d$
2. Using an estimation of the RT being 7% of the clock frequency
   a. $Period_{clock} = RT/0.07 \simeq 15RT$
   b. $Period_{clock} = 15 * 0.35/BW$
   c. $BW_{clock} = 5F_{clock}$

Test Results

Twisted Wire Analysis- Propagation Coef

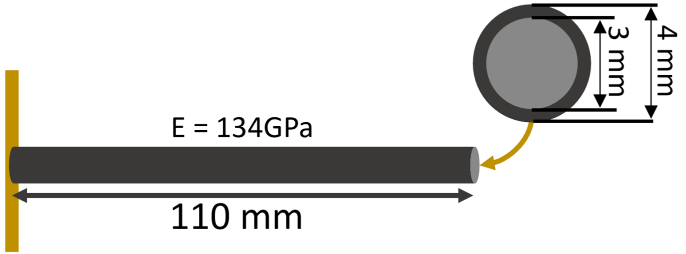
Skin depth explanation



*Showing majority of current flows through copper even at 1 MHz

Single Rod Verification

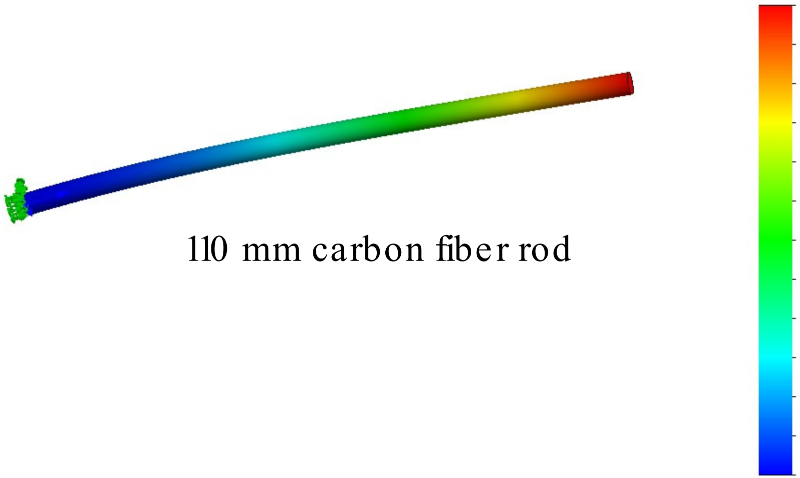
Analytical Method



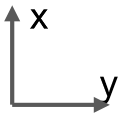
[1] $$I = \frac{\pi}{4}\left(R_0^4 - R_i^4\right)$$

[2] $$f = 0.56\sqrt{\frac{EI}{qL^4}}$$

Solidworks Method



110 mm carbon fiber rod

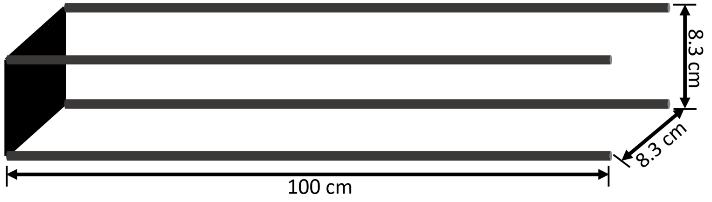


Analytic Result	Solidworks Result	Percent Difference
452.2 Hz	452.6 Hz	0.0885%

Four Rod Verification

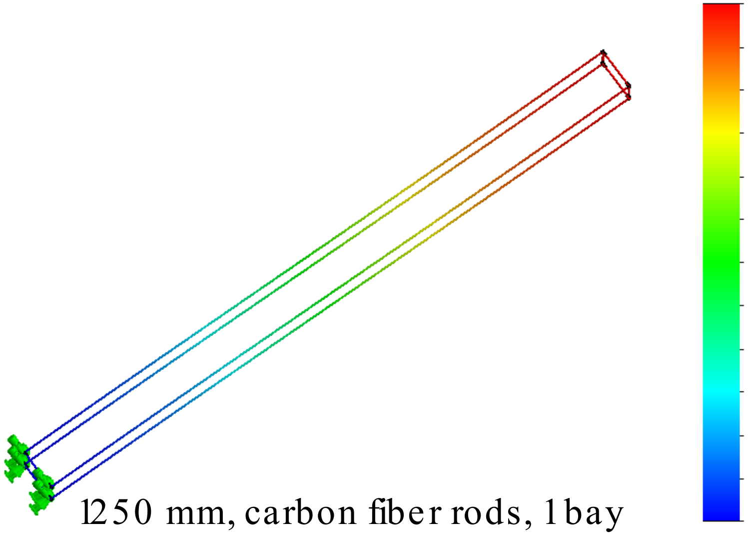
Analytical Method

*Assume: Bending response dominated by longeron axial stiffness.

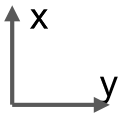


[3] $EI = \frac{n}{2} E A_1 R \qquad f = \sqrt{\frac{EI}{4mL^4}}$

Solidworks Method

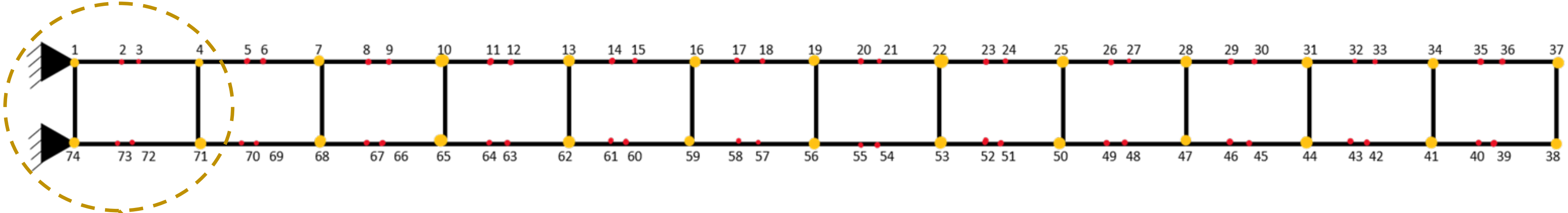


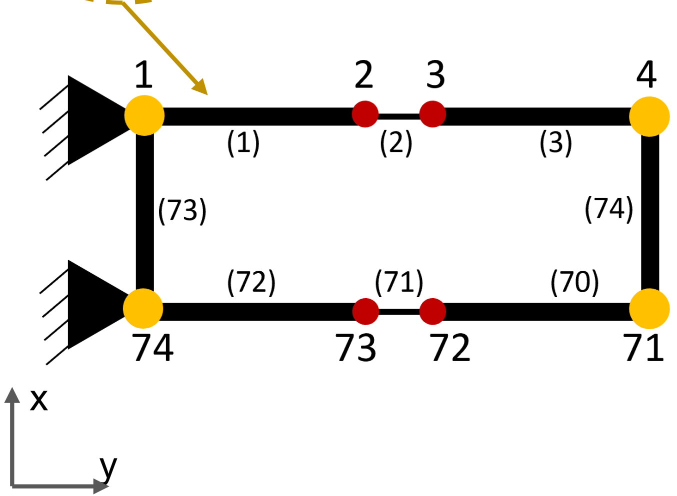
1250 mm, carbon fiber rods, 1 bay



Analytic Result	Solidworks Result	Percent Difference
53.9 Hz	61.1 Hz	13.4%

12 Bay Truss Verification- Direct Stiffness Method (DSM)





Frequency: $[\mathbf{K} - \omega^2 \boldsymbol{M}] = \mathbf{0}$

Global Master Stiffness Matrix (**K**):

- Populated by DSM and Fixed Pointer Method[4]

Mass Matrix (**M**):

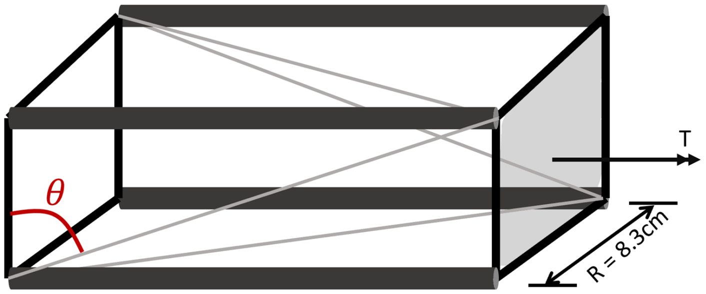
- Populated by Node by Node Lumping Method[5]

Torsion Analysis

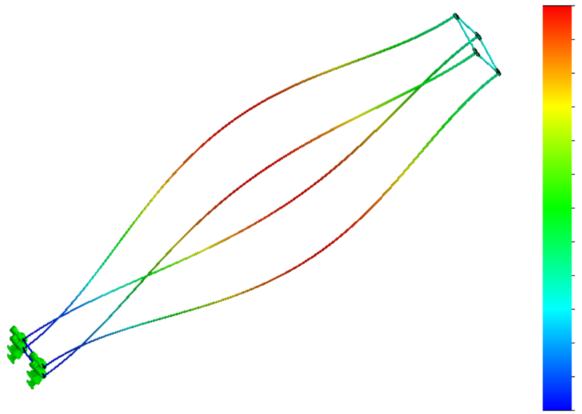
Analytical Method

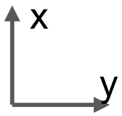
[3] $$GJ = \alpha n E A_d R^2 cos^2\theta sin\theta cos^2\left(\frac{\pi}{n}\right)$$

Diagonal Stiffness — Polar Moment of Inertia



Solidworks Method





Analytic Result	Solidworks Result	Percent Difference
24.5 Hz	21.3 Hz	13.1%

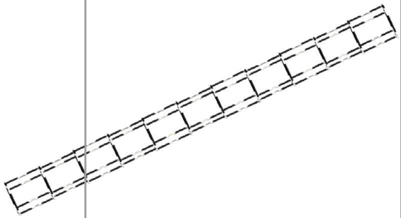
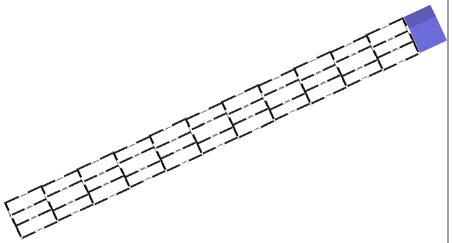
Test Overview

Boom Structure Feasibility- Vibration

Analytical Validation of Solidworks Vibration Analysis for First Resonant Frequency

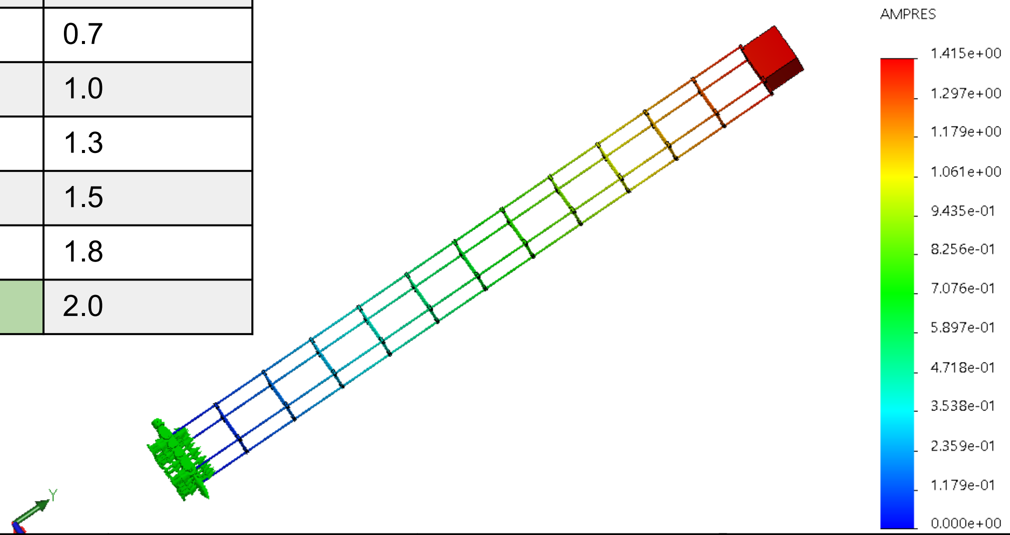
	Simplified Model	Analytic Result	Solidworks Result	Error
Bending	Single Rod, 110 mm, no payload mass	452.2 Hz	452.6 Hz	0.0885%
Bending	4 Rods, 1250 mm, no payload mass	53.9 Hz	61.1 Hz	13.4%
Bending	12 bay truss, 1250 mm, no payload mass	71.6 Hz (in plane)	31.1 Hz	56.6%
	4 Rods, 1250 mm, torsion analysis	24.5 Hz	21.3 Hz	13.1%

Resonant Frequency

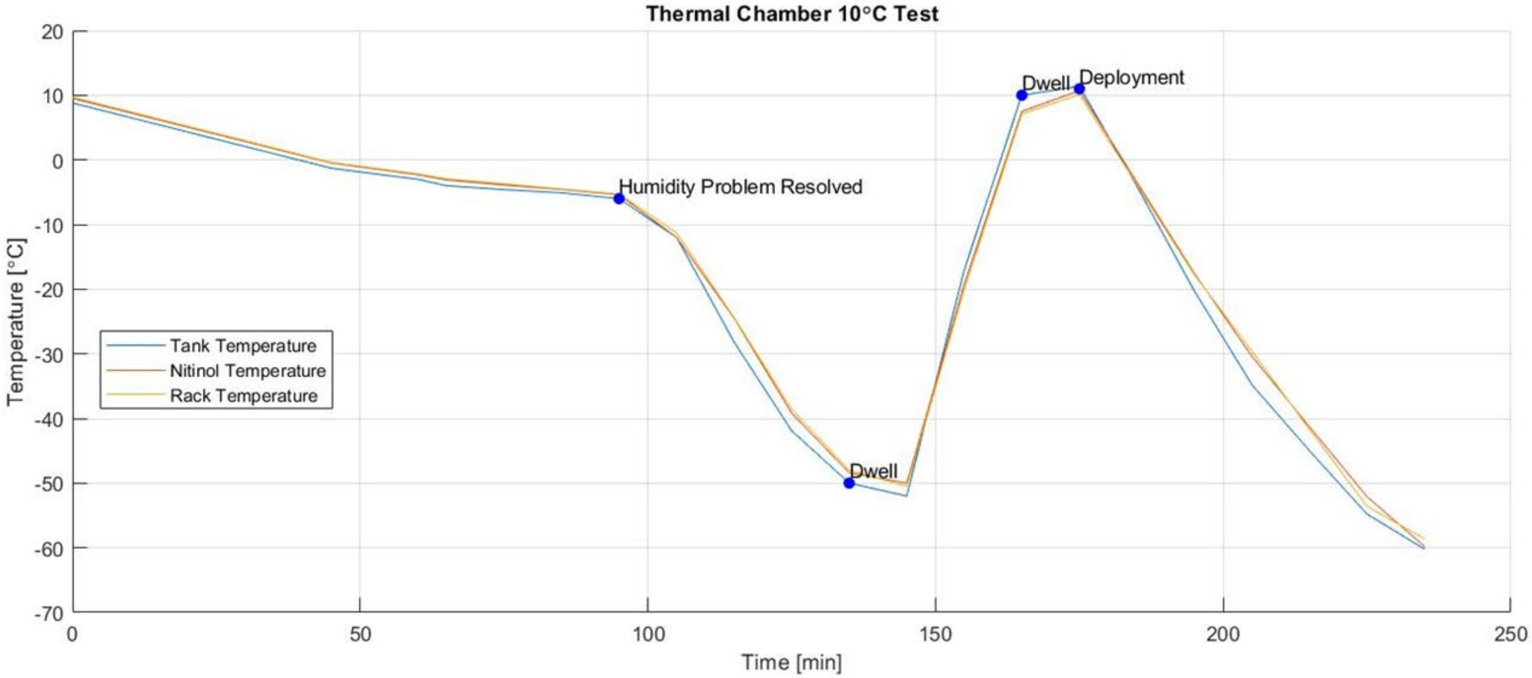
	Single Bay	Full Boom	Full Boom + Instrument
Analytical Method	401.5 Hz	71.6 Hz	N/A
SOLIDWORKS	371.24 Hz	31.1 Hz	8.8 Hz
Ansys	302.5 Hz	N/A	N/A
Visual			

Vibration Analysis with Payload using Solidworks

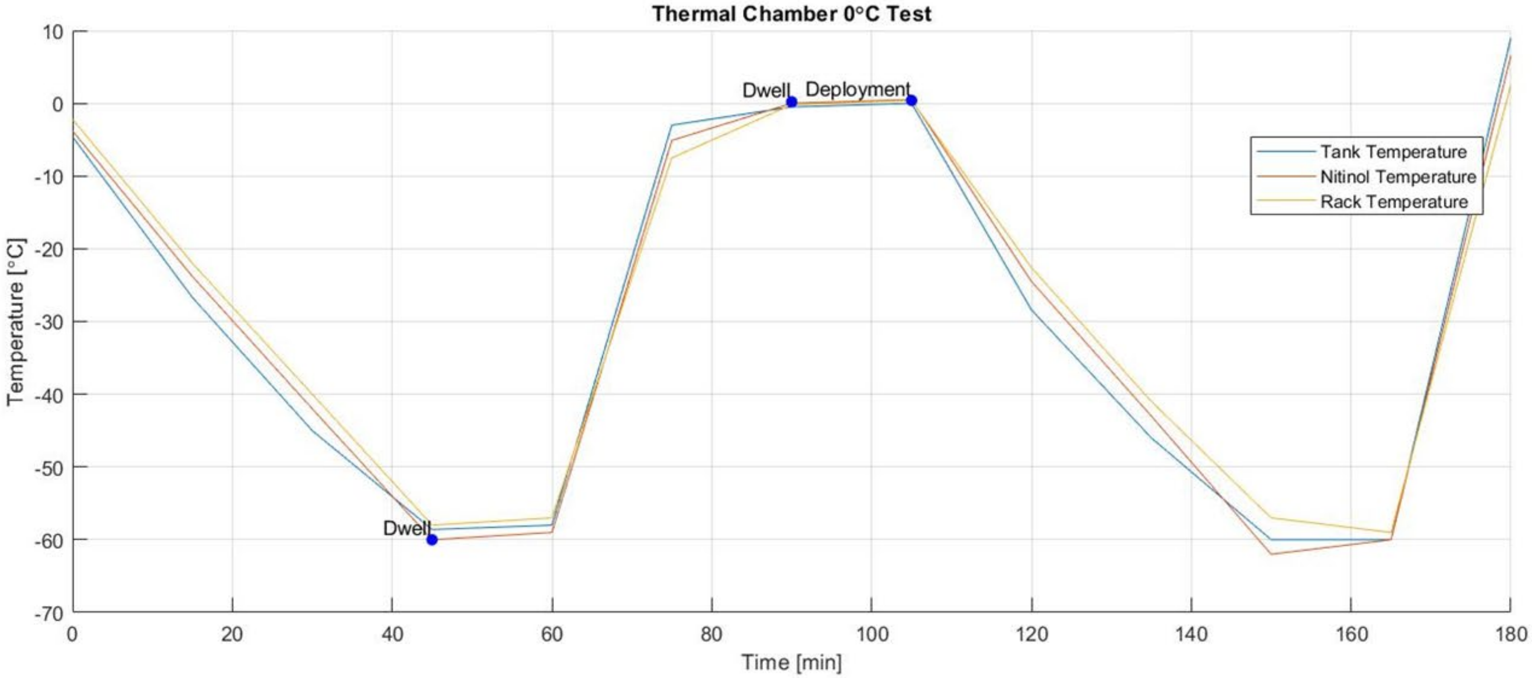
Number of Bays	No Instrument [Hz]	No Instrument - Error [Hz]	500 gram Instrument [Hz]	500 gram Instrument - Error [Hz]
1	236.1	2.25	35.0	0.3
2	111.0	4.59	19.8	0.5
3	76.2	6.75	14.7	0.7
4	56.8	9.00	12.1	1.0
5	46.0	11.25	10.3	1.3
6	38.3	13.50	9.0	1.5
7	31.7	15.75	8.1	1.8
8	27.9	18.00	7.2	2.0



LASP Thermal Test – Temperature Profile 10°C



LASP Thermal Test- Temperature Profile 0℃



Thermal Model