CU Boulder Engineers Creating Universal Boom Extensions for CUBEsats

Customer: Professor Robert Marshall
Advisor: Professor Sanghamitra Neogi
Purpose & Objectives
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

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

Purpose & Objectives

CONCEPT OF OPERATIONS

MASS & DIMENSION TEST
LAUNCH VIBRATION TEST
FULL DEPLOYMENT TEST

PREDEPLOYMENT

BOOM EXTENSION

BOOM RESILIENCE

FULL BOOM EXTENSION

DEPLOYMENT VERIFICATION

THERMAL TEST

CABLE ROUTING TEST

RESONANT FREQUENCY VIBRATION TEST

Phase 01

Phase 02

Phase 03

Phase 04

Launch Vibration Test

(House Ascent)

(Early Exposed)

Pico Electric Hammer

(Attitude Adjustments)


*7 Days
**CUBE³ Project**

**Deployment System**
- Arduino Due
- Relay
- Power Supply
- MATLAB GUI app (on Laptop)

**Boom Structure**
- Nitinol Hinges
- Thermistor

**Telemetry Circuit**
- Photo-Diode Gate
- Pulley

**Payload Connectivity**
- Power Cable
- Data Cable

**Key:**
- Power/Energy
- Data
  - Bought by Team
  - Made by Team

**Deployment Command**
- Deployment Confirmation

**Test Interface**
- Test Personnel
- START
- END
## Critical Project Elements

<table>
<thead>
<tr>
<th>1. <strong>Deployable Boom Structure</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>○ Stow in 1.5U with an 8x8x8 cm, 500 g payload</td>
</tr>
<tr>
<td>○ First resonant frequency ≥ 2.5 Hz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2. <strong>Payload Connectivity</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>○ Power/data cable provisions</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>3. <strong>Software Interface</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>○ Command and telemetry</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>4. <strong>Deployment System</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>○ Deploy on command</td>
</tr>
<tr>
<td>○ Confirm deployment via telemetry</td>
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</tbody>
</table>

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<thead>
<tr>
<th>5. <strong>Environmental Resilience</strong></th>
</tr>
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<tbody>
<tr>
<td>○ LEO radiation/thermal environment</td>
</tr>
<tr>
<td>○ Vibrational launch environment</td>
</tr>
</tbody>
</table>
Baseline Design - Deployment Mechanism

To Boom Top Plate

Polyethylene Burn Rope

Nichrome Burn Wire

Polyethylene Restraining Cord (to top plate)

IR LED and IR Phototransistor

IR LED and IR Phototransistor
Release Pin Stand Alone Testing

Polyethylene Burn Rope and Pin Movement (Nichrome Current = 800 mA)
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
Baseline Design - Test Electronics

- **Not for delivery**
- 3 separate circuits
  - IR LED and phototransistor voltage divider
  - Thermistor voltage divider
  - Burn wire relay
<table>
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<th>Full Deployment</th>
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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

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<tr>
<th>Requirements Under Test</th>
<th>Description</th>
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<tr>
<td>DR_2.1</td>
<td>Boom shall have capability of routing three-wire power setup</td>
</tr>
<tr>
<td>DR_2.2</td>
<td>Boom shall have capability of routing 3 separate differential cables</td>
</tr>
<tr>
<td>FR_2</td>
<td>Boom shall provide routing for power and signal cabling</td>
</tr>
</tbody>
</table>
Cable Routing Test

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

Analytical Model:

Goal: Estimate maximum data rate in kb/s

Preliminary Testing:
- Continuity Check performed successfully
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 (\( d \gg a \)) \(^1\)
  - 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 - \( R'(R_S(f)) \)
  - \( R_S = \sqrt{2\pi f/\sigma_0} \)

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) = \( \text{Real}\{\gamma(f)\} \) \( \text{[Np/m]} \)

Cable Routing Test, Steps 3 and 4

Analytical Model

Goal: Estimate maximum data rate in kb/s

From steps 1 and 2: Attenuation\( f \) = \text{Real}\( \left[ \sqrt{(R(f)' + j\omega L')(G' + j\omega C')} \right] \)

Step 3: Rise Time Defined by Bandwidth

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

Step 4: Data Rate Limitation

- Estimating \( RT_{10-90} \) as 7\% of the digital signal period
  - \( \text{period} = 0.35\mu s/7\% = 5\ \mu s \)
  - \( f = 1/\text{period} = 200\ kHz \)
- 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

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LASP Thermal Chamber

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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

<table>
<thead>
<tr>
<th>Requirements Under Test</th>
<th>Details</th>
</tr>
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<tbody>
<tr>
<td>FR_7</td>
<td>Survive 10 G vibrations in the undeployed state.</td>
</tr>
<tr>
<td>DR_7.1</td>
<td>Survive under the conditions of the launch environment in the undeployed state.</td>
</tr>
</tbody>
</table>

Risk Reduction:
- Ensure that the boom will survive the launch environment and function as expected afterwards
Goal: Determine if restraining cord can survive launch

Max load (12g’s): 70 N
Absolute Max: 15.87 g’s

Launch Environment - Restraining Cord

- Payload: 0.5 kg
- Launch: 10-12 g’s
- Nitinol: 11.12 N
- Restraining Cord

Graph showing Restraining Cord Strength vs g’s.

- g’s vs N line
- 10-12 g range
- Maximum Restraining Cord Capacity
<table>
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</table>
Resonant Frequency Tests

Analytical Method

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

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: \[ [K - \omega^2 M] = 0 \]

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

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

<table>
<thead>
<tr>
<th></th>
<th>Single Rod</th>
<th>Single Bay</th>
<th>Full Boom</th>
<th>+ Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Analytical</strong></td>
<td>452.2 Hz</td>
<td>401.5 Hz</td>
<td>71.6 Hz</td>
<td>-</td>
</tr>
<tr>
<td><strong>SOLIDWORKS</strong></td>
<td>452.6 Hz</td>
<td>371.24 Hz</td>
<td>31.1 Hz</td>
<td>7.22 Hz ± 2 Hz</td>
</tr>
<tr>
<td><strong>Ansys</strong></td>
<td>-</td>
<td>302.5 Hz</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Testing</strong></td>
<td>-</td>
<td>Inconclusive</td>
<td>-</td>
<td>2.6 Hz / 0.5Hz</td>
</tr>
</tbody>
</table>

![Single Rod Diagram](image1.png)

![Instrument Diagram](image2.png)

![Full Boom Diagram](image3.png)
Resonant Frequency Tests

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

Requirements Under Test

| FR_6  | Demonstrate a resonant frequency greater than 2.5 Hz when fully deployed. |

Facilities:
- Electronics shop

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

General Procedure:
- Setup deployed boom on shaker table with accelerometers
  - Data has been processed
- Sweep through low frequencies and measure the driven response
- Hit the boom with a mallet and measure the impulse response
  - Data not yet processed
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
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 1 mm
  - 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
Project Management Systems Engineering Test Results Test Overview Design Description Purpose & Objectives

**LASP Thermal Chamber**

- **Cable Routing**
  - Planned
  - Scheduled
  - Preliminary
  - Completed
  - Processed

- **Launch Environment**
  - Planned
  - Scheduled
  - Preliminary
  - Completed
  - Processed

- **Resonant Frequency**
  - Planned
  - Scheduled
  - Preliminary
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- **Full Deployment**
  - Planned
  - Scheduled
  - Preliminary
  - Completed
  - Processed

- **Mass / Dimension**
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  - Preliminary
  - Completed
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- **LASP Thermal Chamber**
  - Planned
  - Scheduled
  - Preliminary
  - Completed
  - Processed

---

**Test Overview**
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, +/- 1 cm
- 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

Risk Reduction:
- Proves that the boom assembly fully deploys as intended and demonstrates designed capabilities
Full Deployment Test

1. **STOWED**
   - CUBE\(^3\) Shell

1. **DEPLOYMENT COMMANDED**
   - CUBE\(^3\) Shell

1. **DEPLOYMENT IN PROGRESS**
   - CUBE\(^3\) Shell

1. **DEPLOYMENT COMPLETE**
   - CUBE\(^3\) Shell
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

The graphs show the displacement, velocity, and acceleration over time. The displacement graph indicates the movement in both the X and Y directions. The velocity graphs show the velocity in the X and Y directions. The acceleration graph shows the total acceleration in the X, Y, and total directions.

The analysis focuses on the Test Results with detailed graphs illustrating the movement and acceleration patterns during the full deployment test.
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
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</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Requirements Under Test</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR_3.1</td>
<td>Stow with a length less than or equal to 15 cm, including instrument</td>
</tr>
<tr>
<td>DR_3.2</td>
<td>Stow with a height less than or equal to 10 cm, including instrument</td>
</tr>
<tr>
<td>DR_3.3</td>
<td>Stow with a width less than or equal to 10 cm, including instrument</td>
</tr>
<tr>
<td>DR_3.4</td>
<td>Provide 6 mm by 6 mm accommodation space at each corner for NanoRacks guide rails</td>
</tr>
<tr>
<td>FR_9</td>
<td>The whole system, including instrument, will have a maximum total mass of 2kg</td>
</tr>
</tbody>
</table>
## Mass/Dimension Test

<table>
<thead>
<tr>
<th>Req. ID</th>
<th>Expected Result</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR_3.1</td>
<td>Length = 15 cm</td>
<td>Length = 14.99 cm</td>
</tr>
<tr>
<td>DR_3.2</td>
<td>Height = 10 cm</td>
<td>Height = 9.95 cm</td>
</tr>
<tr>
<td>DR_3.3</td>
<td>Width = 10 cm</td>
<td>Width = 9.95 cm</td>
</tr>
<tr>
<td>DR_3.4</td>
<td>Guide Rail Space = 6 mm x 6 mm</td>
<td>Guide Rail Space = 6 mm x 6 mm</td>
</tr>
<tr>
<td>FR_9</td>
<td>Mass ≤ 2 kg</td>
<td>Mass = 0.89 kg</td>
</tr>
</tbody>
</table>
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 °C
- Ramp up to 10 °C
- Deploy Boom
- Ramp down to -60 °C
- 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.

<table>
<thead>
<tr>
<th></th>
<th>Temp Max</th>
<th>Temp Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>STK</td>
<td>56 °C</td>
<td>-76 °C</td>
</tr>
<tr>
<td>MATLAB</td>
<td>10 °C</td>
<td>-60 °C</td>
</tr>
</tbody>
</table>

Manufacturer specifies super elasticity lost at -10°C

Deployment temperatures tested are: -10°C, 0°C, 10°C
LASP Thermal Chamber Test

<table>
<thead>
<tr>
<th>Temperature</th>
<th>No Deployment</th>
<th>Partial Deployment</th>
<th>Full Deployment</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10 °C</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 °C</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 °C</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>10 °C</td>
<td></td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>

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

Established Deployment Temperature

-10 °C No Deployment

5 °C Partial Deployment

10 °C Full Deployment
LASP Thermal Chamber Test

Video of Thermal Deployment at 10°C
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
**Analysis** indicates greater than 1 year lifespan on orbit.

**DR_8.1** Survive under the thermal fluctuations of space

**DR_8.2** Survive under the radiation of space

**FR_8** Survive for one year of deployment in the space environment

---

**DR_1.1** Attach a 500 g or less instrument with dimensions 8 x 8 x 8 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_1.1** Attach a 500 g or less instrument with dimensions 8 x 8 x 8 cm

**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_2.1** Accommodate a 12 wire set up

**FR_2** Accommodate a 12 wire set up

**FR_3** Stow in less than 1.5U, including instrument

---

**FR_6** Demonstrate a resonant frequency ≥ 2.5 Hz 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_4** The boom assembly can inform the spacecraft of a successful deployment or not

---

**FR_6** Demonstrate a resonant frequency ≥ 2.5 Hz 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_4** The boom assembly can inform the spacecraft of a successful deployment or not

---

**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

**FR_8** Survive for one year of deployment in the space environment

---

**Design Requirements (Short Text)**

**DR_3** Length ≥ 15 cm

**DR_3.1** Length ≥ 15 cm

**DR_3.2** Height ≥ 10 cm

**DR_3.3** Width ≥ 15 cm

**SR_1.4.1** Acceleration Limit of the attached instrument will not exceed 10 G's

---

**Functional Requirements (Short Text)**

**FR_3** Stow in less than 1.5U, including instrument

**FR_6** Demonstrate a resonant frequency ≥ 2.5 Hz 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_6** Demonstrate a resonant frequency ≥ 2.5 Hz 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

---

**Customer Requirements**

---

**Critical Project Elements**

---

**Factors of Concern**
## Key Trade Study: Design Baseline Concept

<table>
<thead>
<tr>
<th>Trade</th>
<th>Weight</th>
<th>ISS-Like</th>
<th>Stackable</th>
<th>Inch Worm</th>
<th>Coilable Truss</th>
<th>Screw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>10%</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Manufacturability</td>
<td>20%</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Complexity</td>
<td>20%</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Heritage</td>
<td>15%</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Rigidity</td>
<td>15%</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Team Knowledge</td>
<td>20%</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>4.6</td>
<td>4.3</td>
<td>3.9</td>
<td>4.4</td>
<td>3.8</td>
</tr>
</tbody>
</table>
## Key Trade Studies: Deployment Telemetry

<table>
<thead>
<tr>
<th>Trade</th>
<th>Weight</th>
<th>LiDAR Module</th>
<th>Electric Sensor</th>
<th>Camera</th>
<th>Break-Wire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>10%</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Volume</td>
<td>15%</td>
<td>5</td>
<td>5</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Team Knowledge</td>
<td>20%</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Risk</td>
<td>20%</td>
<td>2</td>
<td>4</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Accuracy</td>
<td>35%</td>
<td>5</td>
<td>5</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100%</strong></td>
<td><strong>84%</strong></td>
<td><strong>96%</strong></td>
<td><strong>56%</strong></td>
<td><strong>91%</strong></td>
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</tbody>
</table>
### Key Trade Studies: Deployment Progress Sensor

<table>
<thead>
<tr>
<th>Trade</th>
<th>Weight</th>
<th>Snap Switch</th>
<th>IR Sensor</th>
<th>Optical Encoder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical Complexity (0-5)</td>
<td>30%</td>
<td>2</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Redundancy Opportunity (0-1)</td>
<td>10%</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Software Complexity (0-5)</td>
<td>10%</td>
<td>5</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Power Draw (0-5)</td>
<td>10%</td>
<td>5</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Size (0-5)</td>
<td>40%</td>
<td>1</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100%</td>
<td><strong>40%</strong></td>
<td><strong>96%</strong></td>
<td><strong>74%</strong></td>
</tr>
</tbody>
</table>
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

Deployment Mechanism
Cable Routing Hook

Boom Assembly
Cable Coils
<table>
<thead>
<tr>
<th></th>
<th>Probability</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>9. Test Execution</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>2. Cold Environment</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>7. Manufacturing Schedule Slip</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>3. Nitinol Failure</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>12. Temperature Flux Induced Failure</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>4. Radiation/UV</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>13. Budget Overload</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>11. Cold Welding</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>5. Test Unavailability</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>10. Deployment Release Failure</td>
<td>1</td>
<td>5</td>
</tr>
</tbody>
</table>

**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
Project Management

Purpose & Objectives
Design Description
Test Overview
Test Results
Systems Engineering
Project Management
Organizational Chart

Project Manager
Rowan Gonder

Finance Lead
Travis Peccorini

Systems Engineer
Michael Burke

Project Advisor
Sanghamitra Neogi

Project Customer
Robert Marshall

Electrical Lead
Evan Johnson

Software Lead
Roger Heller

Environmental Lead
Michael Strong

Test Lead
Venus Gonder

Structures Lead
Britnee Staheli

Manufacturing Lead
Collin Doster

Quality Assurance Lead
Adam Hu

Risk Management Lead
Ben Pearson
Team Hours Worked

Total: 5267 Hours
## Project Budget Evolution

### Margin Analysis

<table>
<thead>
<tr>
<th>Margin Analysis</th>
<th>CDR</th>
<th>+ Contingency</th>
<th>Final</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Best Estimate</td>
<td>$5,000.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Expected Value</td>
<td>$4,500.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Possible Value</td>
<td>$5,000.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final</td>
<td>$4,000.00</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Project Budget Evolution

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

Materials Cost Breakdown

- Machine Shop: 9.5%
- Shipping: 8.1%
- LASP: 4.7%
- Wiring: 10.9%
- Nitinol: 8.0%
- Carbon Fiber: 17.1%
- Tooling:
  - Hardware: 7.1%
  - Epoxy: 4.9%
  - PEEK: 20.9%

Total Project Cost Breakdown

- Materials: 1.1%
- Salary: 98.9%

Total: $332,774.84

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.
- Overall, 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

71. Materials
72.-75. Cable Routing
76. Twisted Wire Analysis
77.-83. Resonant Frequency Analysis
84.-86. Thermal Chamber Analysis
# Environmental - Structure Material

<table>
<thead>
<tr>
<th>Material</th>
<th>Temp Range °C</th>
<th>Radiation</th>
<th>Outgassing</th>
</tr>
</thead>
</table>
| 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°C | High UV tolerance    | Low outgassing         |
Cable Routing Test - Step 1

Steps:
1. Circuit Equivalent Model
   a. Find: \( R', G', C', L' \)

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

\[
\frac{L'}{\Delta t} \Delta v_{n+1} - \frac{L'}{\Delta t} \Delta v_{n} \rightarrow \frac{\partial v(t,z)}{\partial t} \quad \Rightarrow \quad L' \frac{\partial v(t,z)}{\partial t} = \frac{v_{n+1} - v_{n}}{\Delta z} = 0
\]

A solution to the differential equation:

\[
V(z) = V_+ e^{-j\beta z} + V_- e^{j\beta z}
\]
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 wave's 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 1090 Rise Time \([3]\)

\[
\text{BW} = \frac{0.35}{\text{RT}}
\]
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. $\text{Period}_{\text{clock}} = \frac{RT}{0.07} \approx 15RT$
   b. $\text{Period}_{\text{clock}} = 15 \times 0.35 / \text{BW}$
   c. $\text{BW}_{\text{clock}} = 5F_{\text{clock}}$
Twisted Wire Analysis- Propagation Coef

Skin depth explanation

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

Analytical Method

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

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

Solidworks Method

110 mm carbon fiber rod

<table>
<thead>
<tr>
<th>Analytic Result</th>
<th>Solidworks Result</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>452.2 Hz</td>
<td>452.6 Hz</td>
<td>0.0885%</td>
</tr>
</tbody>
</table>
Four Rod Verification

Analytical Method

*Assume: Bending response dominated by longeron axial stiffness.

\[ EI = \frac{n}{2} E A_l R \]
\[ f = \sqrt{\frac{EI}{4mL^4}} \]

Solidworks Method

1250 mm, carbon fiber rods, 1 bay

<table>
<thead>
<tr>
<th>Analytic Result</th>
<th>Solidworks Result</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>53.9 Hz</td>
<td>61.1 Hz</td>
<td>13.4%</td>
</tr>
</tbody>
</table>
12 Bay Truss Verification - Direct Stiffness Method (DSM)

Frequency: \[ [K - \omega^2 M] = 0 \]

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

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

Diagonal Stiffness
Polar Moment of Inertia

Solidworks Method

<table>
<thead>
<tr>
<th>Analytic Result</th>
<th>Solidworks Result</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.5 Hz</td>
<td>21.3 Hz</td>
<td>13.1%</td>
</tr>
</tbody>
</table>

Test Overview

80
## Analytical Validation of Solidworks Vibration Analysis for First Resonant Frequency

<table>
<thead>
<tr>
<th>Simplified Model</th>
<th>Analytic Result</th>
<th>Solidworks Result</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Rod, 110 mm, no payload mass</td>
<td>452.2 Hz</td>
<td>452.6 Hz</td>
<td>0.0885%</td>
</tr>
<tr>
<td>4 Rods, 1250 mm, no payload mass</td>
<td>53.9 Hz</td>
<td>61.1 Hz</td>
<td>13.4%</td>
</tr>
<tr>
<td>12 bay truss, 1250 mm, no payload mass</td>
<td>71.6 Hz (in plane)</td>
<td>31.1 Hz</td>
<td>56.6%</td>
</tr>
<tr>
<td>4 Rods, 1250 mm, torsion analysis</td>
<td>24.5 Hz</td>
<td>21.3 Hz</td>
<td>13.1%</td>
</tr>
</tbody>
</table>
## Resonant Frequency

<table>
<thead>
<tr>
<th></th>
<th>Single Bay</th>
<th>Full Boom</th>
<th>Full Boom + Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Analytical Method</strong></td>
<td>401.5 Hz</td>
<td>71.6 Hz</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>SOLIDWORKS</strong></td>
<td>371.24 Hz</td>
<td>31.1 Hz</td>
<td>8.8 Hz</td>
</tr>
<tr>
<td><strong>Ansys</strong></td>
<td>302.5 Hz</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Visual</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Vibration Analysis with Payload using Solidworks

<table>
<thead>
<tr>
<th>Number of Bays</th>
<th>No Instrument [Hz]</th>
<th>No Instrument - Error [Hz]</th>
<th>500 gram Instrument [Hz]</th>
<th>500 gram Instrument - Error [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>236.1</td>
<td>2.25</td>
<td>35.0</td>
<td>0.3</td>
</tr>
<tr>
<td>2</td>
<td>111.0</td>
<td>4.59</td>
<td>19.8</td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>76.2</td>
<td>6.75</td>
<td>14.7</td>
<td>0.7</td>
</tr>
<tr>
<td>4</td>
<td>56.8</td>
<td>9.00</td>
<td>12.1</td>
<td>1.0</td>
</tr>
<tr>
<td>5</td>
<td>46.0</td>
<td>11.25</td>
<td>10.3</td>
<td>1.3</td>
</tr>
<tr>
<td>6</td>
<td>38.3</td>
<td>13.50</td>
<td>9.0</td>
<td>1.5</td>
</tr>
<tr>
<td>7</td>
<td>31.7</td>
<td>15.75</td>
<td>8.1</td>
<td>1.8</td>
</tr>
<tr>
<td>8</td>
<td>27.9</td>
<td>18.00</td>
<td>7.2</td>
<td>2.0</td>
</tr>
</tbody>
</table>
LASP Thermal Test: Temperature Profile 10°C
LASP Thermal Test - Temperature Profile 0°C
Thermal Model

Outer Shell and Inner Boom Temperatures over 2 Orbits

Temperature [°C]

Time from Start of Eclipse [min]