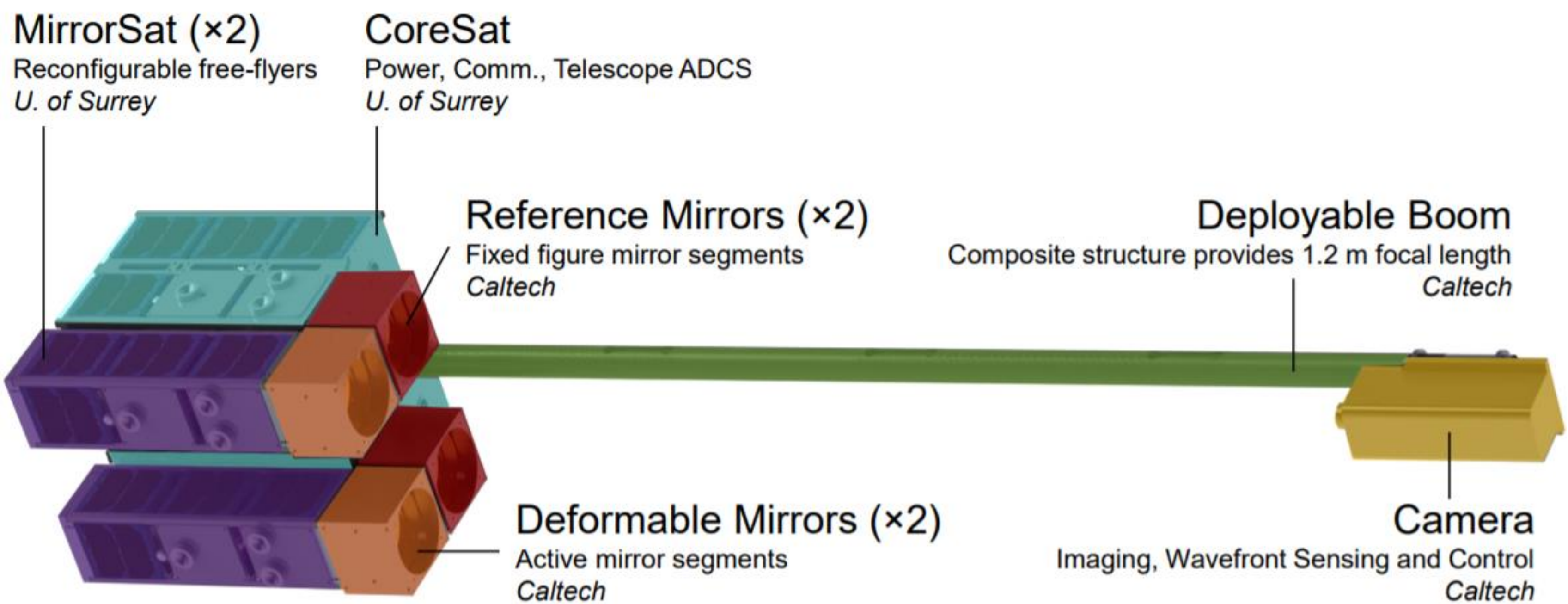
# AAReST Coresat Detailed Design Review

September 11 2017

# AAReST Subsystems




| | | | |
|---|---|---|---|
| Mass: <40 kg | Prime focus telescope | UHF down (9600 bps) | Ref. orbits: |
| Launch Volume: 46 × 34 × 30 cm | 465 nm – 615 nm bandpass | VHF up (1200 bps) | ~650 km SSO |
| Camera: 10 × 10 × 25 cm | 0.34° field of view | S-Band & Zigbee ISL | ISS (400 km, |
| Boom: Ø 3.8 cm,1.5 m long | 1.2 m focal length | | 52 deg. incl.) |

# Presentation Agenda

- Telescope Overview
- Deformable Mirrors
- Camera Instrument
- Mirror boxes Overview
- Electronics
- Software
- Boom Subsystem

# Outline

- Review of Optomechanical Design
- Telescope Requirements
- Optical Systems status
  – RMs, DMs, Camera Lens Assembly
- Overview of Active Element Control
  – Rigid Body Actuation
  – DM actuator control and measurement with SHWFS



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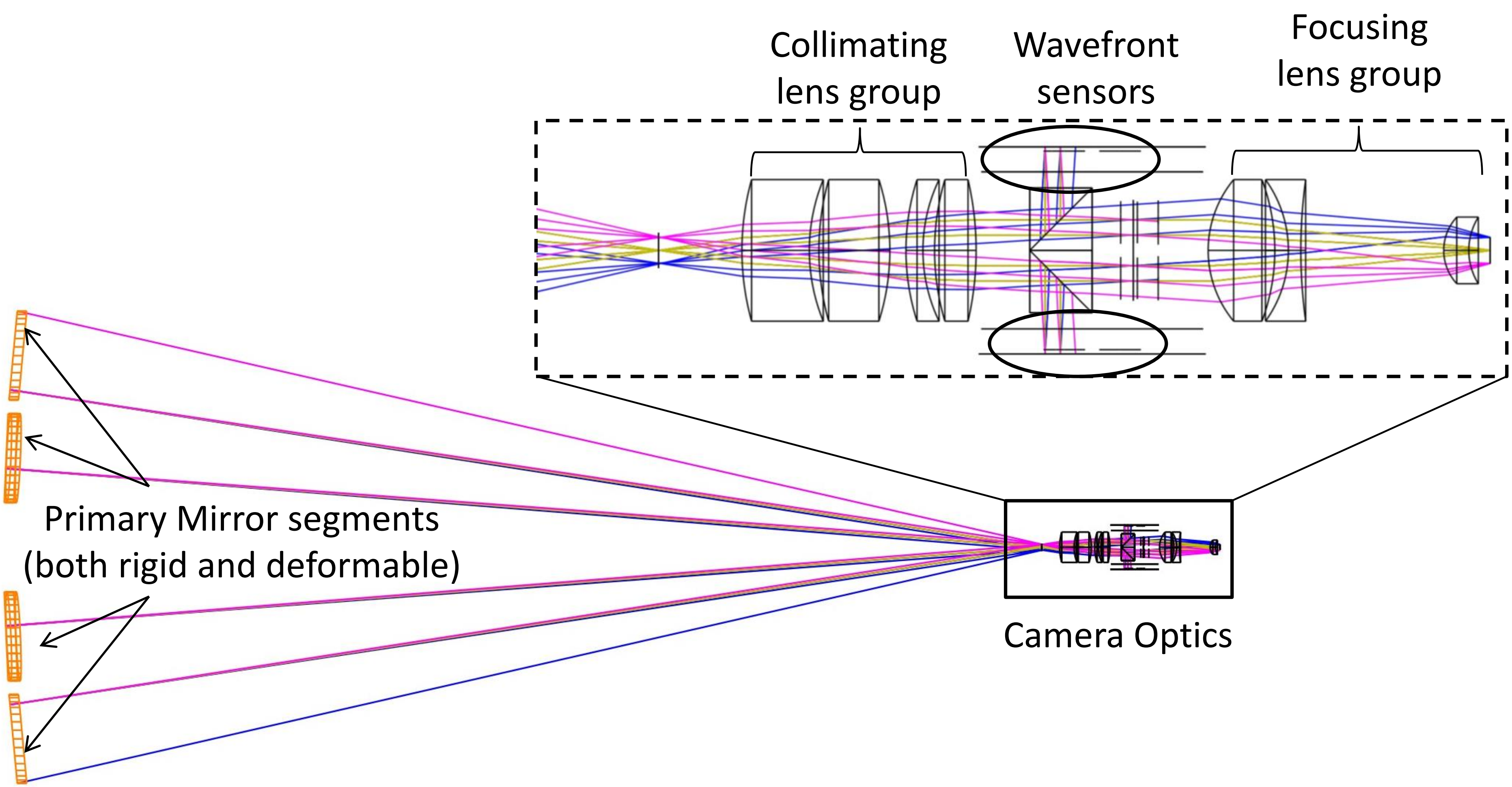
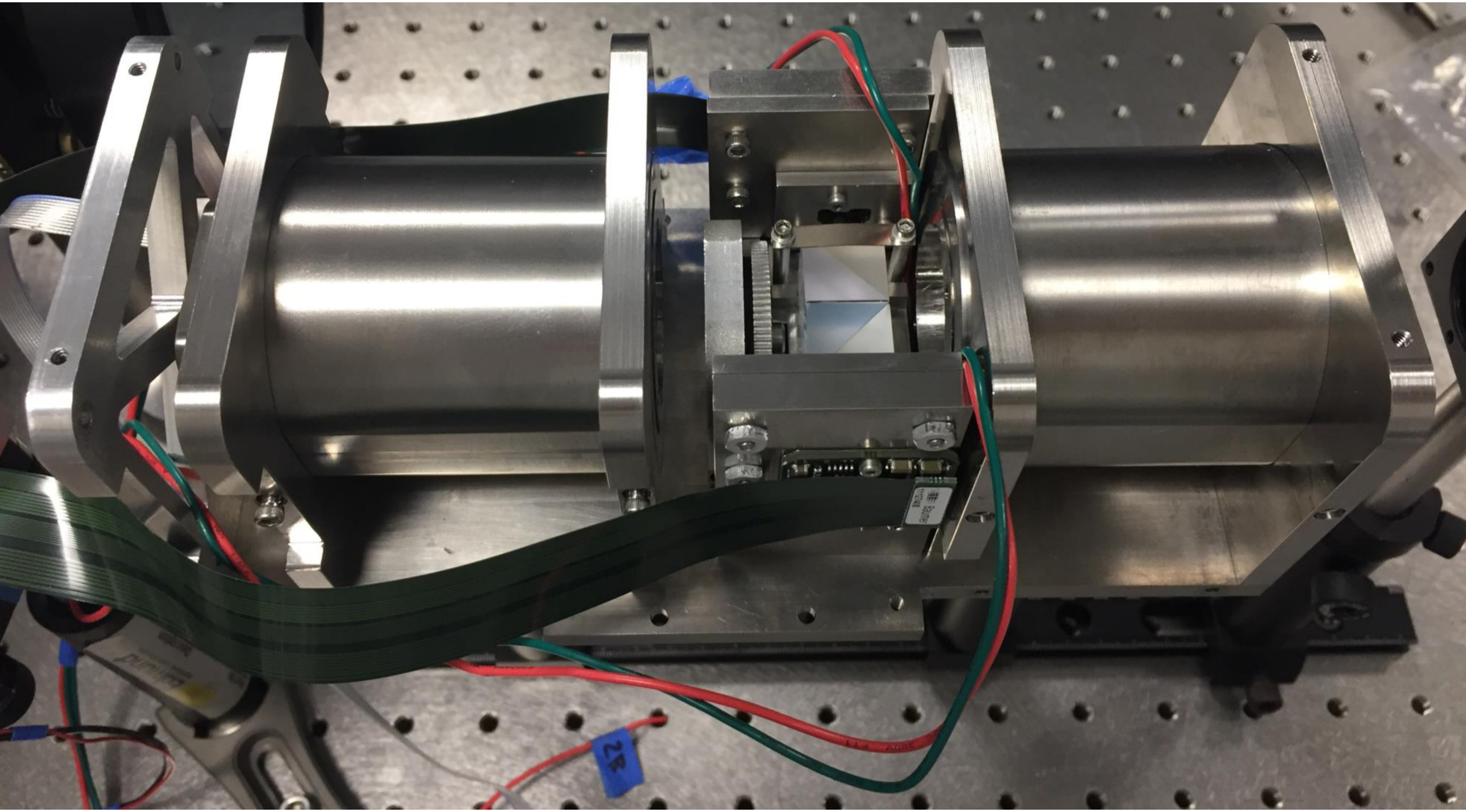
# Baseline Requirements

- Science Camera field of view: 0.34$^{o}$ across diagonal
- PSF of each mirror Segment: 80% encircled energy in 50μm diameter circle.
- Signal to Noise ratio: >100/lenslet for 50μs exposure on Shack-Hartmann WFSs and >100 on science imager for magnitude 2 stars or brighter

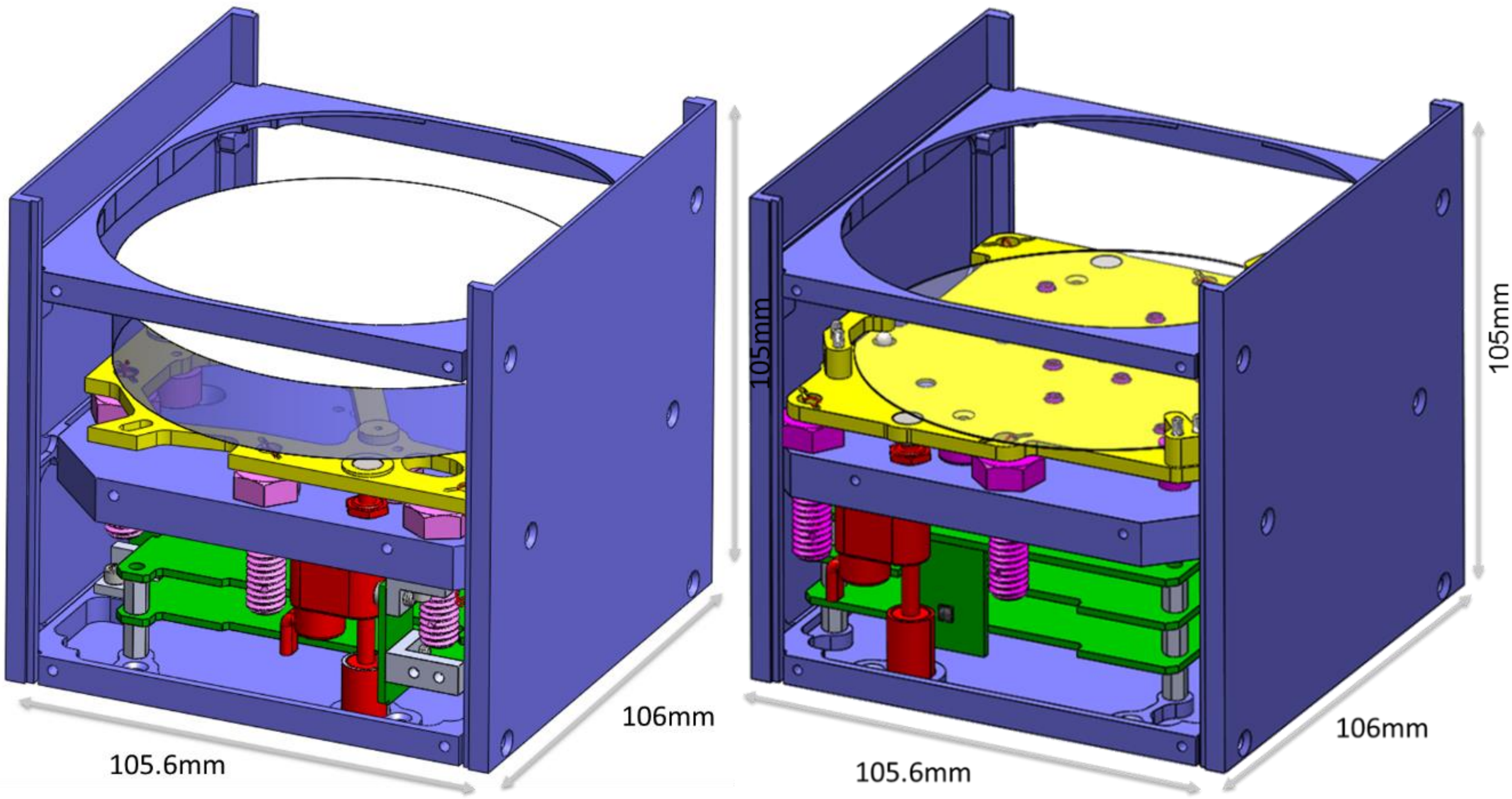
# Optical System Overview



# Camera



# Mirror Boxes



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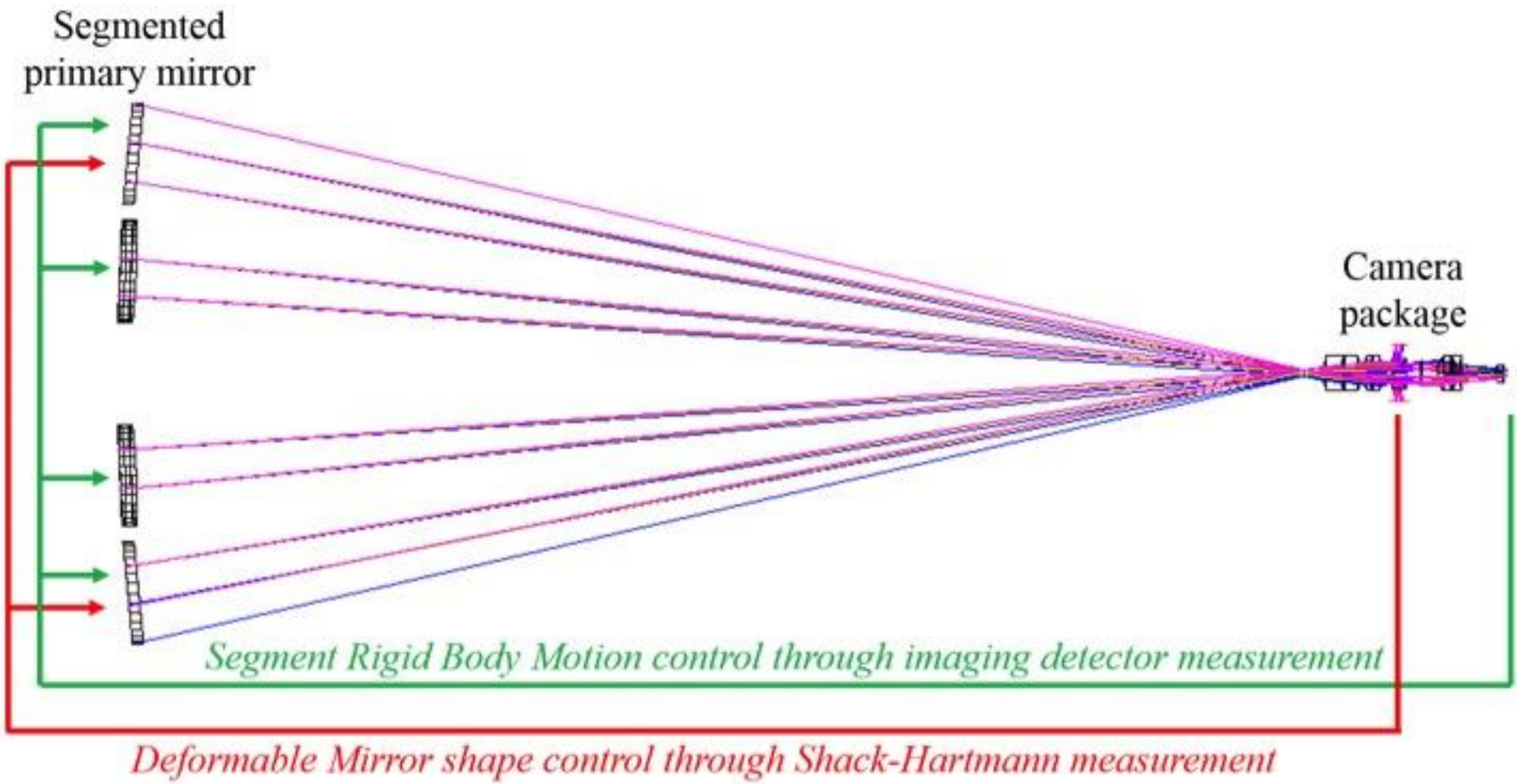
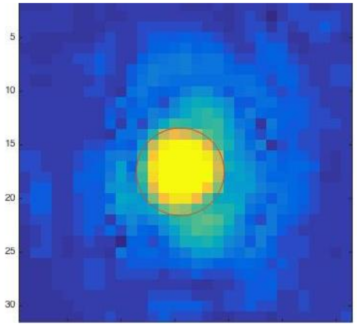
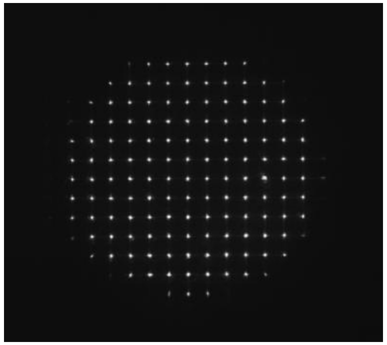
# Active Element Control



# Optical Systems Status




- Theoretical performance prediction
  - Science cam SNR  = 116
  - WFS SNR = 110/lenslet
- Camera Lens assembly
  - Verify lenses are manufactured and aligned correctly
- Rigid Mirrors
  - Integration into testbed with science imager for coarse alignment and SHWFS for fine WFE measurement
- Deformable Mirrors
  - Characterization using high order wavefront sensing
  - Integration into testbed with SHWFS readout
  - Active control in testbed using some flight like electronics.



# Active Element Control

- Rigid body control with three linear actuators per mirror segment
  - Flight like electronics complete
  - Active in mirror boxes on testbed
- Deformable Mirror actuators controlled using proto-flight electronics
  - Flight like electronics and software ready for integration
  - Shape measurement with SHWFS

# Summary

- Optical system has been shown be designed to meet baseline requirement.
- Camera Assembly and lenses are verified.
- Throughput has been computed to meet requirements (test results to follow).
- Rigid mirrors alignment and figure have been verified to produce a PSF that meets requirements and matches simulation.
- DMs are in progress and actuator control is being integrated.

# Future Work

- Bond rigid mirrors to mirror plate and remove temporary mounts
- Execute calibration and closed loop control of DMs using flight camera and SHWFS.

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# Requirements

In closed loop, DM must focus 80% of point source energy to <50 μm diameter spot at focal plane

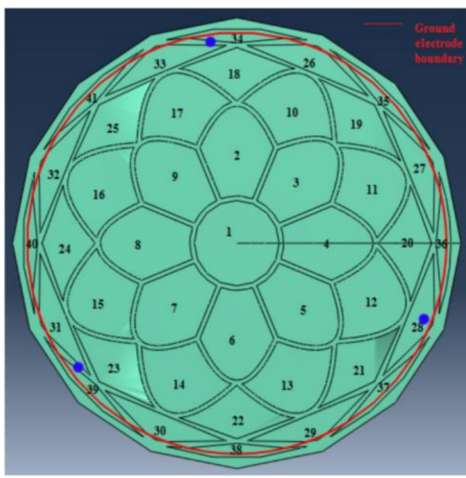
- Initial shape
  - Measured 2.6 μm RMS shape error.  (<30 μm RMS defocus is correctable)
  - Radius of curvature ( +/-6 inch RoC is correctable)
  - High order error (dimples etc.)
    - Must be measurable with SHWS
    - Minimal impact on encircled energy
- Actuation
  - For perfectly spherical optic we need ~3 μm stroke to achieve hyperboloid optical prescription
  - To test real mirror with shape error, we will test with AAReST camera in telescope testbed

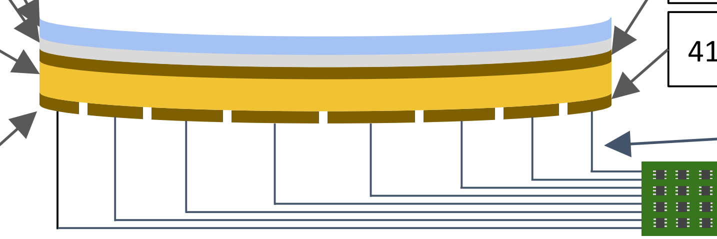
# DM design - PZT and glass

200 µm slumped D263 Schott glass

10 µm glass bead filled Epotek 301 epoxy

300 µm curved piezoceramic meniscus
(PZT5A NCE51 from Noliac)



Ground plane

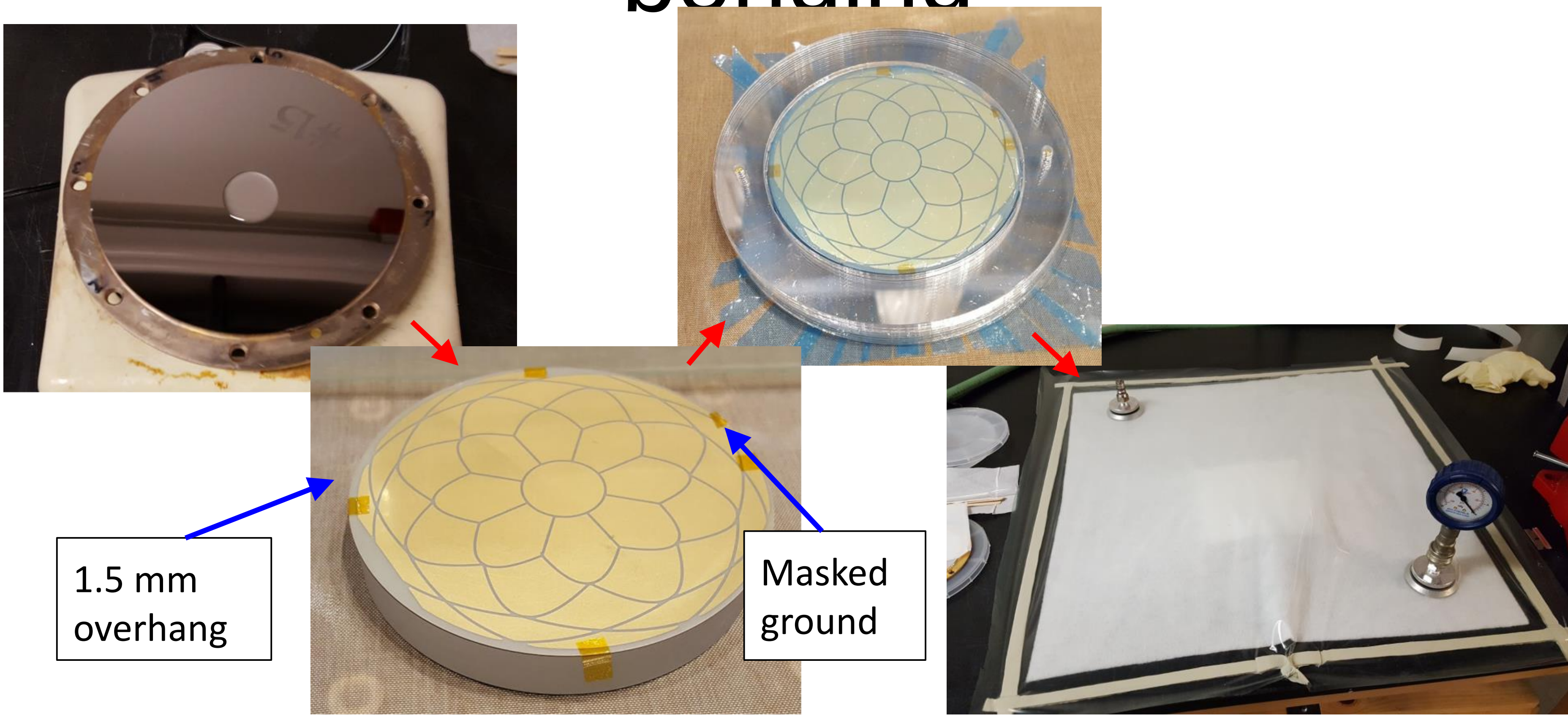
41 patterned electrodes

Routing flex circuit

HV Multiplexer

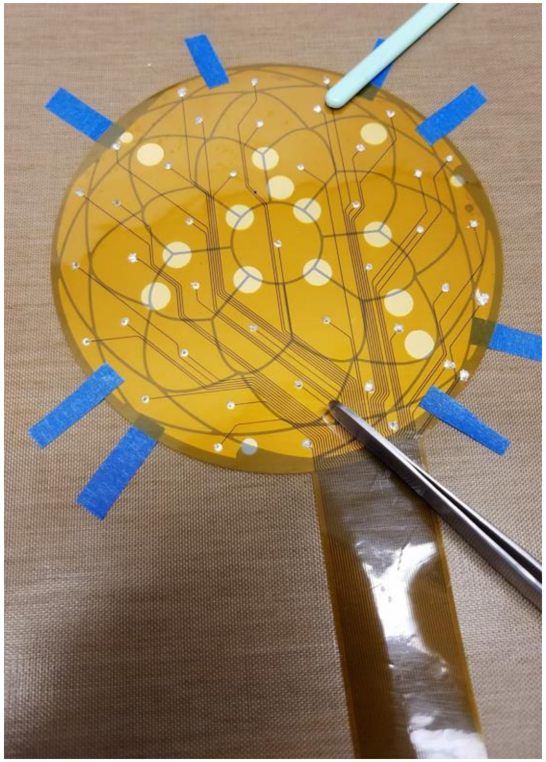
Side view

# Fabrication - Vacuum bag bonding



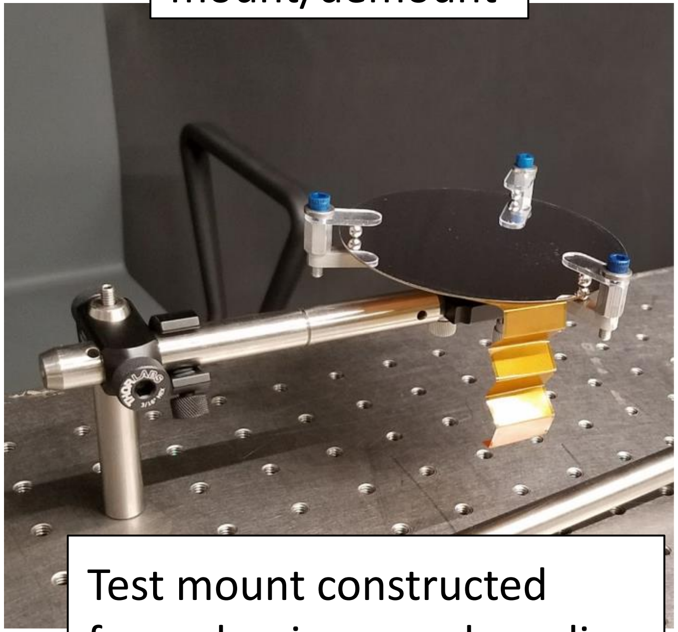
# Fabrication - Electrical routing layer bonding

- Electrical routing layer
  - 0.5 oz copper
  - 1 mil base Kapton
  - 1 mil Kapton coverlay
- Connector
  - TE connectivity
  - 42 pos. 0.5 pitch FFC
- MG Chemicals silver epoxy dripped into vias
  - Add acetone to improve flow
  - Room temperature cure
  - Tape is not tensioned!



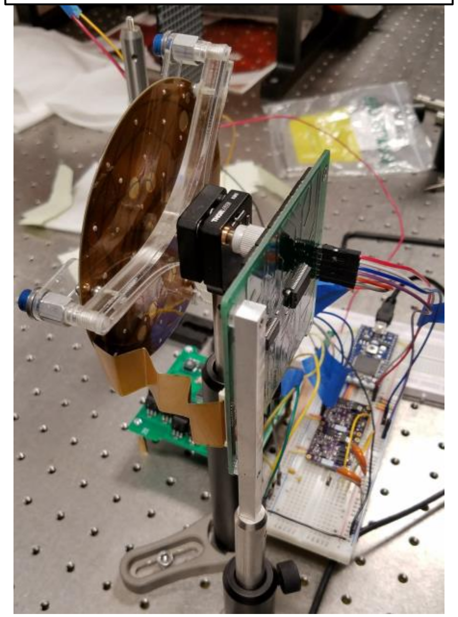
# Fabricated hardware

DM mount/demount

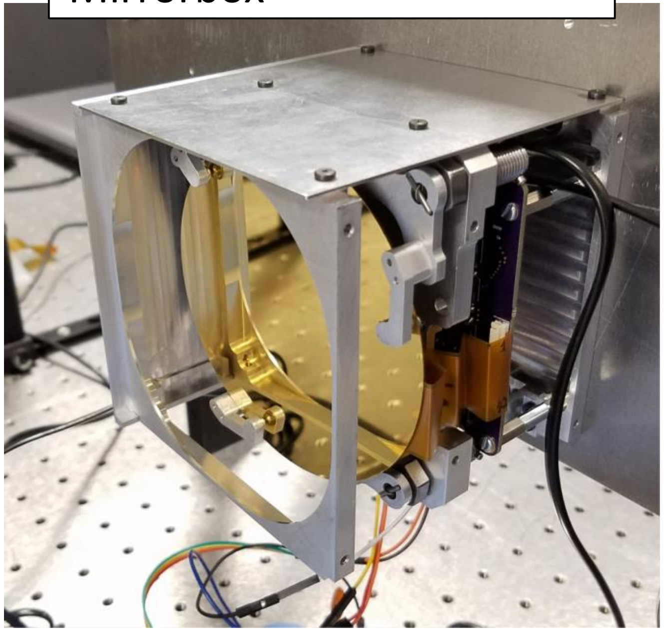


Test mount constructed from aluminum and acrylic to avoid stray magnetic torques on mirror

Phaesics testbed mount

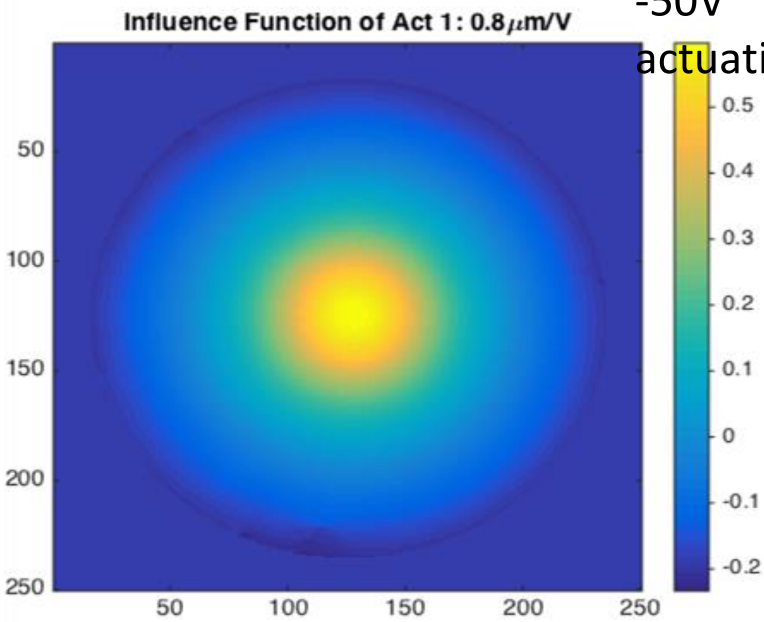


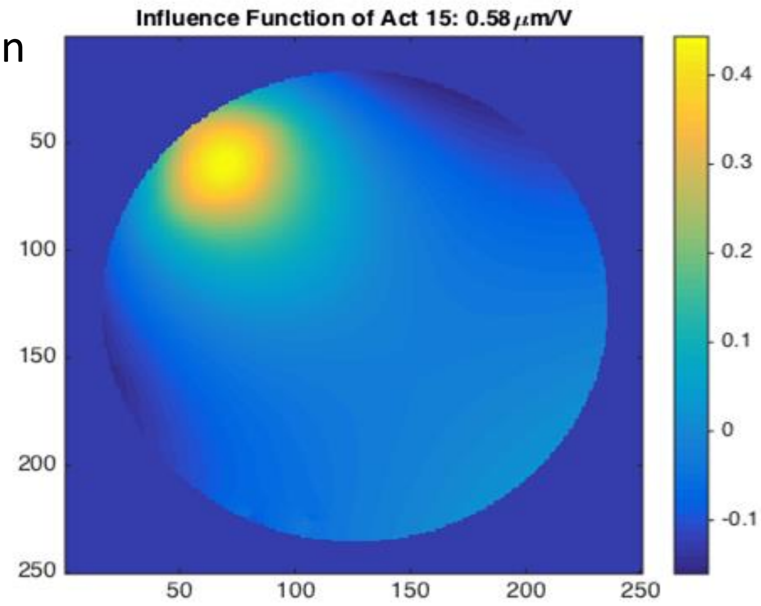
AAReST Deformable Mirrorbox



# Testing - Actuation of PZT1GSF3

-50V actuation



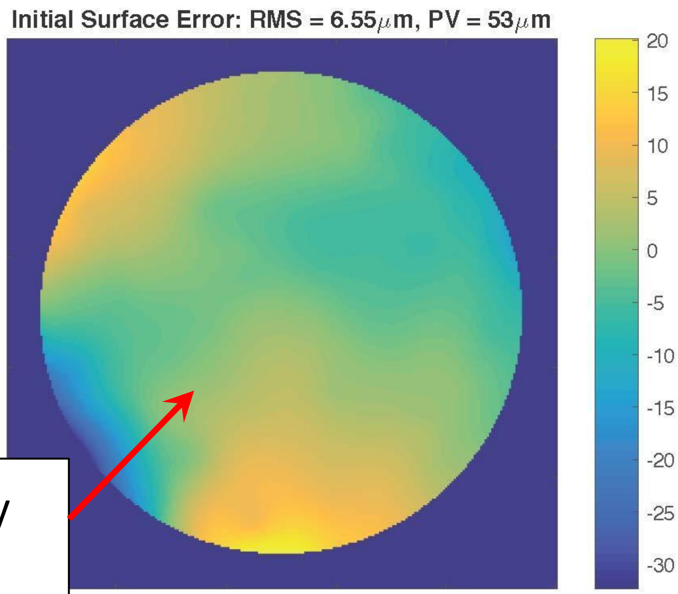




0.21 - 0.96 μm/V expected
0.80 μm/V measured

0.13 - 0.65 μm/V expected
0.58 μm/V measured

# Testing - Best flattening result

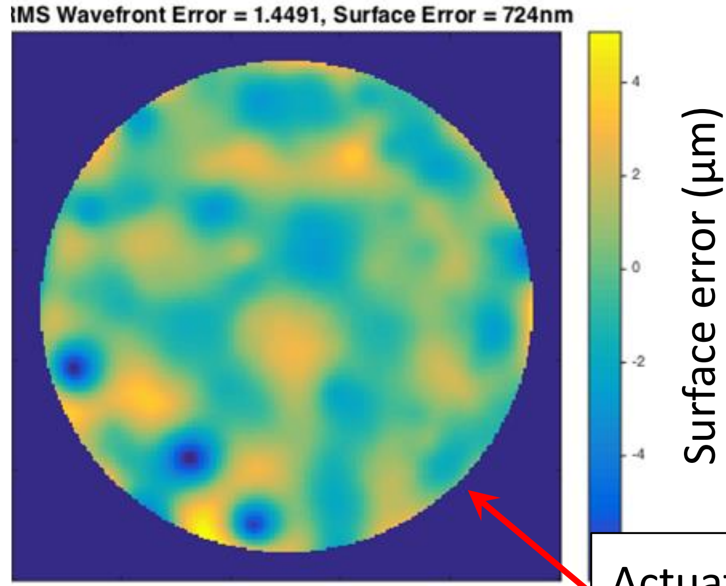
PZT1GSF3 - Resting shape




Dominated by astigmatism

6.55 µm RMS surface error

PZT1GSF3 - Best flattening




Actuator size limited

724 nm RMS surface error



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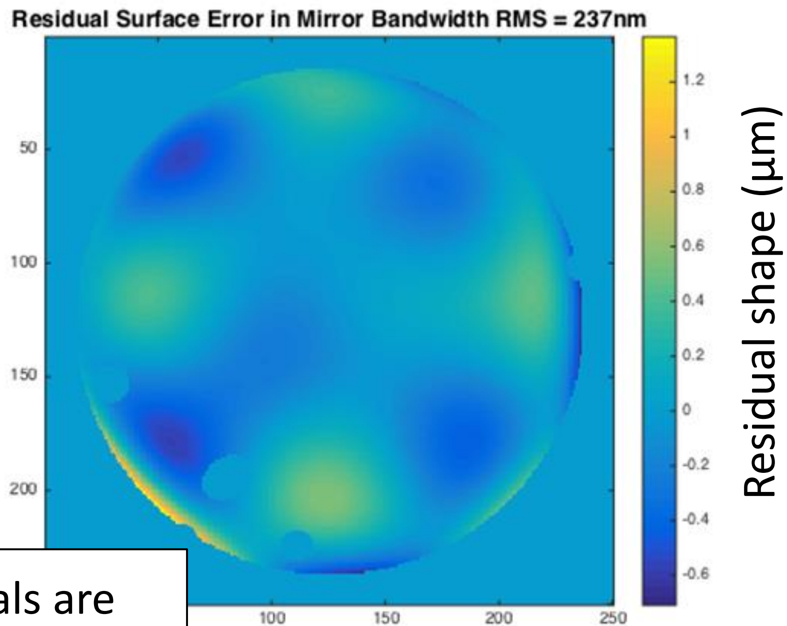
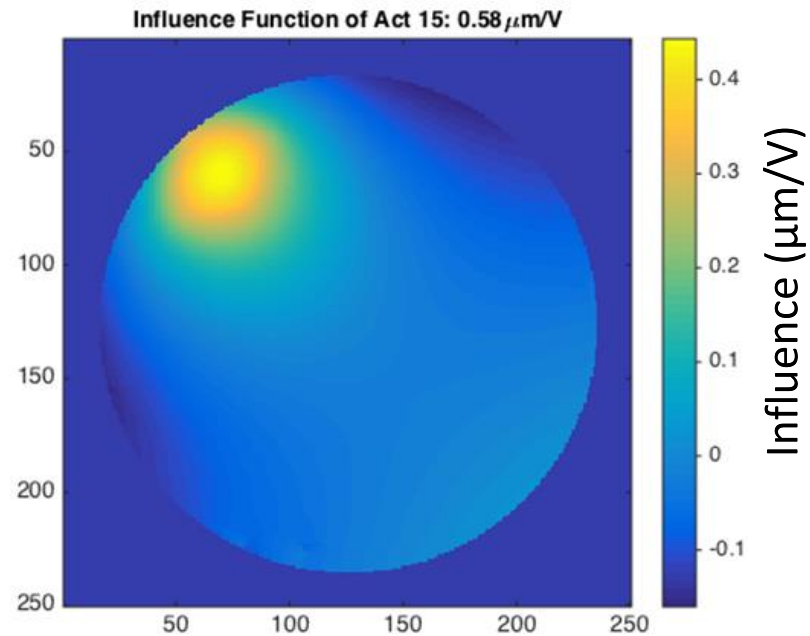
# Testing - Best flattening result

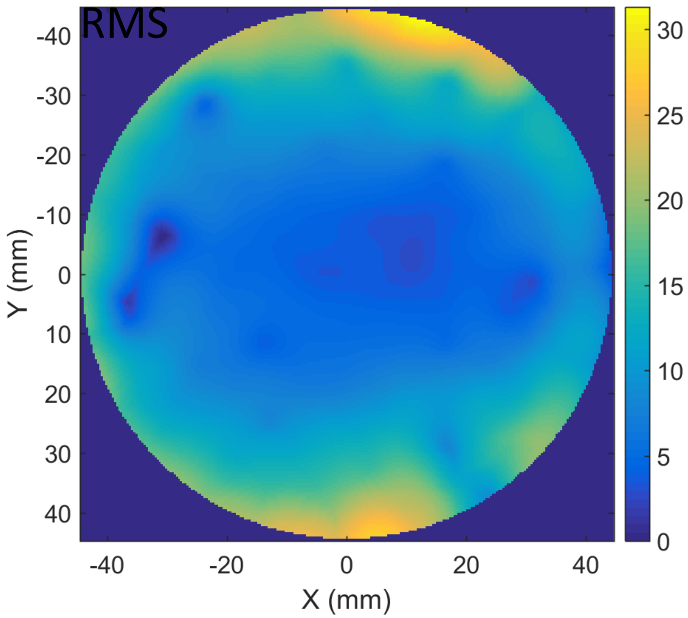


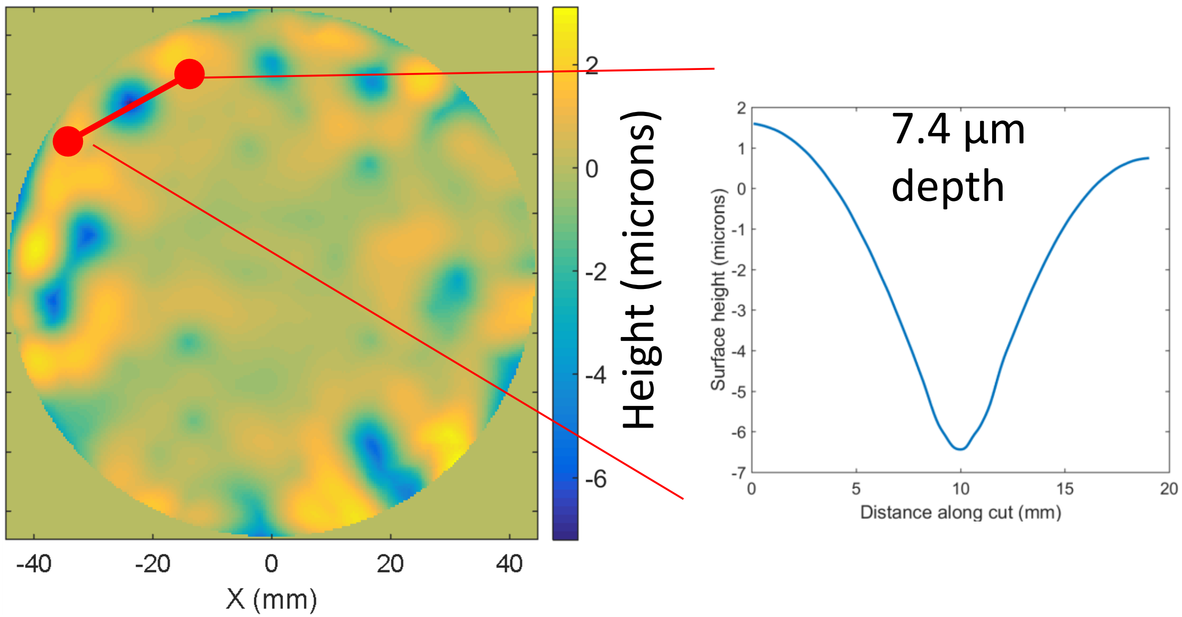

Residuals are the same size as influences

# Testing - Slumped glass dimples

GSF3 10.42 microns RMS

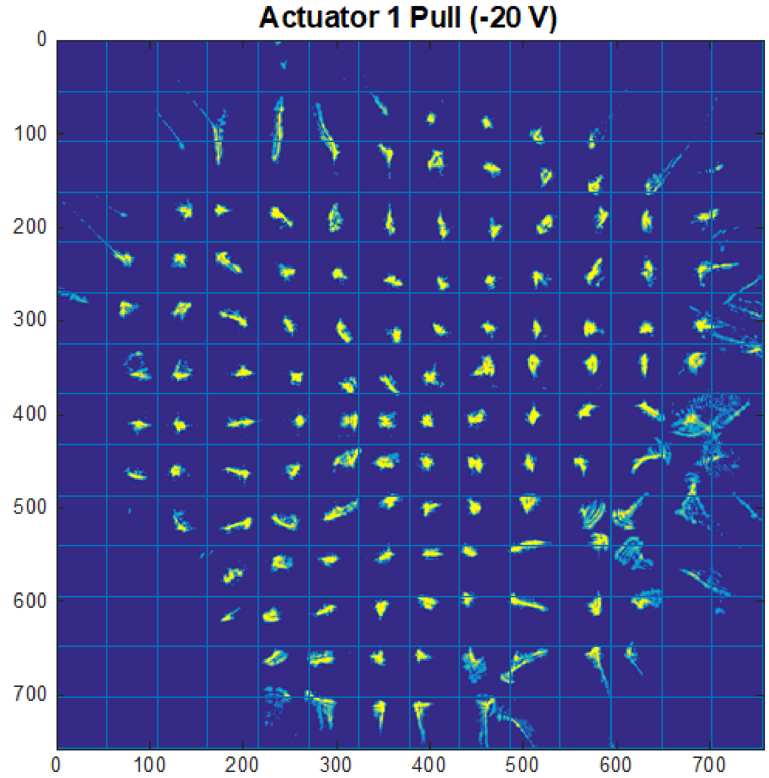



GSF3 modes 1-36 removed 975 nm RMS



# Testing - DM in the AAReST testbed

Mirror errors are within range of AAReST wavefront sensor



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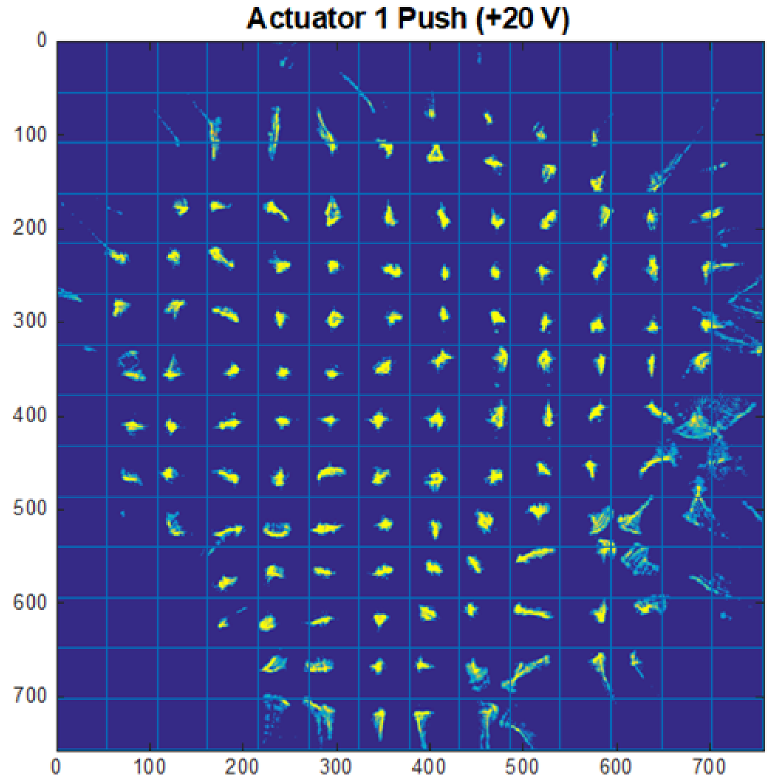

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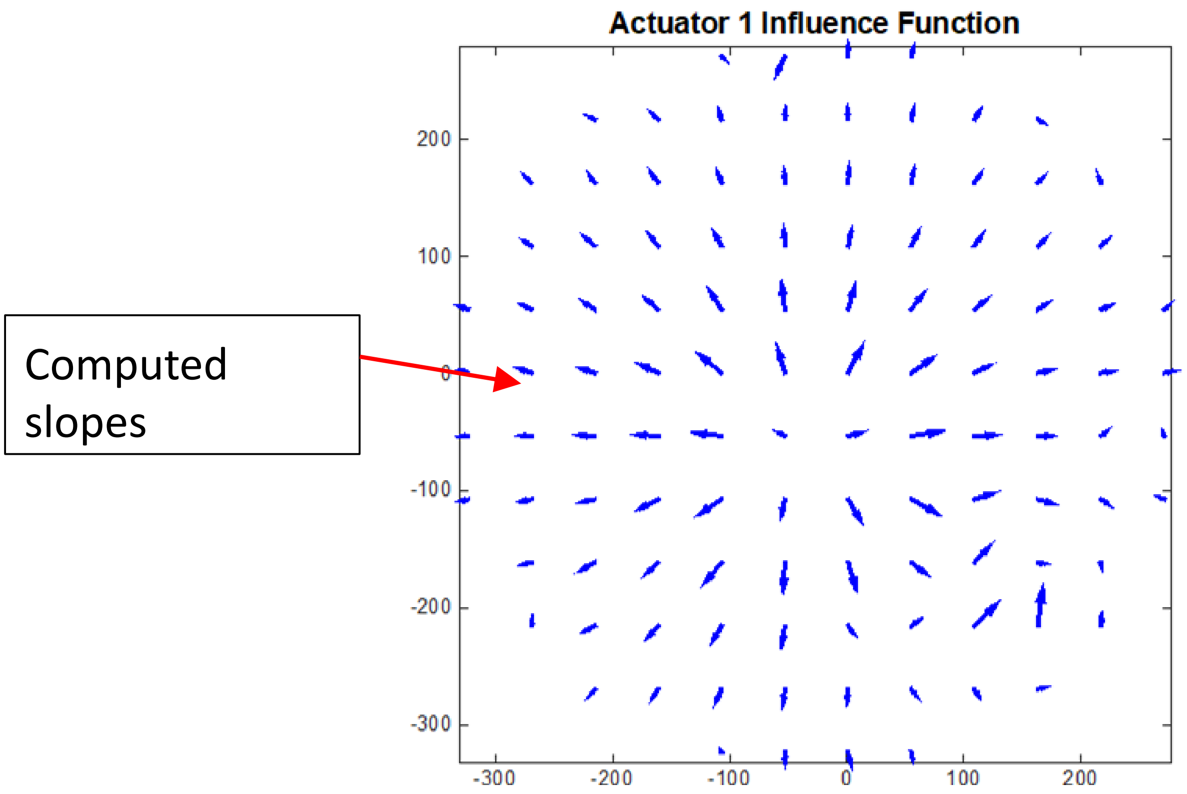
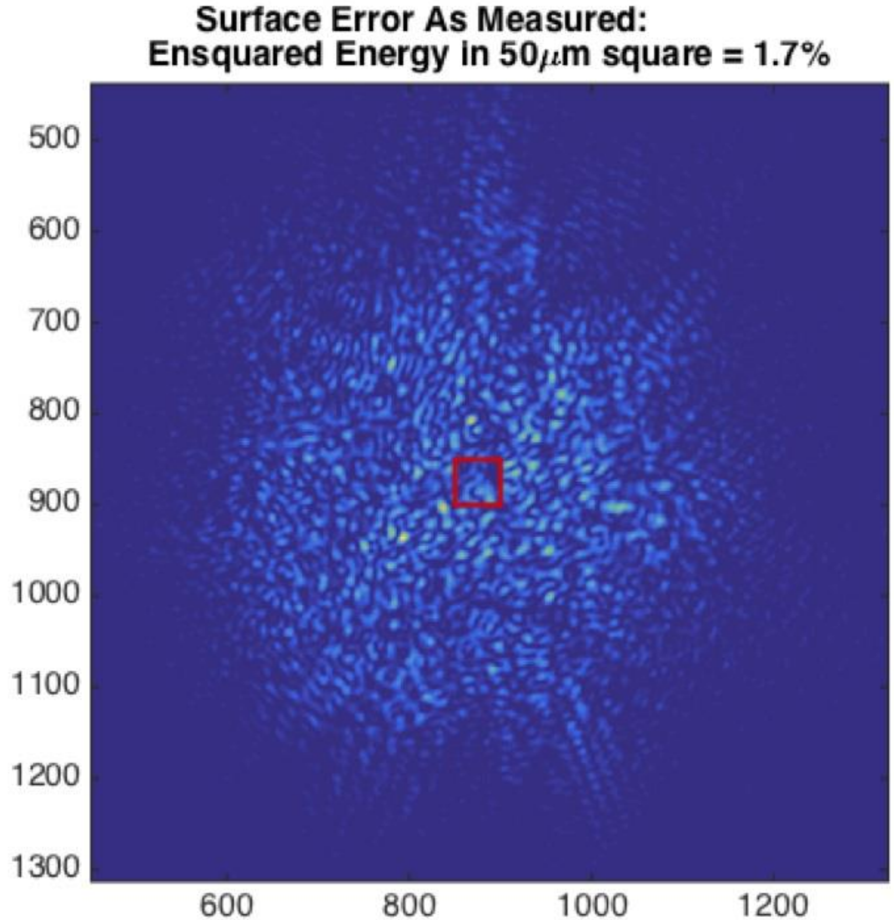
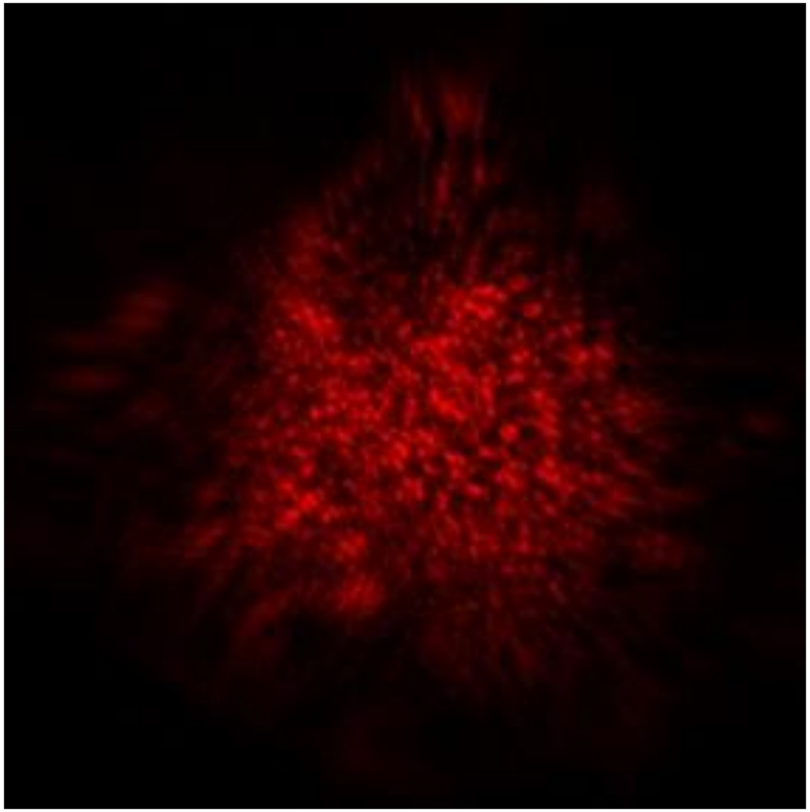



Next step is to close the loop with the AAReST testbed...

# Testing – PSF and RoC

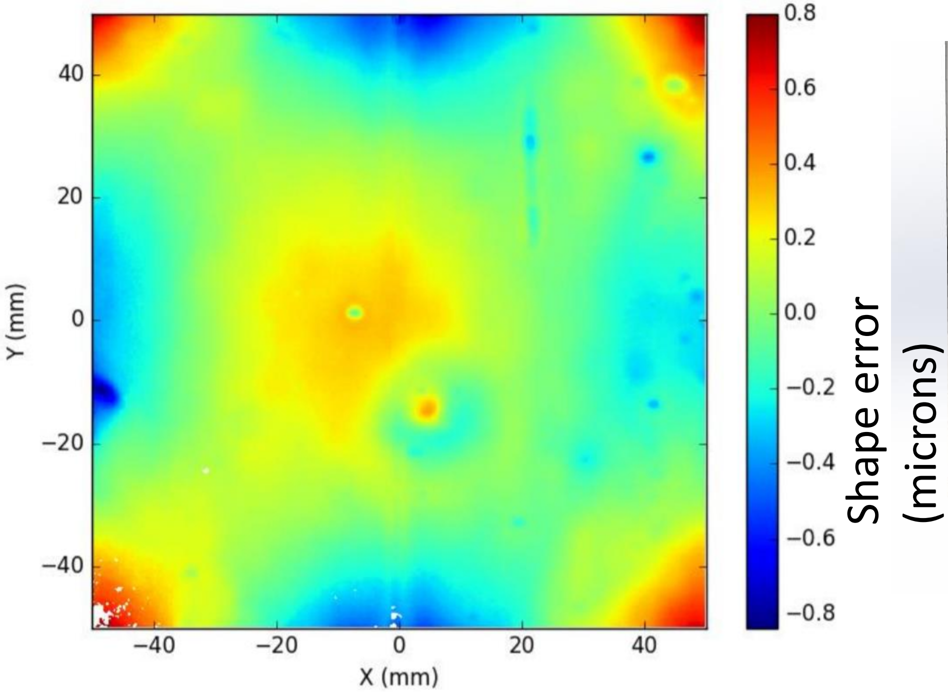


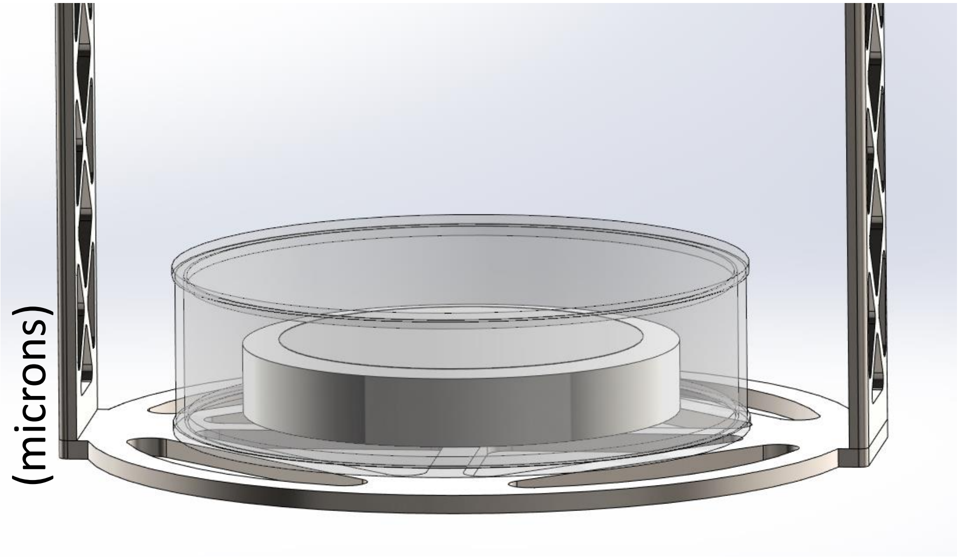

PZT1GSF3 simulated PSF



PZT1GSF3 measured PSF

# Slumping glass at Caltech (JPL R&TD grant)



Cotroneo et al. (2016) SPIE 99650C-5

# Conclusions and future work

- Achievements
  - Designed and built ultra-lightweight deformable mirrors that demonstrate large stroke.
  - Built mirrors that can correct for their own sphere-subtracted shape errors, up to the actuator size limit.
  - Deformable mirrors can be measured and actuated within the AAReST testbed.
- Future work
  - Mid-spatial frequency error in the DM prevents meeting AAReST encircled energy requirement.
  - Bonding procedure imparts focus shift that cannot be actuated away.
  - Continue producing mirrors

# Presentation Agenda

- Telescope Overview
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# Subsystem Requirements

**Functional:**

- Image star using a sparse aperture primary mirror
- Work to reconfigure primary mirror
- Provide feedback on mirror shape
- Take engineering images of CoreSat during MirrorSat reconfiguration

**Constraints:**

- Mass < 4kg
- Volume < 10 x 10 x 35 cm
- Power < 5 W

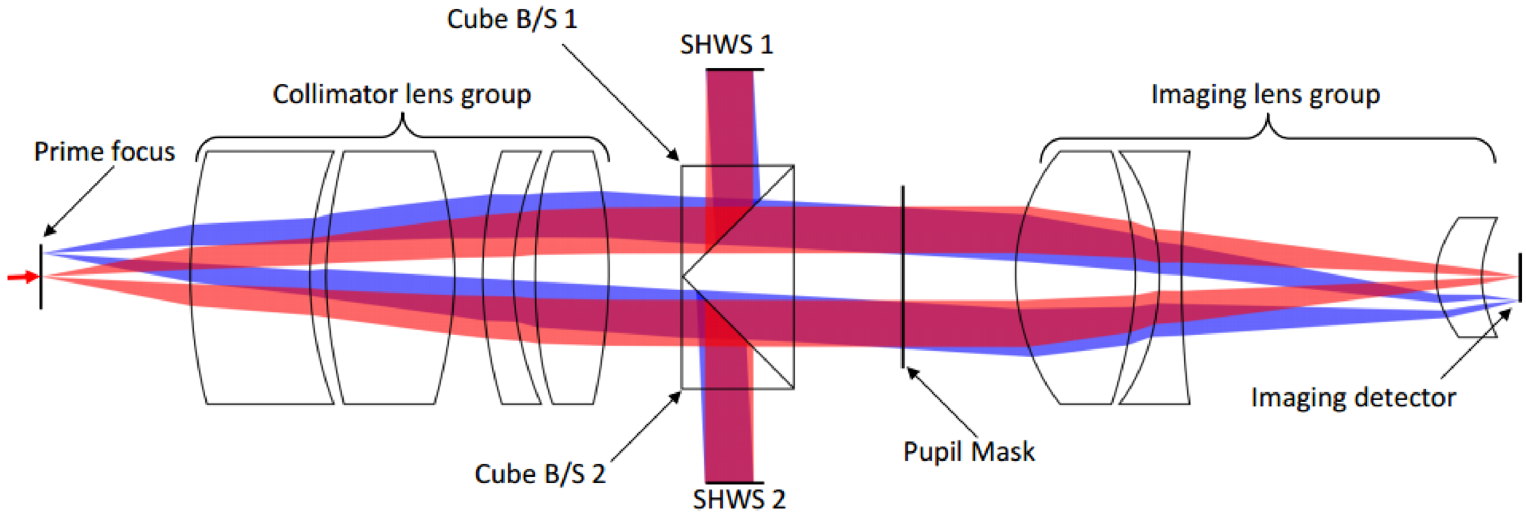
**Performance:**

- 80% encircled energy radius < 90% diffraction limit
- 0.3° full field-of-view
- Bandwidth: 465 – 615 nm
- SNR > 100

**Environmental:**

- Survive launch on PSLV with acceptable optical and mechanical performance
- Survive temperatures of -50$^{o}$C to +50$^{o}$C
- Function in vacuum environment

# Mechanical Overview




- Materials:
  - Titanium for optical mounts; Al6061 for all other parts;
  - Mask gears of dissimilar material to prevent cold welding
  - RTV silicone (low outgassing) padding for B/S and SHWS
- Key accomplishments:
  - Assembly procedures created and executed
  - Fit check, integration with optics, motor functionality, dummy electronic boards
- Mass: 3.1 kg < 4 kg
- Volume: 29.8 X 9.6 X 8.0 $cm^3$ < 35.0 X 10.0 X 10.0 $cm^3$



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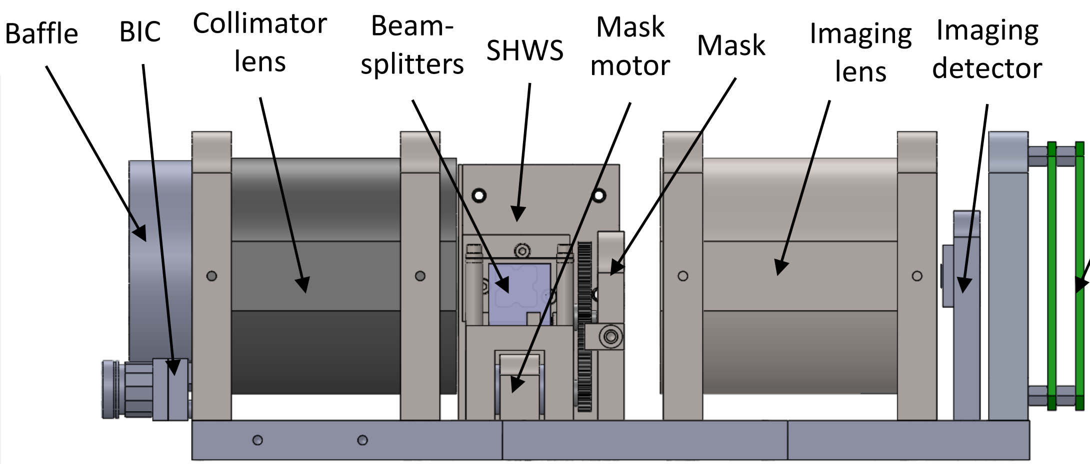
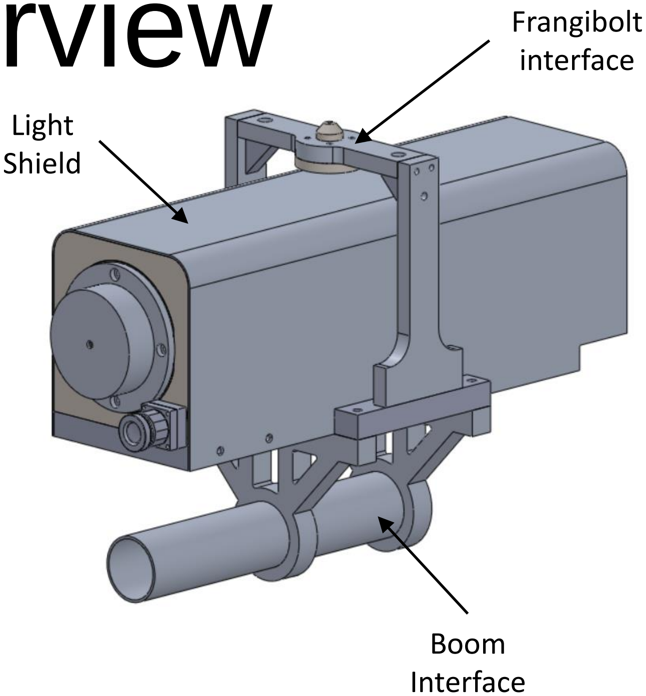
# Mechanical Overview

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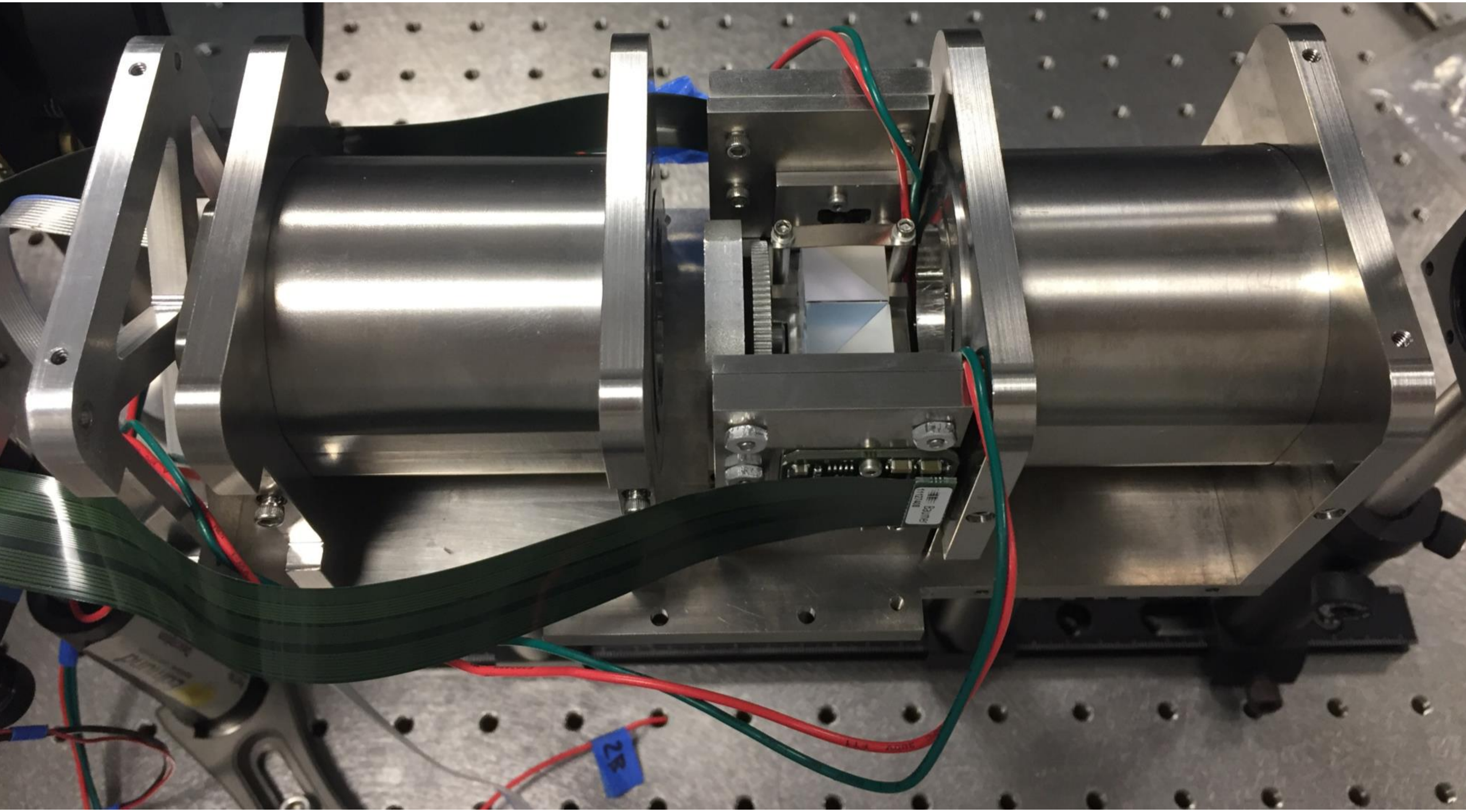



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# Thermal Testing Results

| Test Criteria | Pass/Fail | Comment |
|---|---|---|
| Survivability | Pass | No damage in optics, mechanical assembly |
| Motor Alignment | Pass | Gears mesh after test cycles |
| Science Camera Performance | Pass | Slight shift in spot location; no change in shape/size |
| SHWS Performance | Pass | No spots obscured; negligible change in Zernike coefficients (7 nm max defocus) |

# Vibration Testing Results

| Test Criteria | Pass/Fail | Comment |
|---|---|---|
| Survivability | Pass | No damage in optics or mechanical assembly |
| Motor Alignment | Pass | Gears mesh after test cycles |
| Science Camera Performance | Pass | Slight shift in spot location; no change in shape/size |
| SHWS Performance | Pass | Slight shift in spot location; No spots obscured; negligible change in Zernike coefficients (17 nm max defocus) |



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# Conclusion and Remaining Tests

- Camera meets all requirements
  - Mechanical, functional requirements met
  - Optical performance as expected
  - Environmental testing done to show survivability and functionality
- Remaining work:
  - New optics and B/S have arrived. Installation happening now!
  - Vibration testing to check electronics survivability
  - Fabrication of external interfaces
  - Verification of power requirement (currently met by operating in various modes)

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# Mirror Boxes Overview

## Requirements Overview

- House mirrors and electronics
- Restrain mirrors during launch
- Provide rigid body rotation and axial motion of the mirrors
- Respect weight limit of 1 kg each

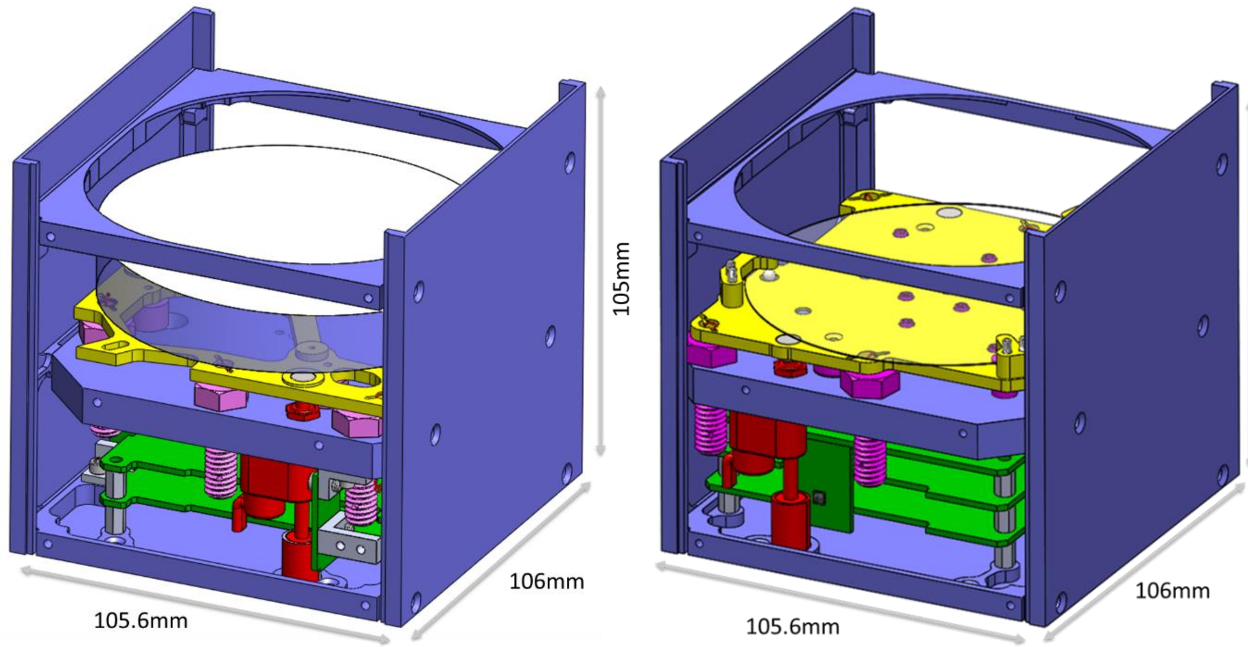
Mirrors & Mounts

Picomotors

Launch Restraint System

Electronics

Frame



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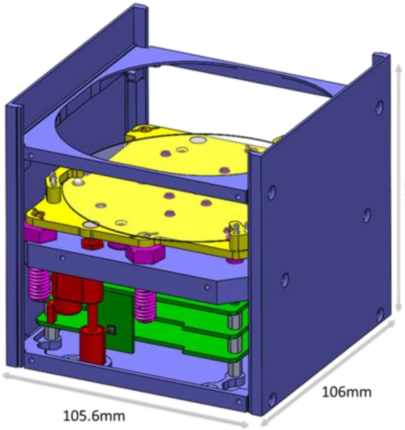
# Outline

- **Accomplishments**
- **Rigid mirror box tests**
  - Vibration tests
  - Bond strength tests
- **Deformable mirror box tests**
  - Vibration tests
  - Failure analysis and new design
- **Separation device tests**
- **Picomotors position control**
- **Summary and systems readiness level**

# Accomplishments

## Assembly

- Fully assembled mirror boxes from CAD models
- Assembly procedures




## Testing

- Vibration tests of both mirror boxes
- Bond strength tests between rigid mirror and supporting plate
- Separation device tests

## Integration

- Integration of rigid mirror box on optical testbed
- Optical alignment



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# New Mirror Mounts Design

<table>
<tr><th>Old Design</th><th>New Design</th></tr>
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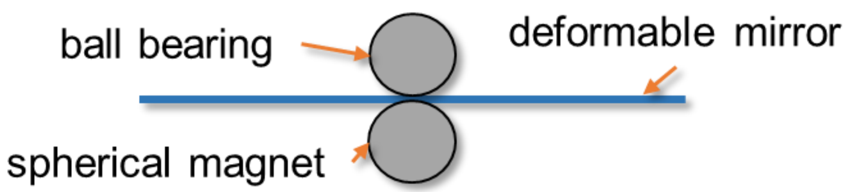

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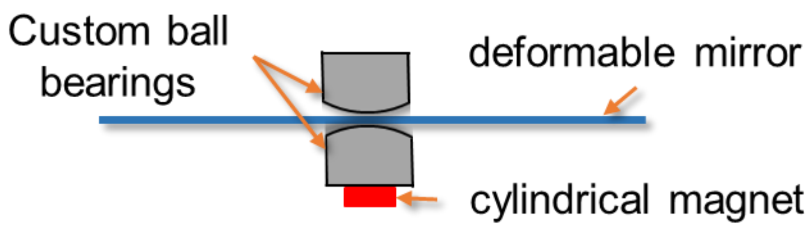
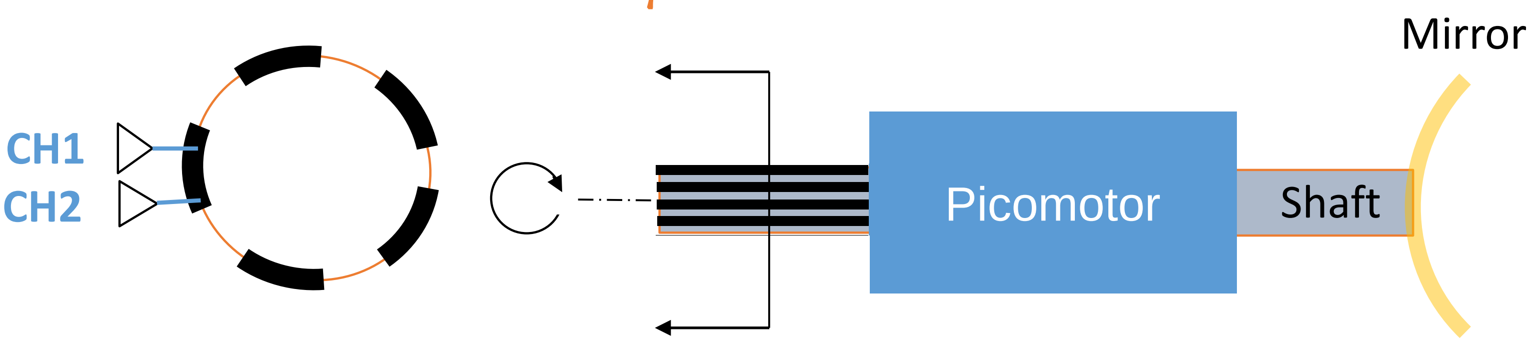


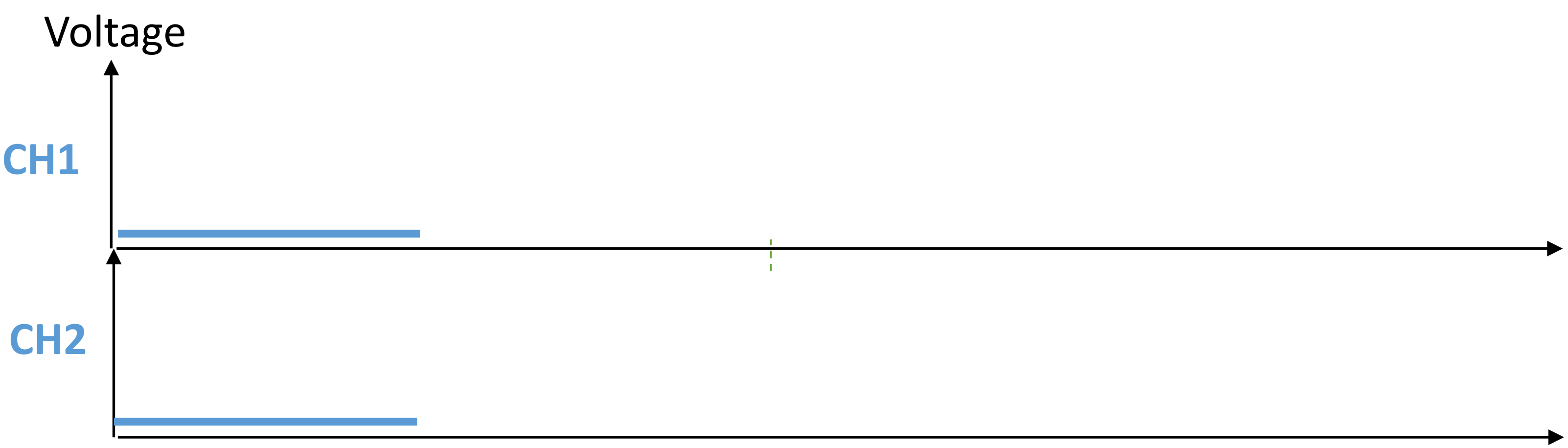
</td></tr>
<tr><td>Spheres radius: $\mathbf{R_{sphere} = 2.38mm}$</td><td>Semi-spheres radius: $\mathbf{R_{new} = 7.65mm}$<br>Bearings thickness: $\mathbf{t_{total} = 2mm}$</td></tr>
<tr><td>Magnet pull force (including mirror thickness): $\mathbf{f_{magnet} = 3.11\ N}$</td><td>Magnet pull force (including bearing and mirror thickness): $\mathbf{f_{new} = 4.67\ N}$</td></tr>
<tr><td>Contact pressure (based on NASA-qualification loads [-6dB)]:<br>**p0 = 1.02 Gpa**</td><td>Contact pressure (based on PSLV-qualification loads): $\mathbf{p0_{new} = 0.407GPa}$<br>Safety factor: **SF = 2**</td></tr>
<tr><td>Contact area (from Hertzian theory):<br>$$\mathbf{a} = \sqrt[2]{\frac{3F}{2\pi p_0}} = 76.2\ \mu m$$</td><td>Contact area (from Hertzian theory):<br>$$\mathbf{a} = \sqrt[2]{\frac{3F}{2\pi p_0}} = 98.4\ \mu m$$</td></tr>
</table>

# Picomotors Position Control

**Encoders** help estimate mirror position within an interval

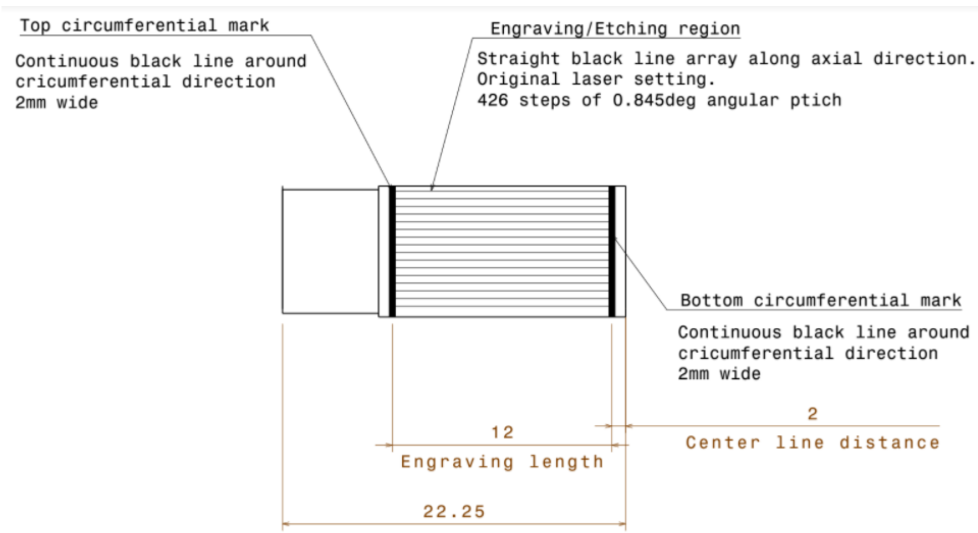
Encoder interval: $41\mu m$

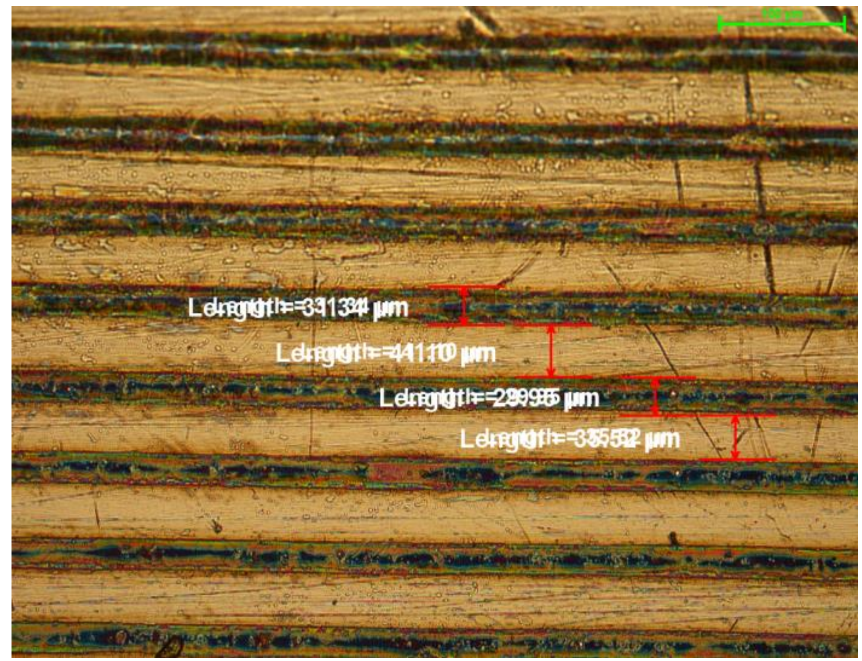


# Encoder Shaft

- Encoder shafts laser engraved at micron pitch. Markings validated on transducer
- Alignment procedure with non-contact laser measurement
- Integrated into RM box on testbed and awaiting testing



428 lines 0.845deg:
Engraved line: 30.5587+-1.14217
reflective interval: 38.6588+-1.93625
Angular pitch of rotary jig: 0.833151deg



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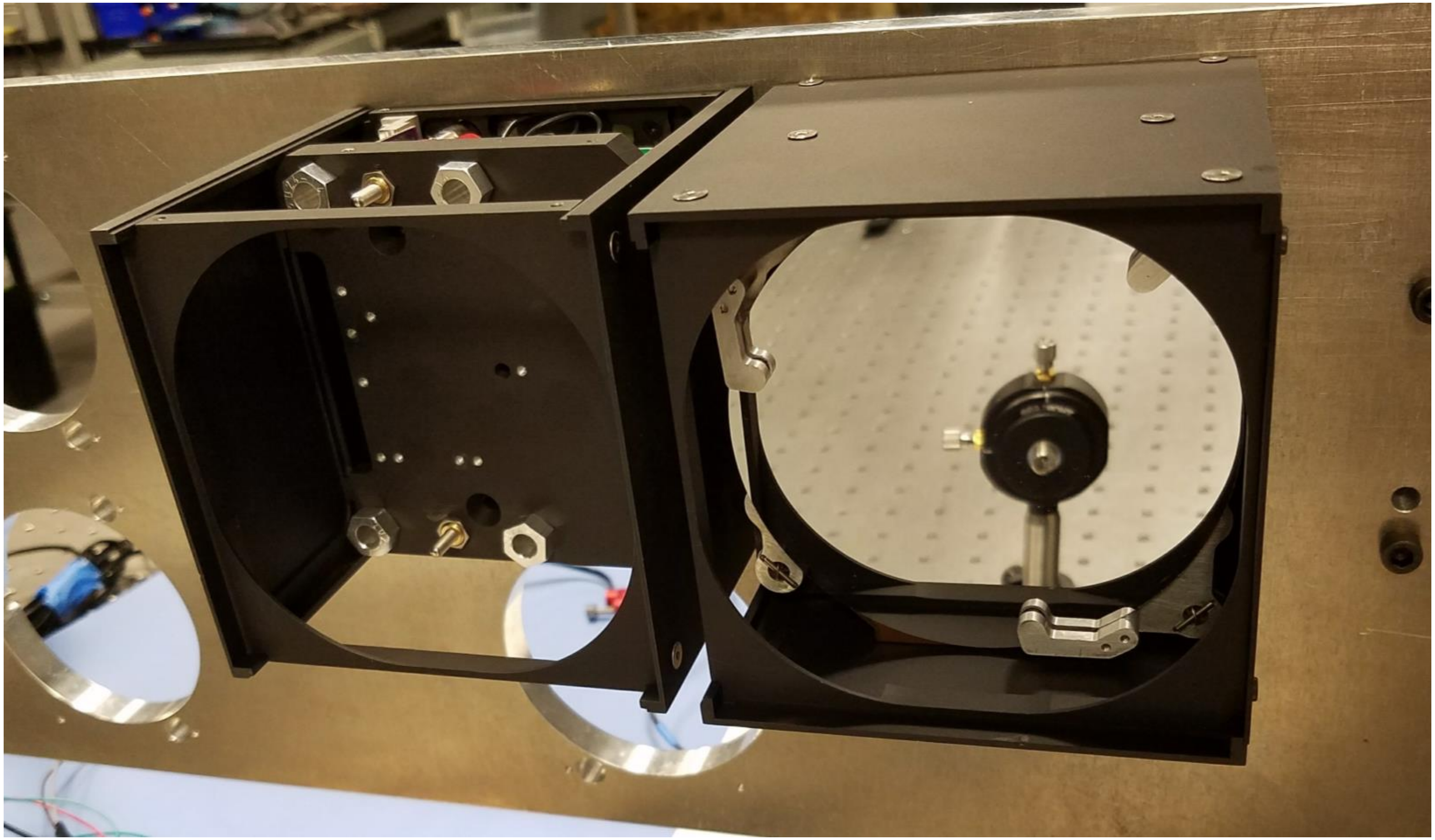
# Flight parts

- Flight mirrorbox parts arrived from manufacturing
- Aluminum bead blasted and hard black anodized
  - Reduces stray light around optics
  - Electrically insulates burnwire mechanisms
- Invar parts bead blasted and coated with 0.0005” high-phos. electroless nickel
  - Protects invar from corrosion

# Flight parts





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# Systems Readiness Level

## Rigid Mirror Box

**Completed**

- Assembly procedure
- Successful vibration tests of box structure in all shaking directions
- Mirror bonding procedure
- Successful bonding tests
- Integration and mirror alignment on optical testbed

**Future Work**

- Vibration tests with flight electronics and flight mirror (using PSLV standard)
- Separation device tests with flight electronics, in vacuum

## Deformable Mirror Box

**Completed**

- Assembly procedure
- Preliminary vibration tests (successful up to -6dB NASA standard)
- New mirror mounts design
- Vibration tests with new mounts, spherical DM, and flight electronics (using PSLV standard)

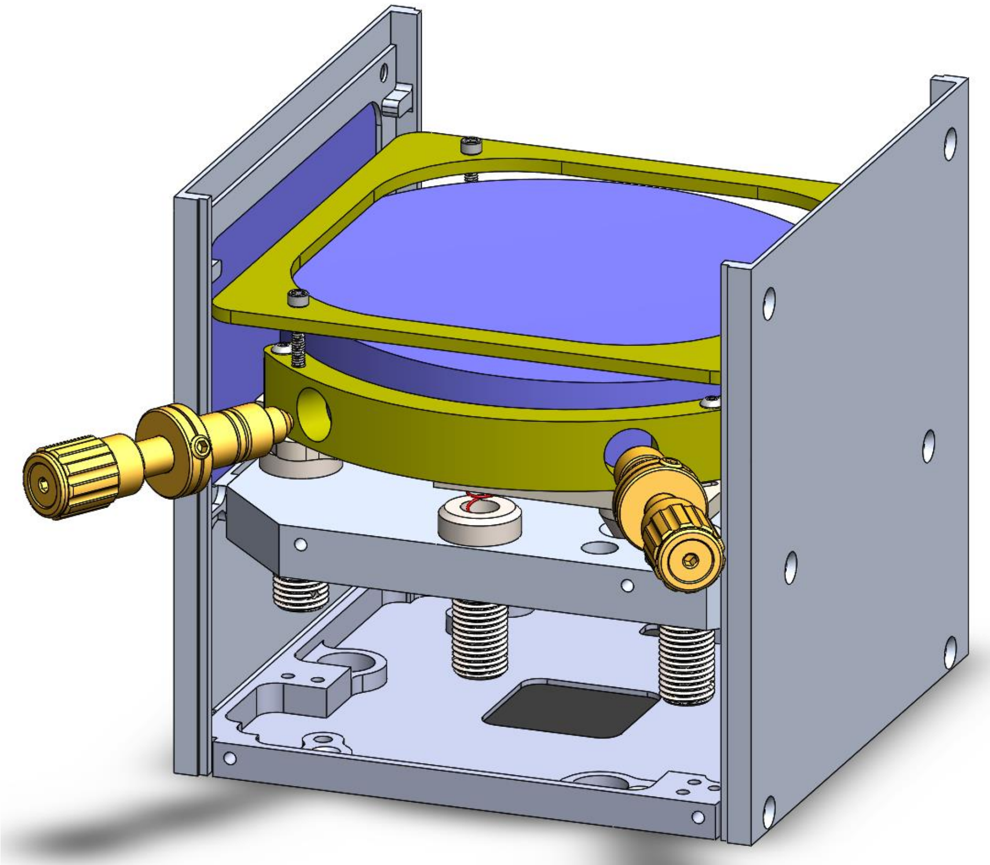
**Future Work**

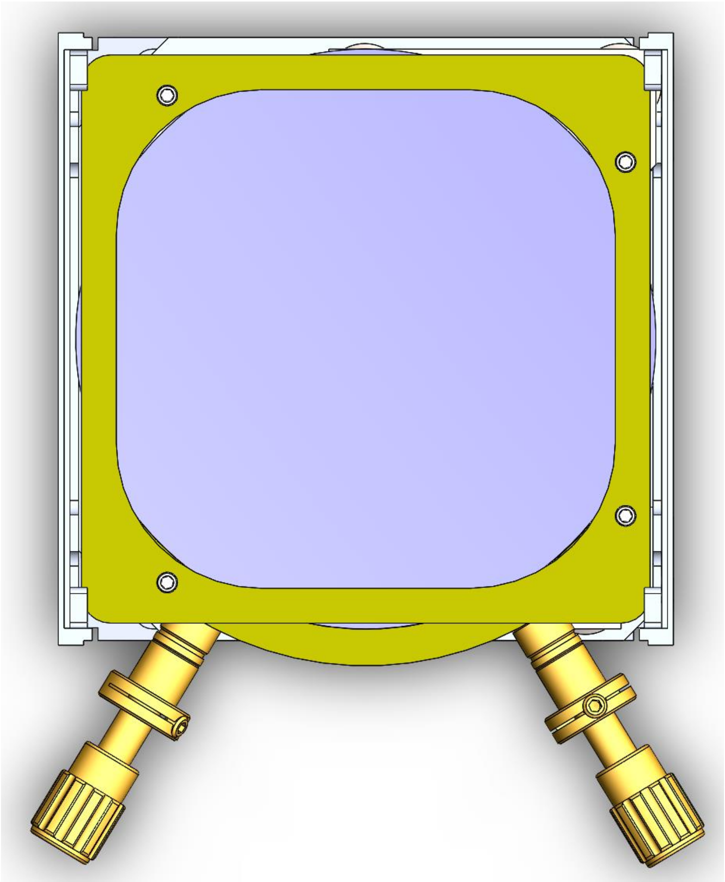
- Integration on optical testbed
- Separation device tests with flight electronics, in vacuum

# Optical Alignment Fixture

**Needs**

- Temporarily support rigid mirror in vertical position when box is mounted onto optical table for alignment procedure
- Free rotation of the mirror and highly sensitive in plane adjustment (µm level sensitivity)
- Fix mirror in its new position, after alignment, to allow for bonding procedure





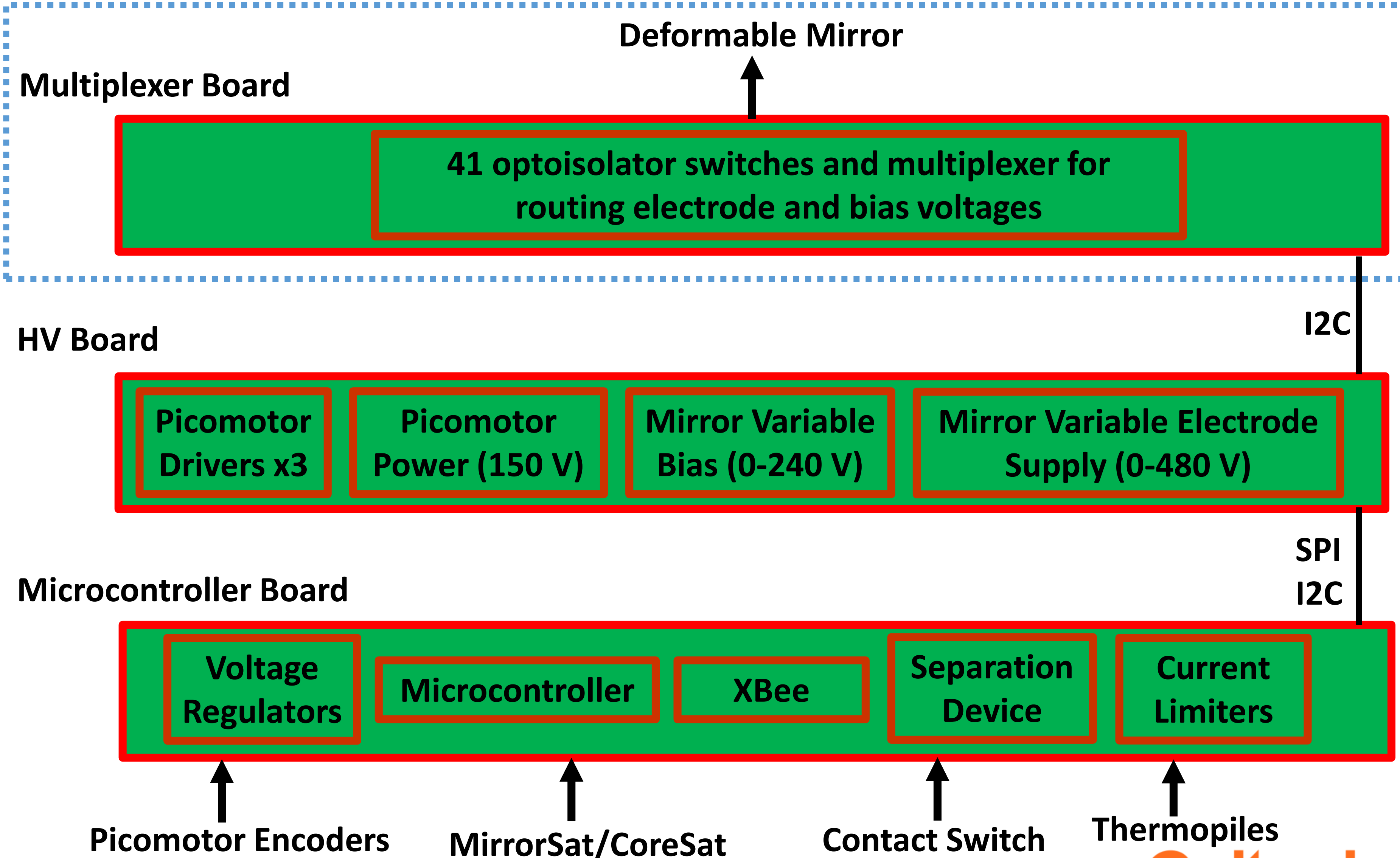
# Presentation Agenda

- Telescope Overview
- Deformable Mirrors
- Camera Instrument
- Mirror boxes Overview
- Electronics
- Software
- Boom Subsystem

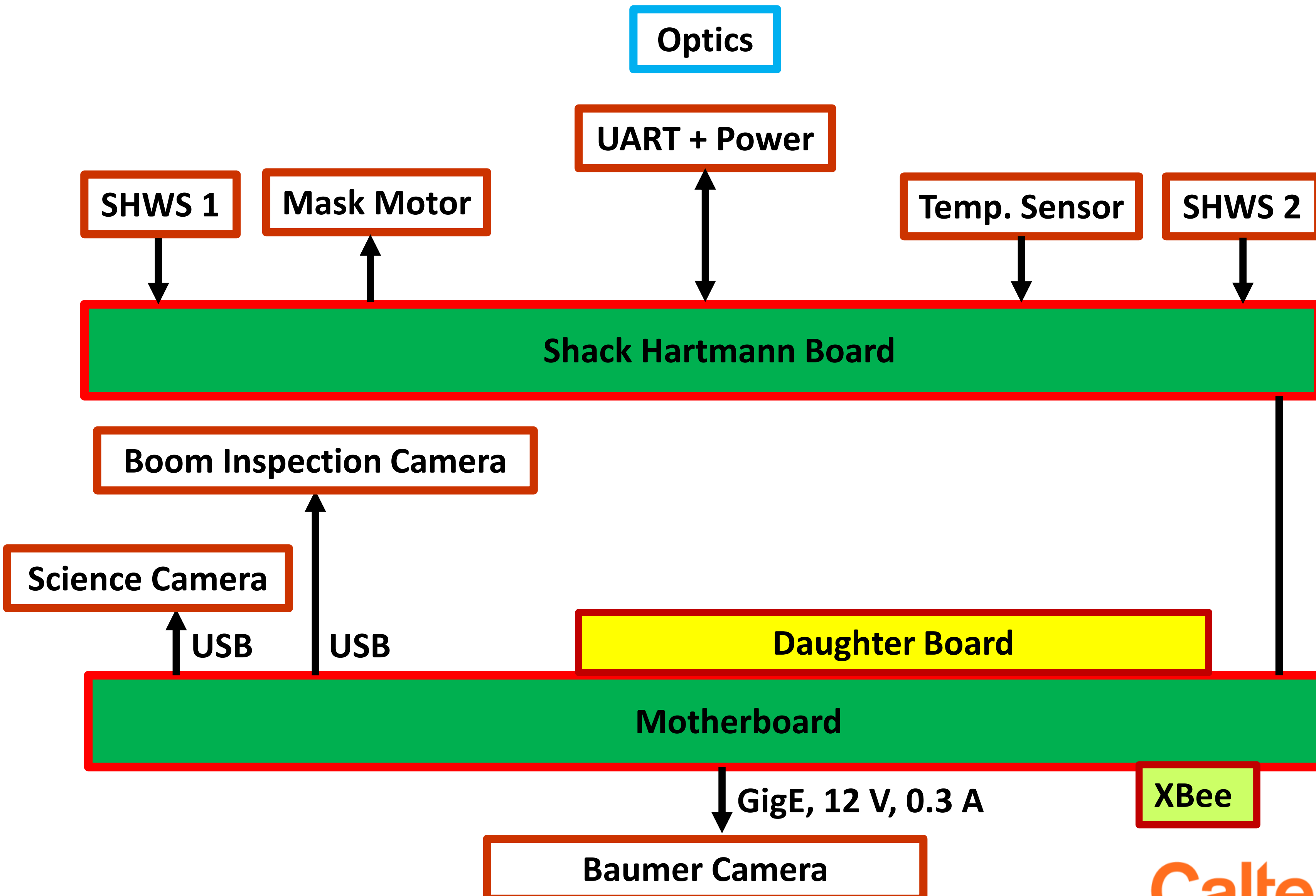
# Overview

- Telescope Electronics Overview
- Current Status
- Mirror Electronics
  - Multiplexer board
  - HV board
  - Microcontroller board
- Camera Electronics
  - Motherboard
  - Shack Hartmann board
- Interface

# Mirror Electronics Overview



# Camera Electronics Overview

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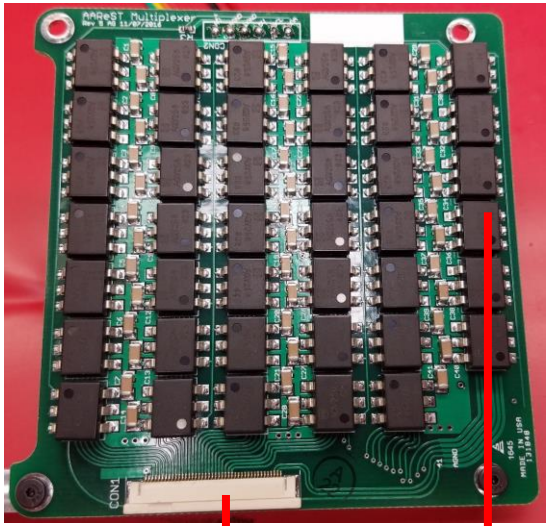
# Current Status

| Board | Status |
|---|---|
| **Mirror Electronics** | |
| Multiplexer board | Flight boards ready and tested |
| HV board | Flight boards ready and tested |
| Microcontroller board | V2.0 functional, too much in-rush current |
| **Camera Electronics** | |
| Motherboard | V1.0 functional, designing V2.0 |
| Shack-Hartmann board | V1.0 functional, need minor changes for V2.0 |

# Mirror Electronics



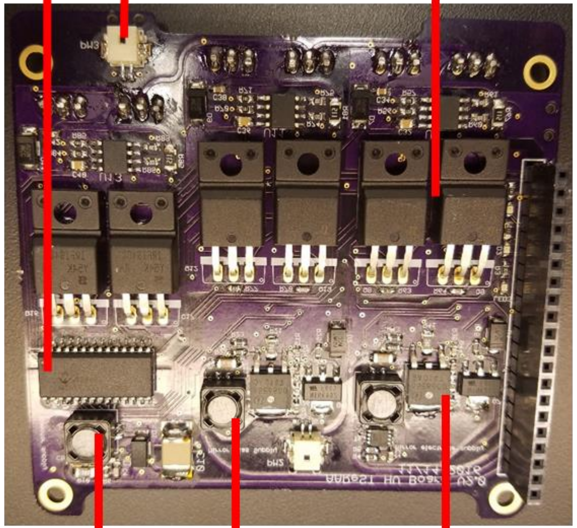
Optoisolator switch

FFC connector for electrode routing layer on the mirror

I/O Expander

Picomotor connector

Picomotor driver x3



Picomotor power

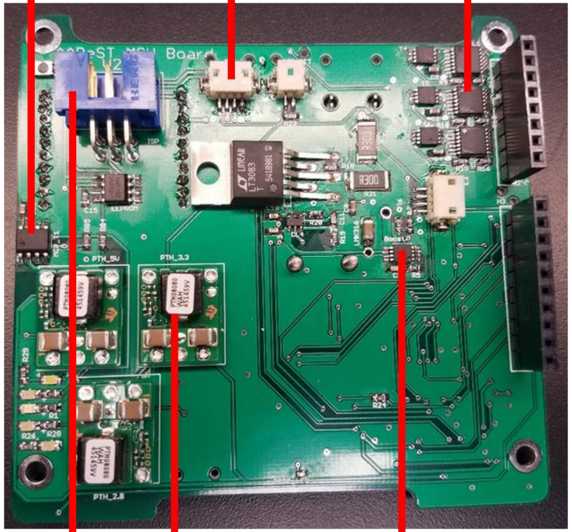
Electrode HV supply

Mirror bias supply

Encoder connector

Temp. Sensor

Current limiting switch



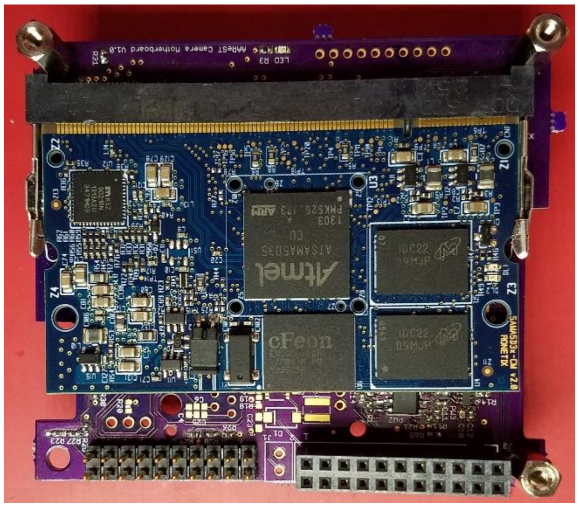
Voltage regulator

Boost converter

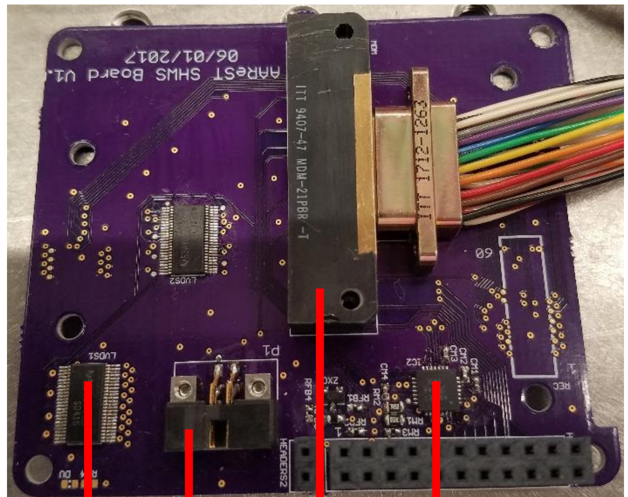
Programming header

# Camera Electronics

**Camera Motherboard**



**Shack Hartmann Switch Board**



**LVDS Switch**

**Mask motor driver**

**Connector for motor and thermistors**

**CoreSat interface connector**

**Baumer Support Board**

# Future Work

- Redesign motherboard with new ethernet port, USB connectors and UART interface
- Change burn wire circuit and resolve boost converter related startup issues in mirror electronics
- Complete cabling for camera and mirrorboxes
- Integrate temperature sensors, encoders, separation detection switches and other electronics inside mirrorboxes

# Presentation Agenda

- Telescope Overview
- Deformable Mirrors
- Camera Instrument
- Mirror boxes Overview
- Electronics
- Software
- Boom Subsystem

# Outline

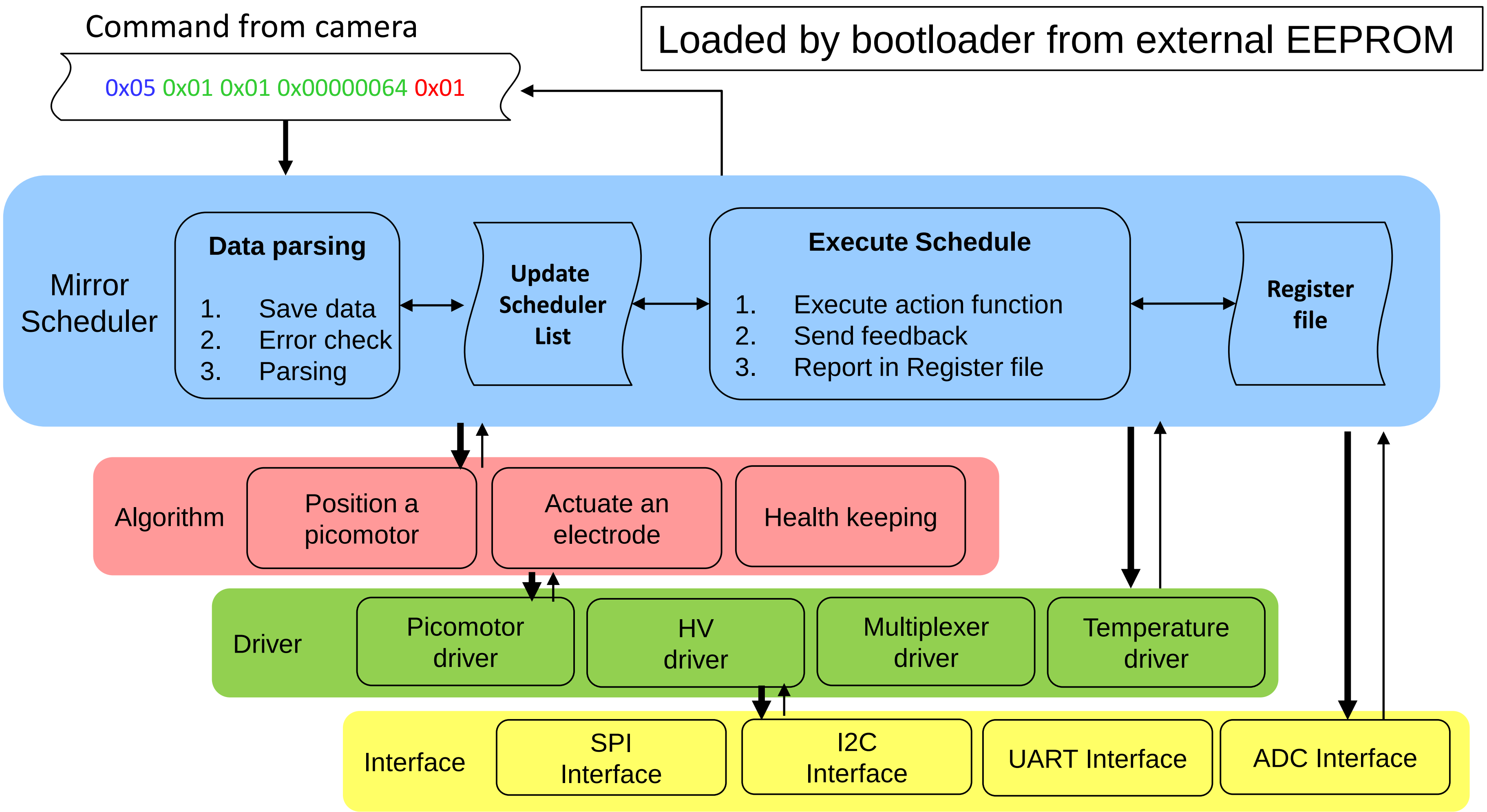
- Requirements
- Mirror box
  - Software architecture
  - Driver update
- Camera
  - Driver update
- Telescope startup procedure
- Error handling
- Future work

# Requirements of AAReST OBSW

- Mirror software
  - Communicate with camera through XBee and with MirrorSat through UART as backup
  - Automated failure detection and safe mode reset
  - Actuate picomotors and electrodes
- Camera software
  - Communicate with CoreSat through UART (USB or SSH protocol)
  - Communicate with 4 mirrors through XBee
  - Automated failure detection and safe mode reset
  - Take images and analyze them

**Both software run in non hard real time mode**

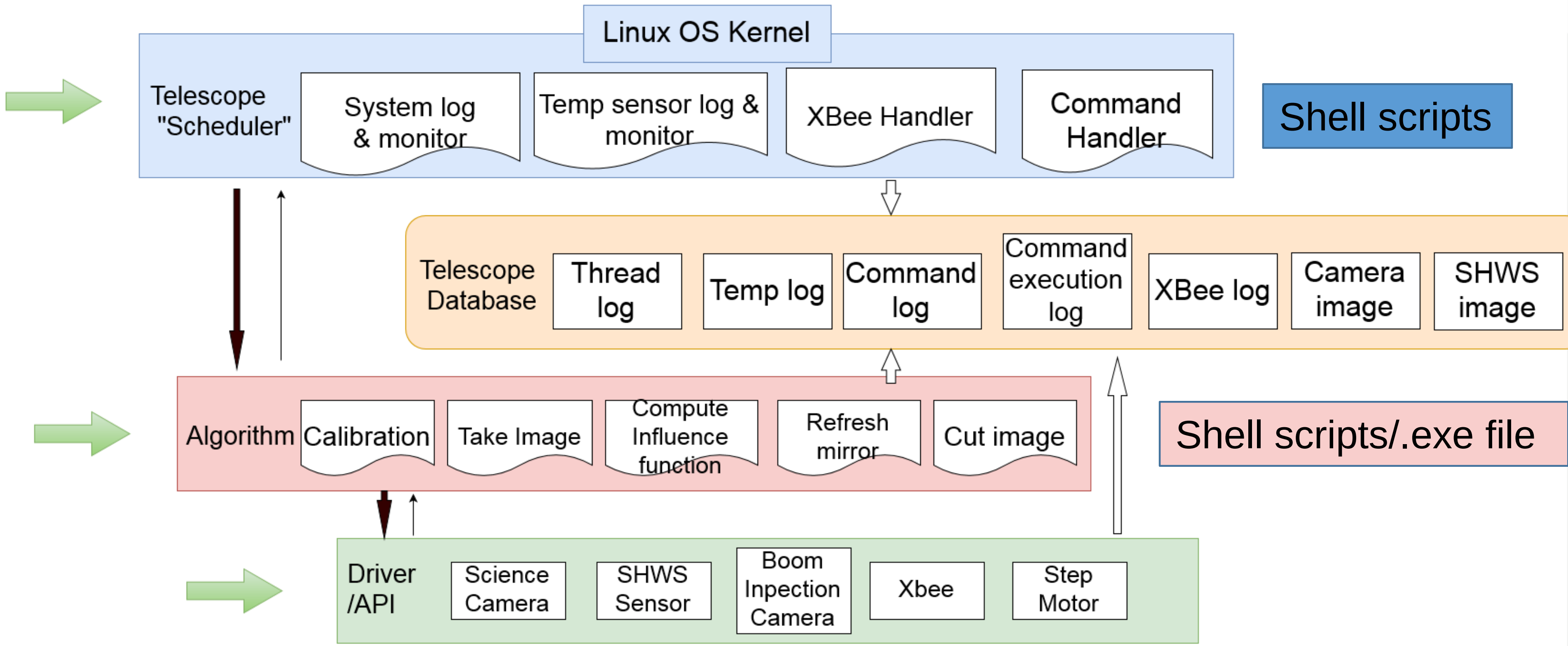
# Mirror Box Software Architecture



# Mirror Box Software update

- Hardware testing of mirror deformation and HV supplies control
- Scheduler implemented, integrated with algorithm and driver layer
- Undergoing tests with flight hardware

# Camera Software Architecture




- Each layer create independent processes; monitored by telescope “scheduler”, terminate itself at end of execution
- Each process owns a dedicated log
- Each layer accessible through CoreSat – camera interface



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# Camera software updates

- Implementation of Algorithm and Drivers on flight CPU
- Preliminary tests of Algorithms with Flight Hardware
- Scheduler layer framework updated, under implementation

# Future work

- Camera side
  - Implementation of camera scheduler layer
  - Finish and test camera drivers on telescope CPU
  - Tailoring of Linux kernel
- Mirror side
  - Flight operation testing on telescope testbed

# Detailed discussions for this week's review

- Framework of Camera scheduler layer
- Failure identification and recovery (FIDR) strategy for camera
- Comm protocol between coresat and camera
- How often to save health and safety data
- General system level testing strategies

# Presentation Agenda

- Telescope Overview
- Deformable Mirrors
- Camera Instrument
- Mirror boxes Overview
- Electronics
- Software
- Boom Subsystem

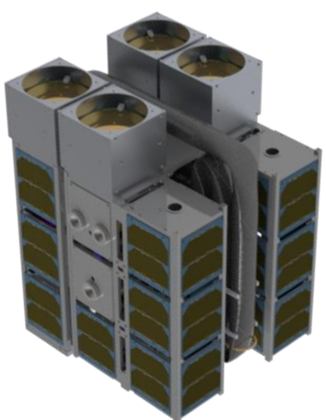
# Subsystem Overview

## Purpose:

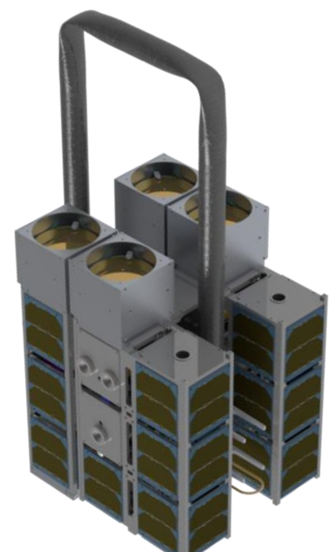
- Guarantee successful deployment of the composite boom
- Ensure alignment of optical systems after deployment

## Main components:

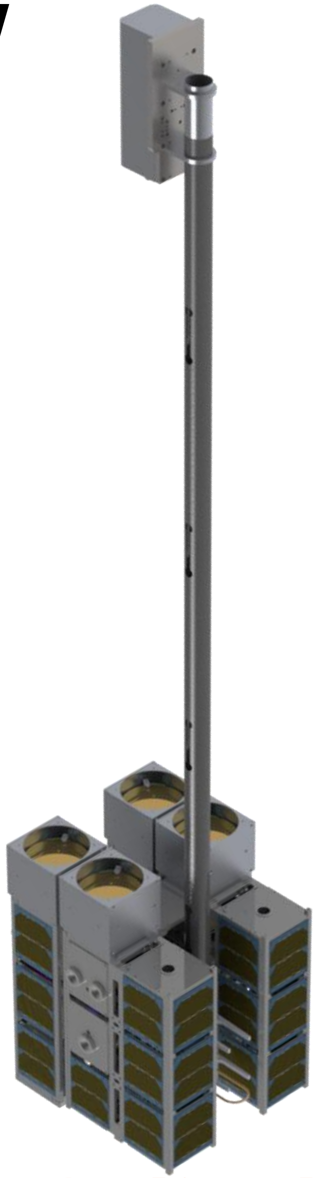
- Kinematic mounts
- Separation device
- Composite boom



Stage 1
Deployment



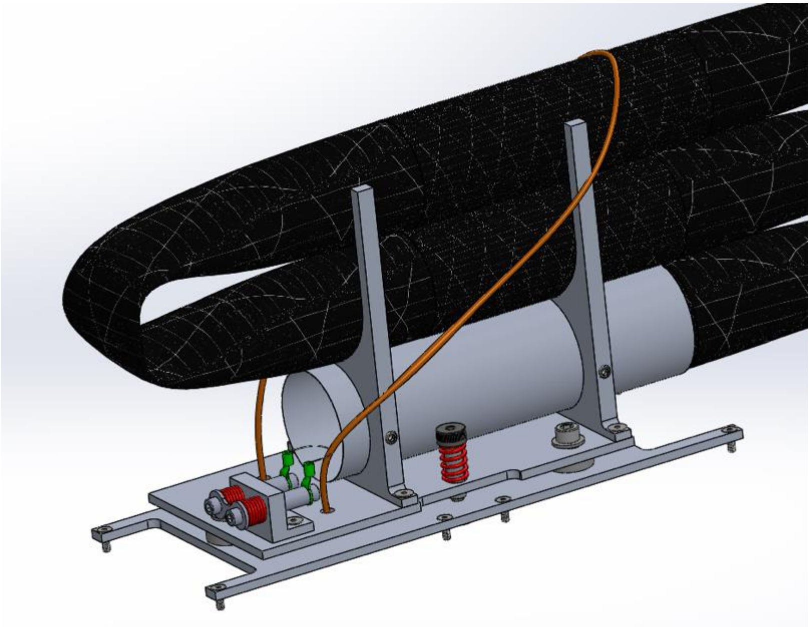
Stage 2
Deployment

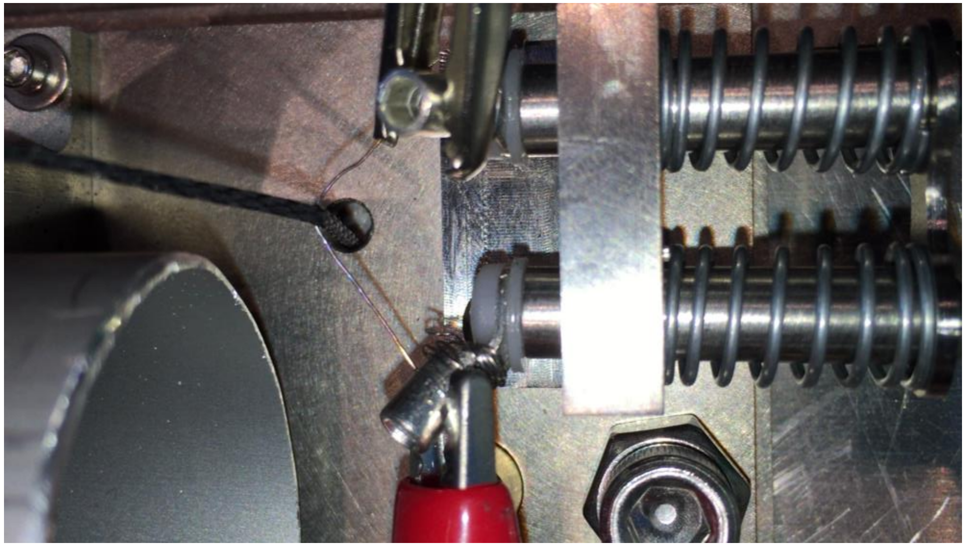


# Subsystem Overview

**Kinematic Mount** allows adjustment of camera relative to CoreSat before final storage; It corrects for misalignments.

**Separation Device** constrains boom during storage and releases stage 1 during deployment.







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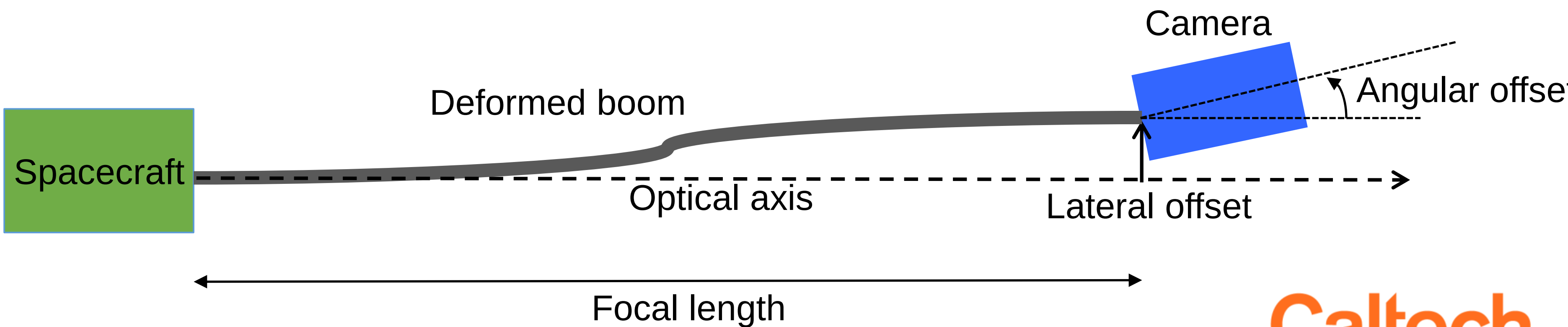
# Boom Subsystem Requirements

| Requirement | Value |
|---|---|
| Focal length [1] | 1163 ± 1 mm |
| Maximum admissible lateral offset [2] | ± 3 mm |
| Maximum admissible angular offset [2] | ± 1° |
| Maximum lateral tip deflection (dynamic) [3] | ± 0.20 mm / s |
| Maximum longitudinal tip deflection (dynamic) [3] | ± 0.05 mm / image |

[1] From the CDR (2015)
[2] Given by Kathryn Jackson
[3] From the PDR (2013)



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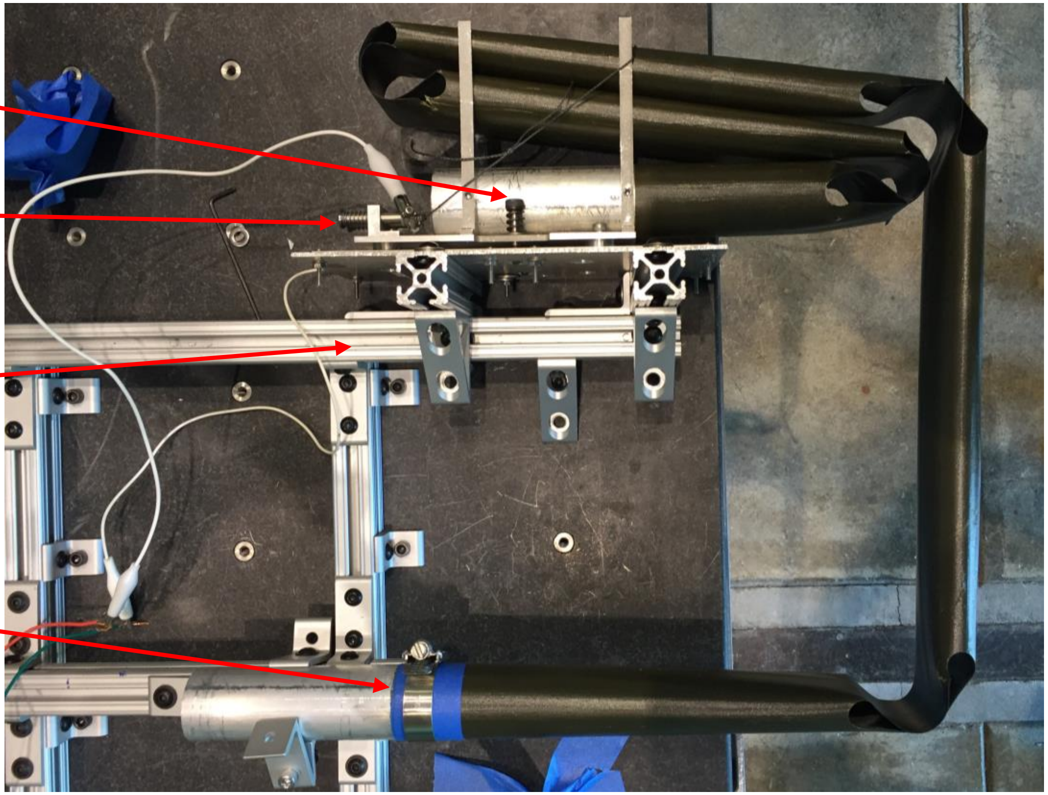
# Boom testing

- Previous review
  - Viscoelasticity
  - Stage 1 and 2 deployments
  - Launch vibration (NASA qualification level)
  - Separation device
  - Deployment accuracy
- New results
  - New boom length
  - Folding fixture
  - Offloading jig
  - Kinematic mount redesign

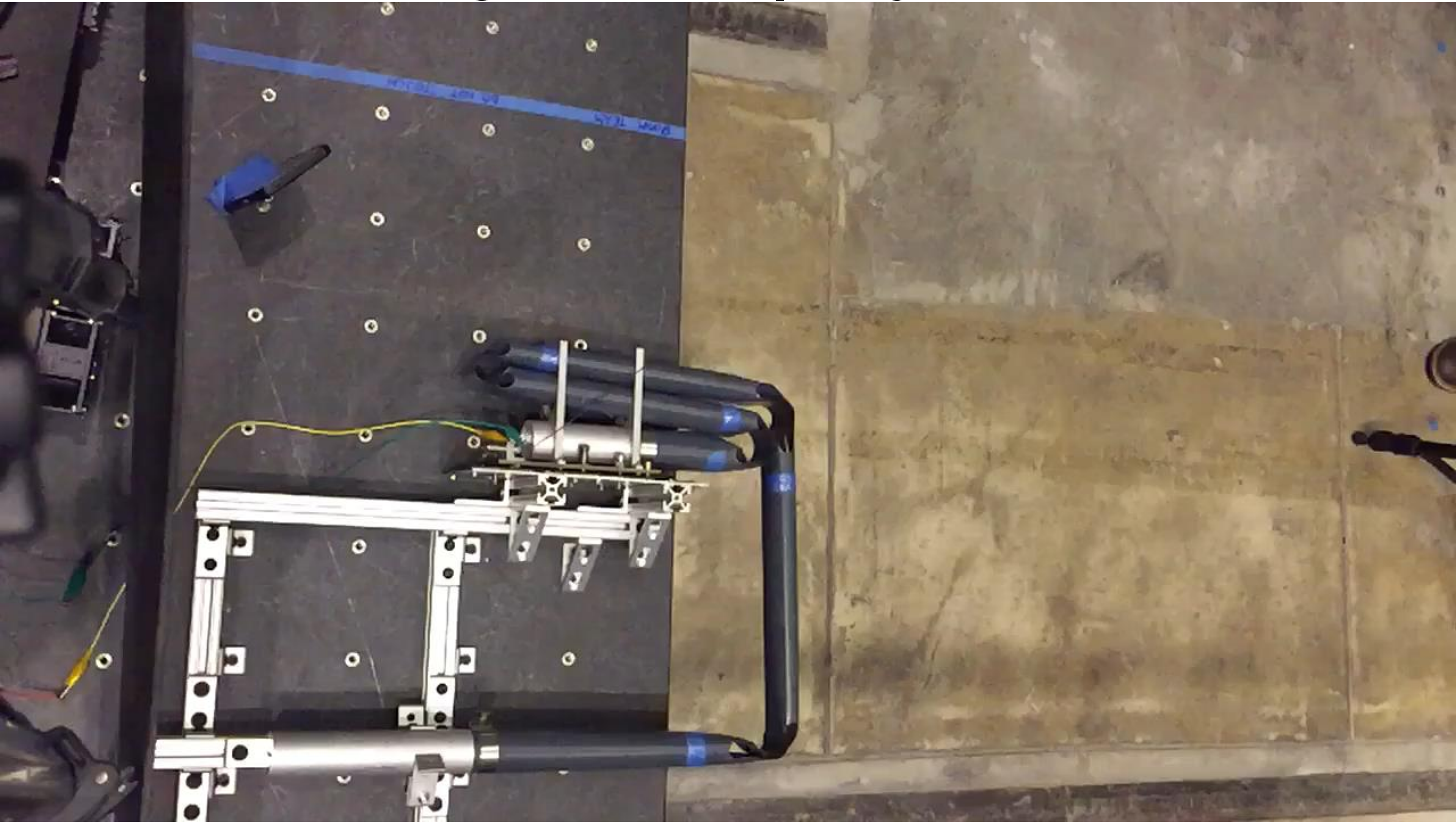
# Stage 1 Deployment

**Objectives:**

- Demonstrate reliable and repeatable stage 1 deployment
- Validate the kinematic mount and the separation device



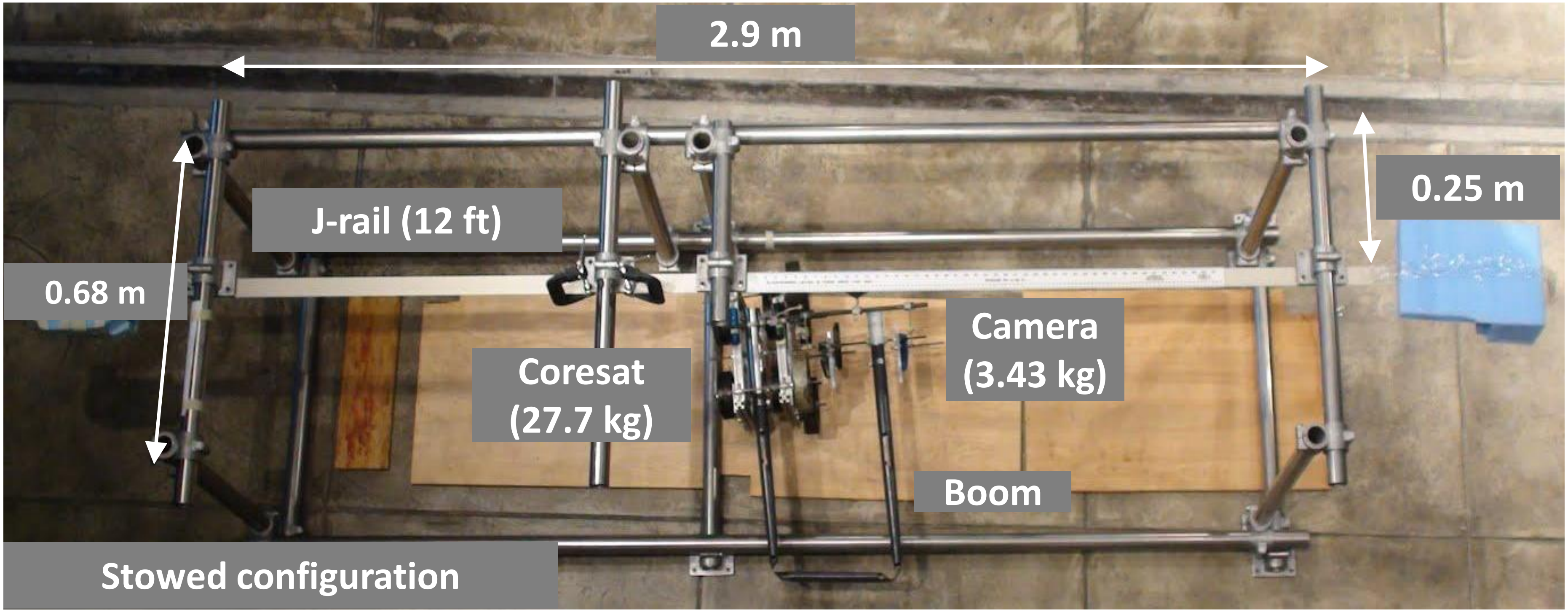
# Stage 1 Deployment



# Stage 2 Deployment Test

**Objectives:**

- Ensure a reliable and repeatable stage 2 deployment
- Determine maximum acceleration due to deployment



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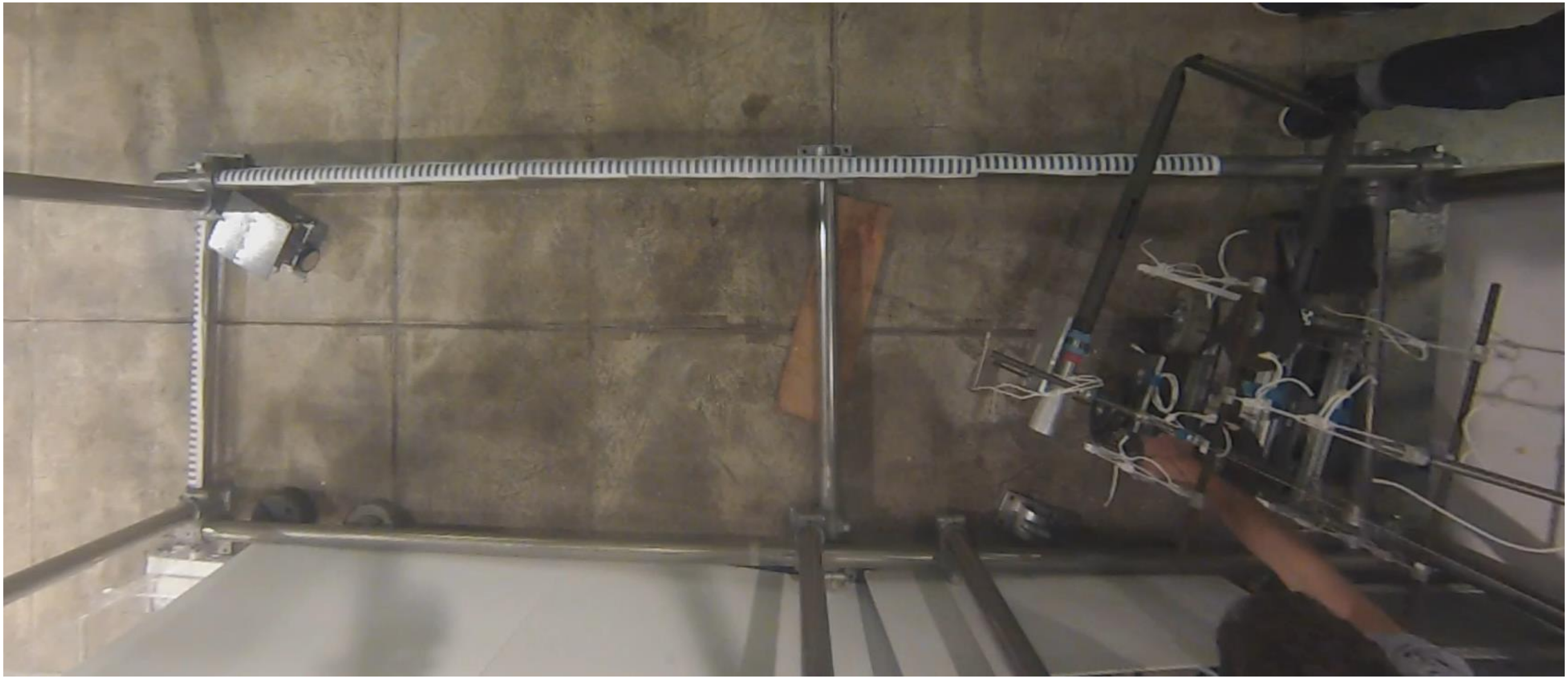
# Stage 2 Deployment





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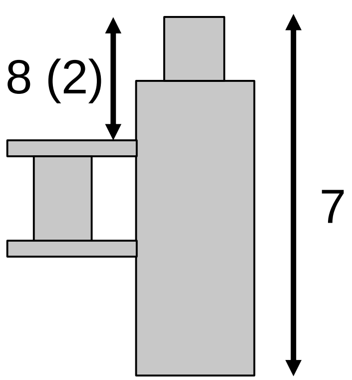
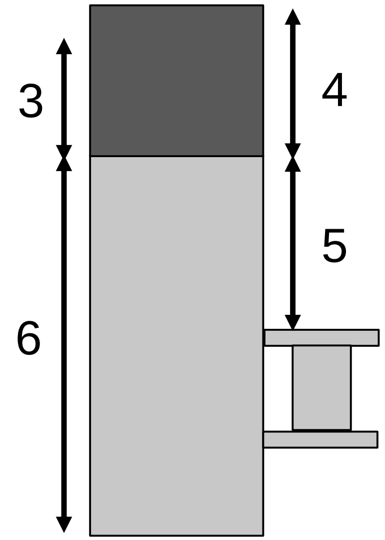
# New Boom Length

- **Objective: optimize the boom length, and the camera and kinematic mount positions based on the following constraints:**
  - Keep the same spacing between the hinges
  - Respect the designed optical focal length
  - Reduce stress in the first hinge from the kinematic mount by increasing as much as possible the length of the first segment

# New Boom Length

- **Main Parameters**
  1. Focal length: 1163 mm
  2. Camera-to-collar optical offset: 82.575 mm
  3. Mirror box optical offset: 77.1026 mm
  4. Mirror box total height: 105 mm
  5. Distance between top of structure and KM collar: 155.75 mm
  6. Length of Coresat (excluding clearance): 325 mm
  7. Length of camera: 296 mm
  8. Offset between front of camera and collar: 84 mm



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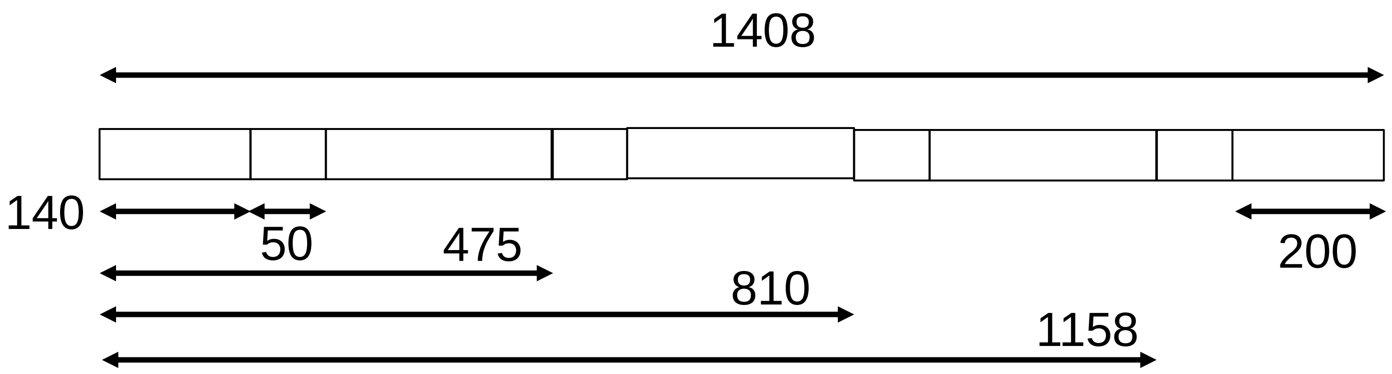
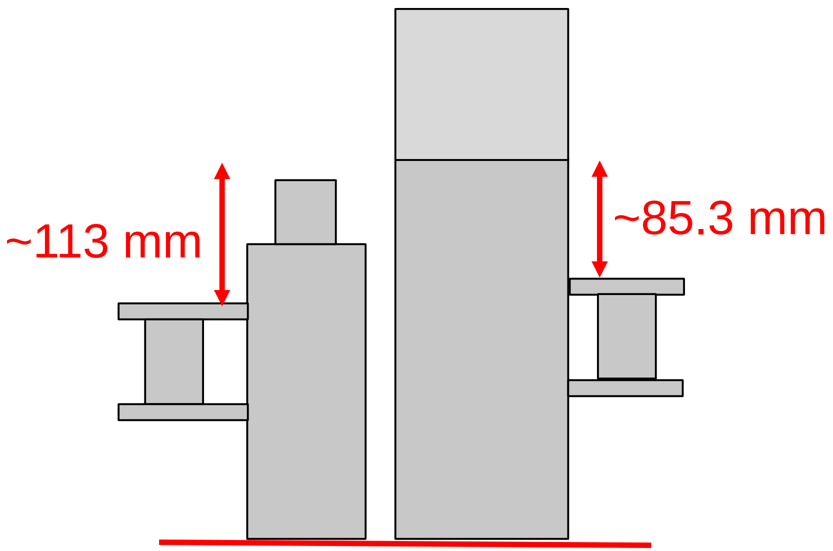
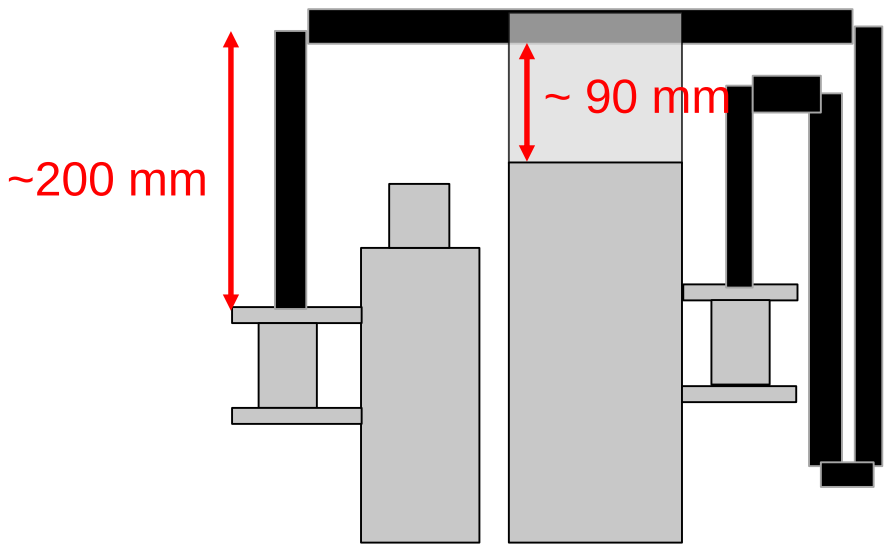
# New Boom Length

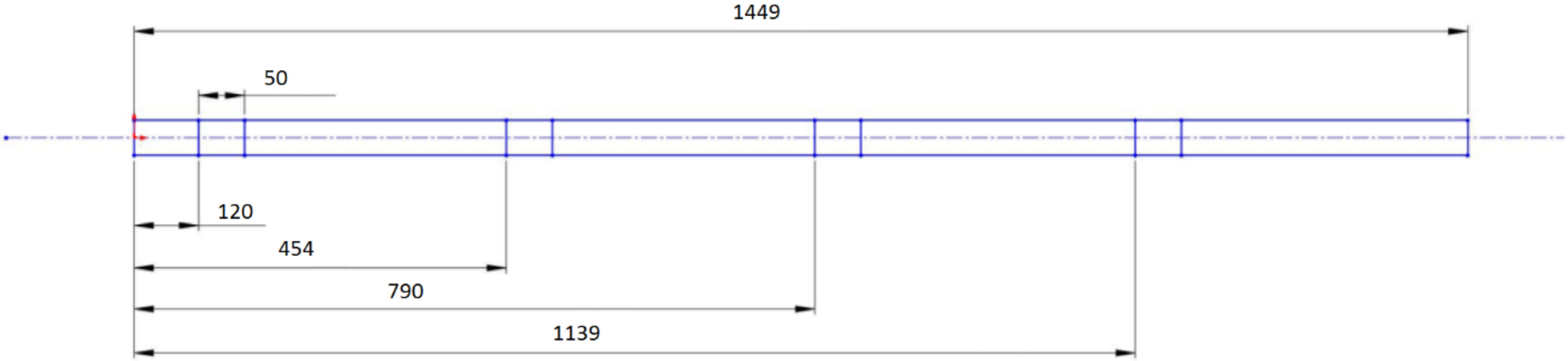



Camera as low as possible
(without going into the clearance)

# Old Boom Length



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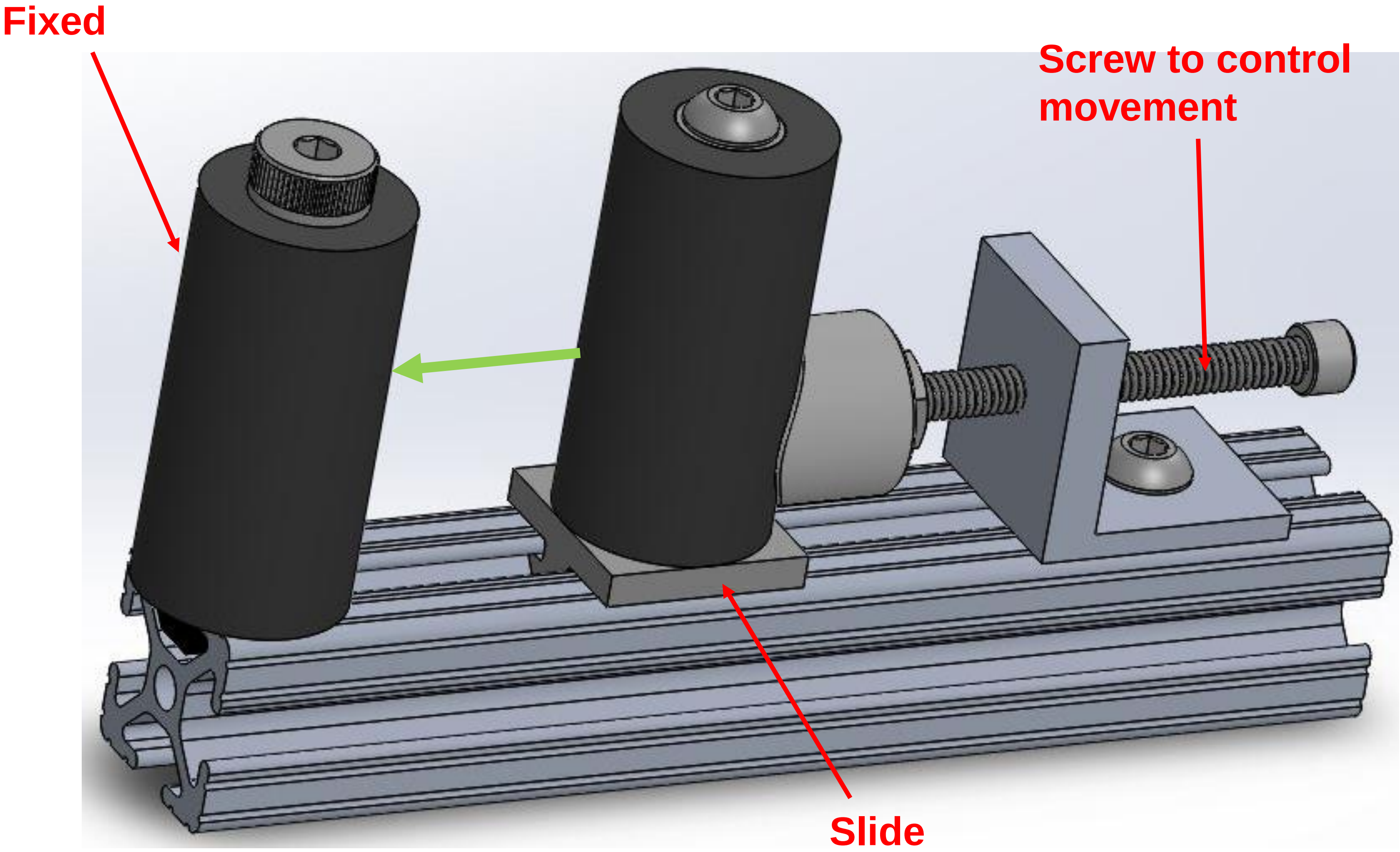
# Folding fixture

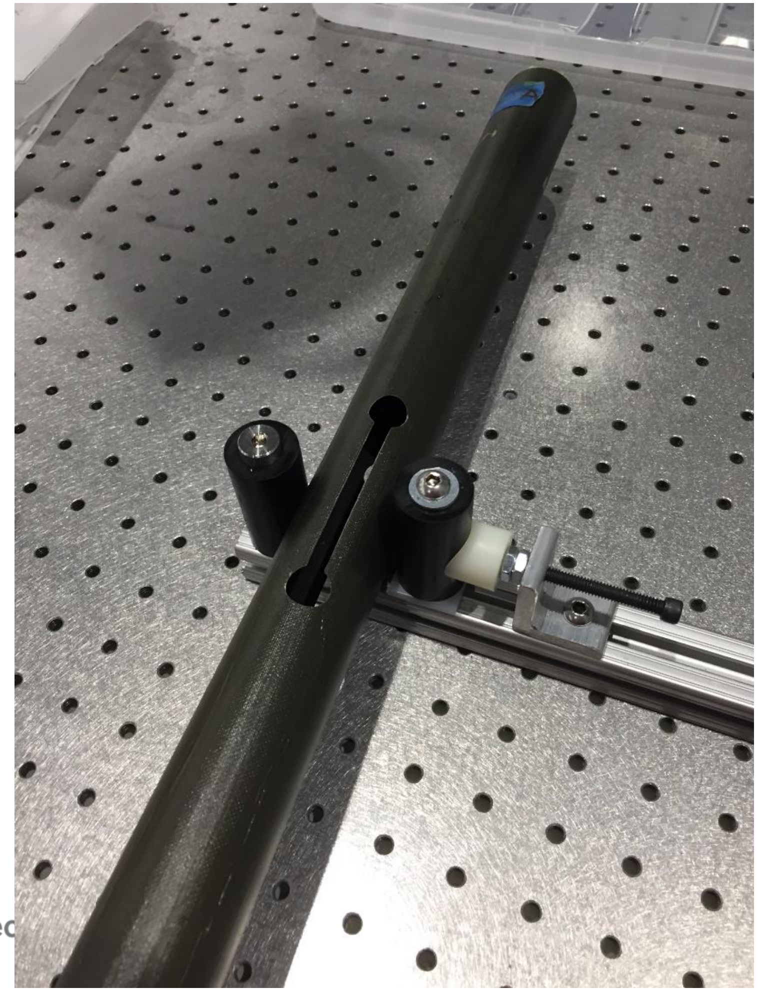
- **Objective: provide a reliable and repeatable way of folding the hinges that does not create cracks**

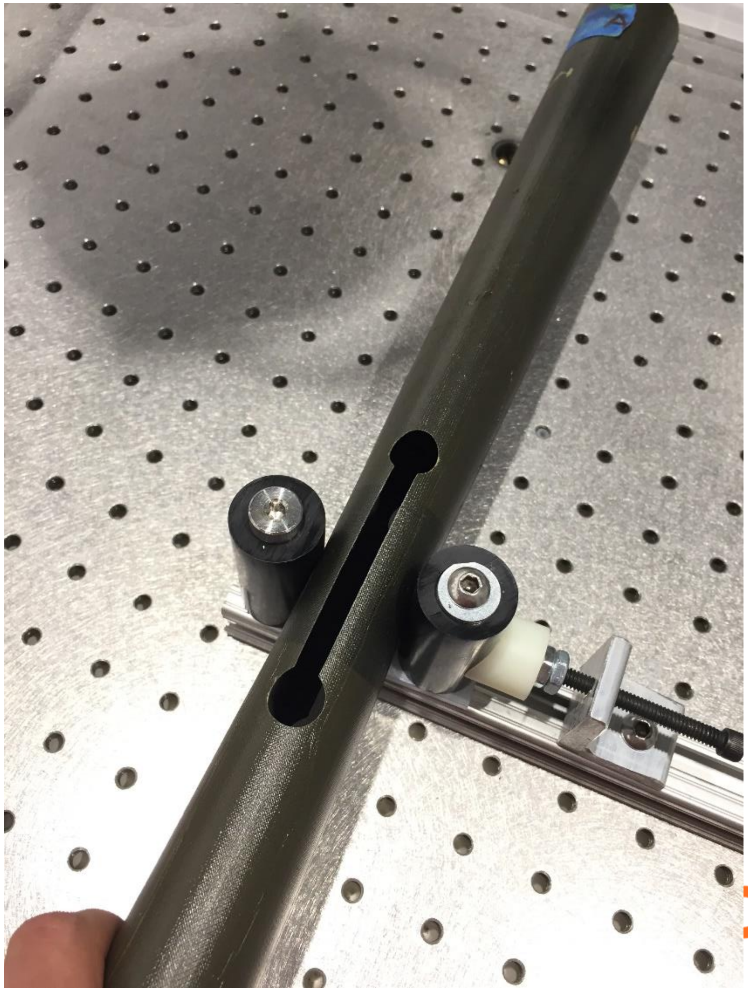
# Folding fixture



# Folding jig

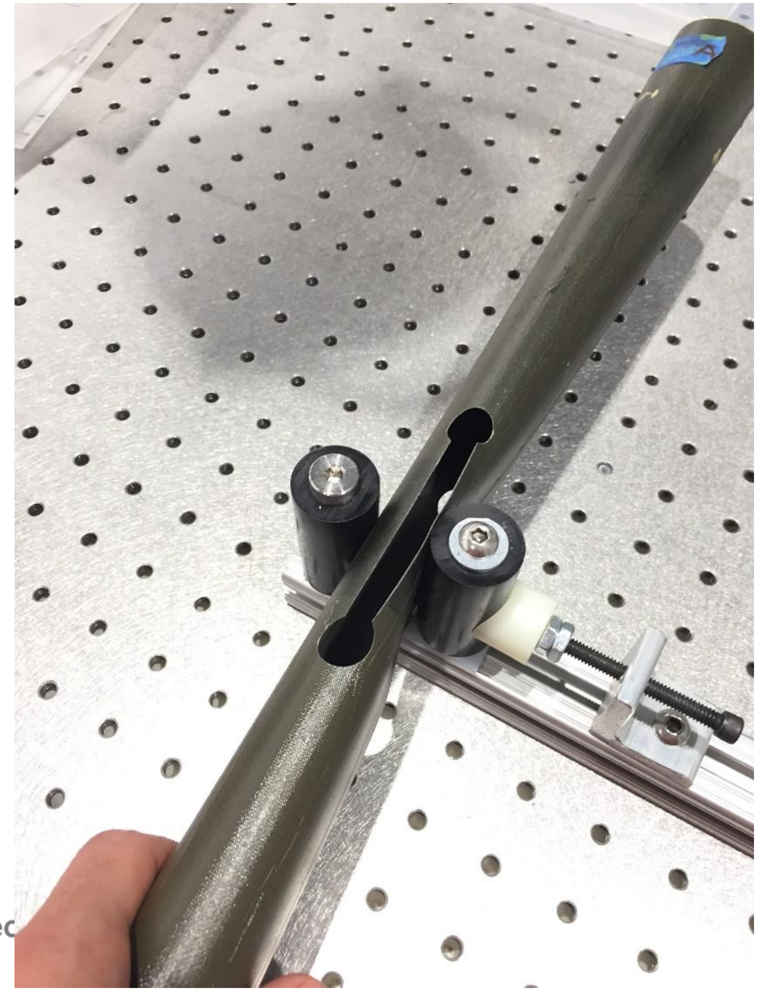
- **Tested with old hinges first, then new hinge (never folded)**

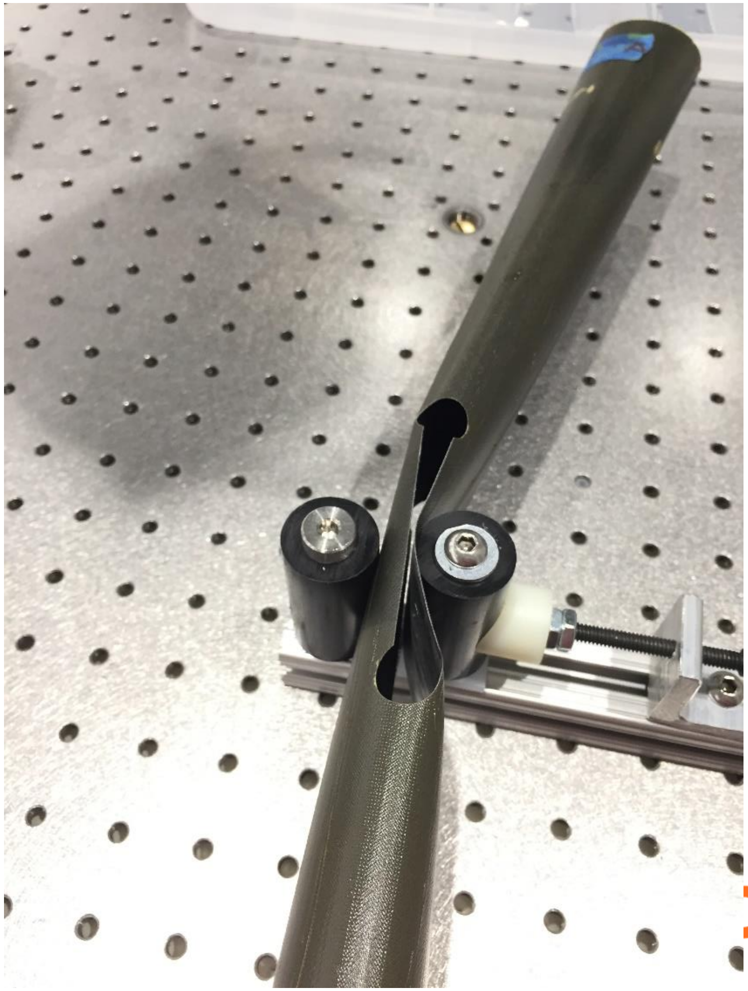




# Folding jig

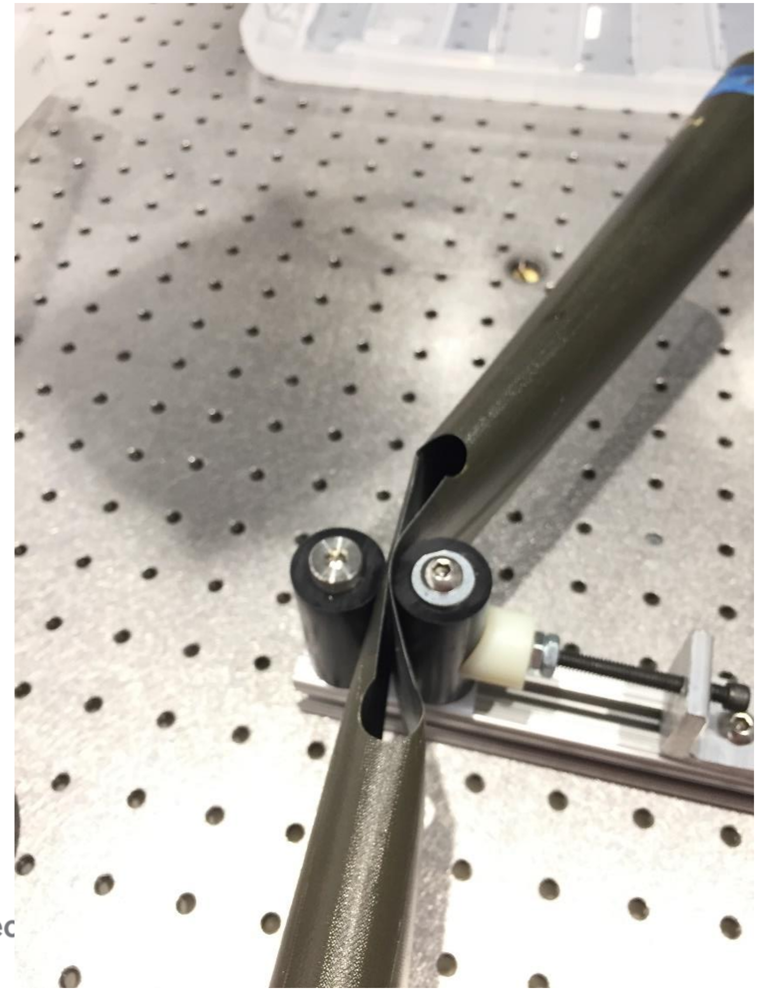
- **Tested with old hinges first, then new hinge (never folded)**

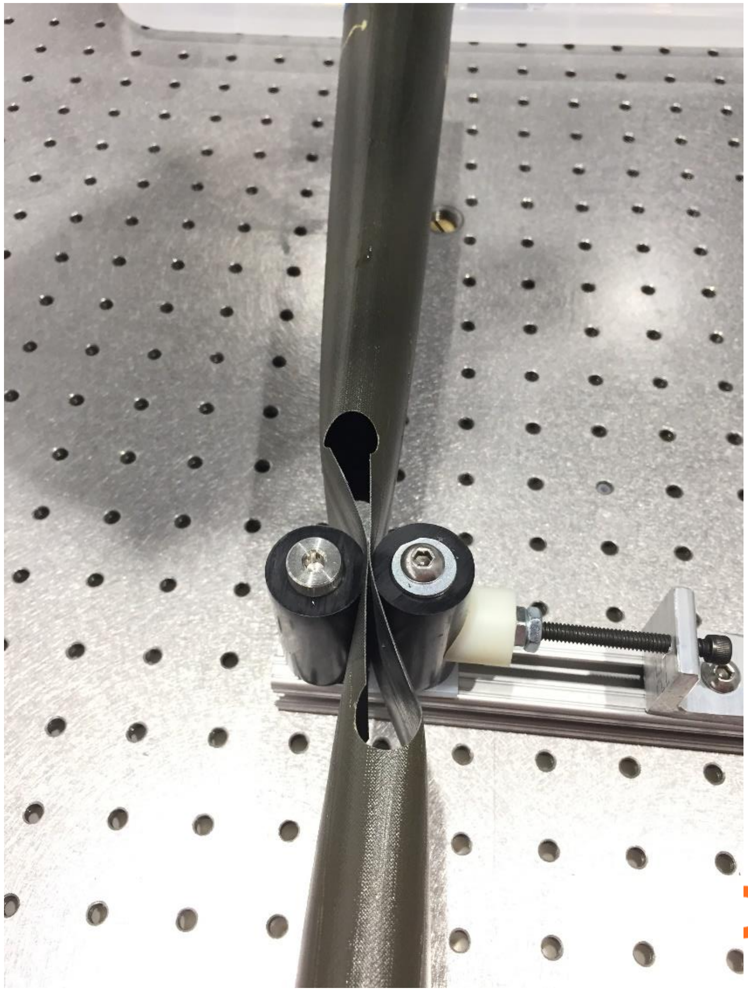




# Folding jig

- **Tested with old hinges first, then new hinge (never folded)**





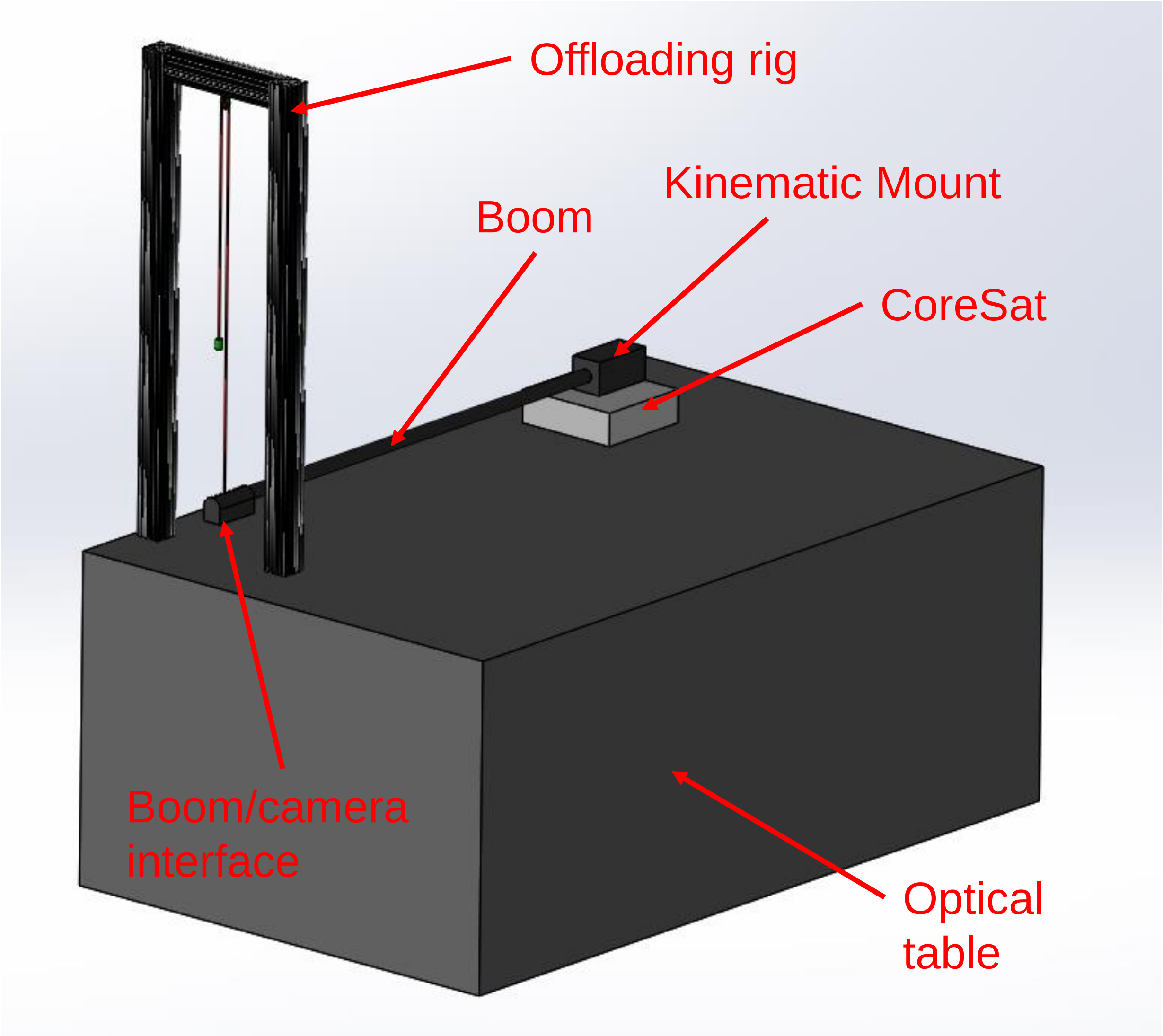
# Folding jig

- No visible damage appeared at the hinge location (folded 3 times)
- Folding is sometime a bit unstable (usually the inside tape spring flatten first, but it can be the opposite)
- You need to manually force the boom to fold in the right direction
- When fully flatten, the 2 tape spring are not always well aligned for complete folding (they need to slip to get to the right position for folding)
- Seems to provide a way to fold the boom with better repeatability

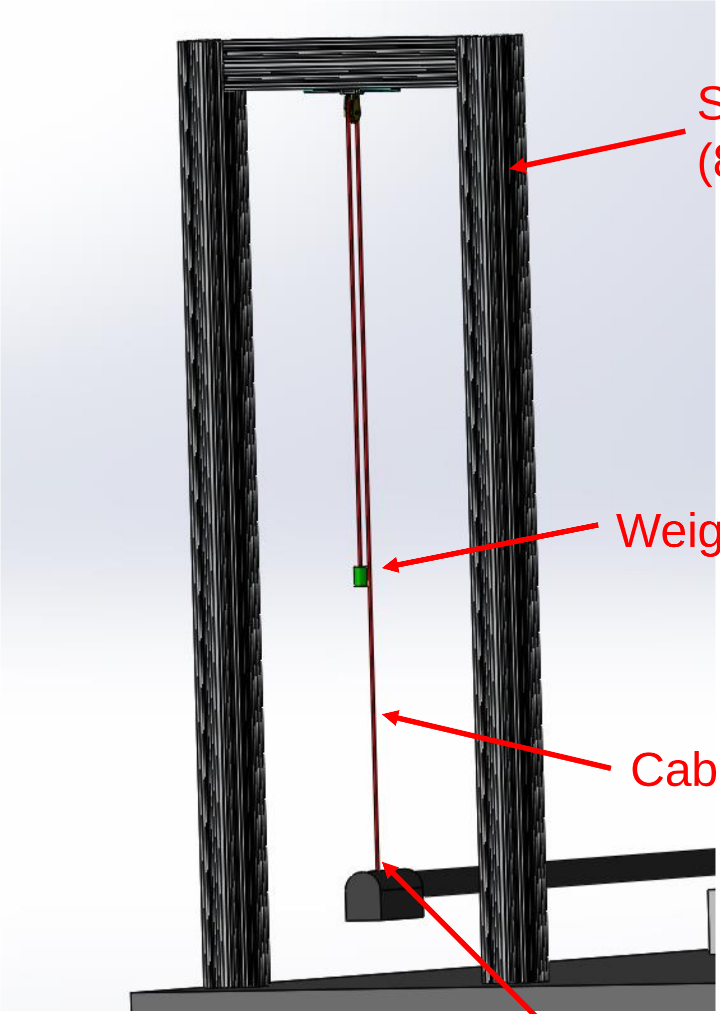
# Boom Offloading Rig

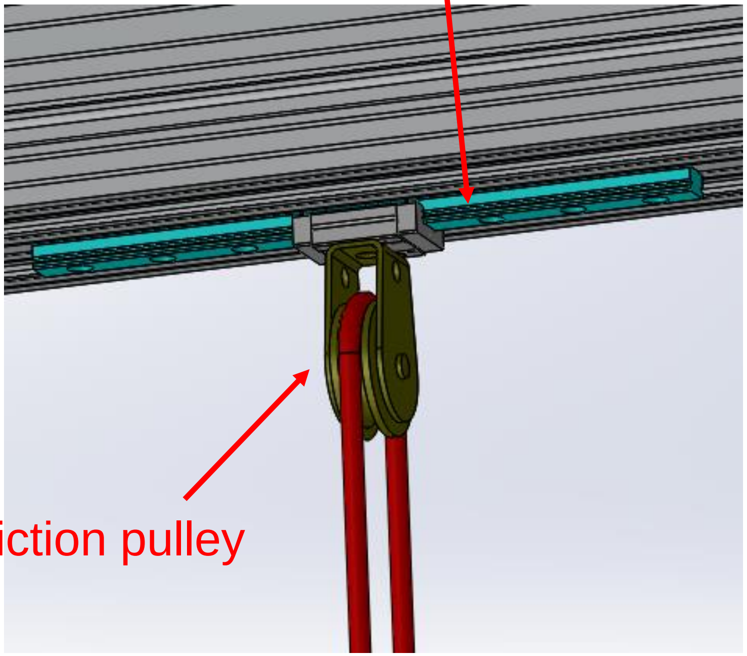
- The objective of the offloading rig is the prevent the boom from deflecting under gravity loading. This will ensure that the boom alignment done on the ground will remain valid once in space

# Boom Offloading Rig



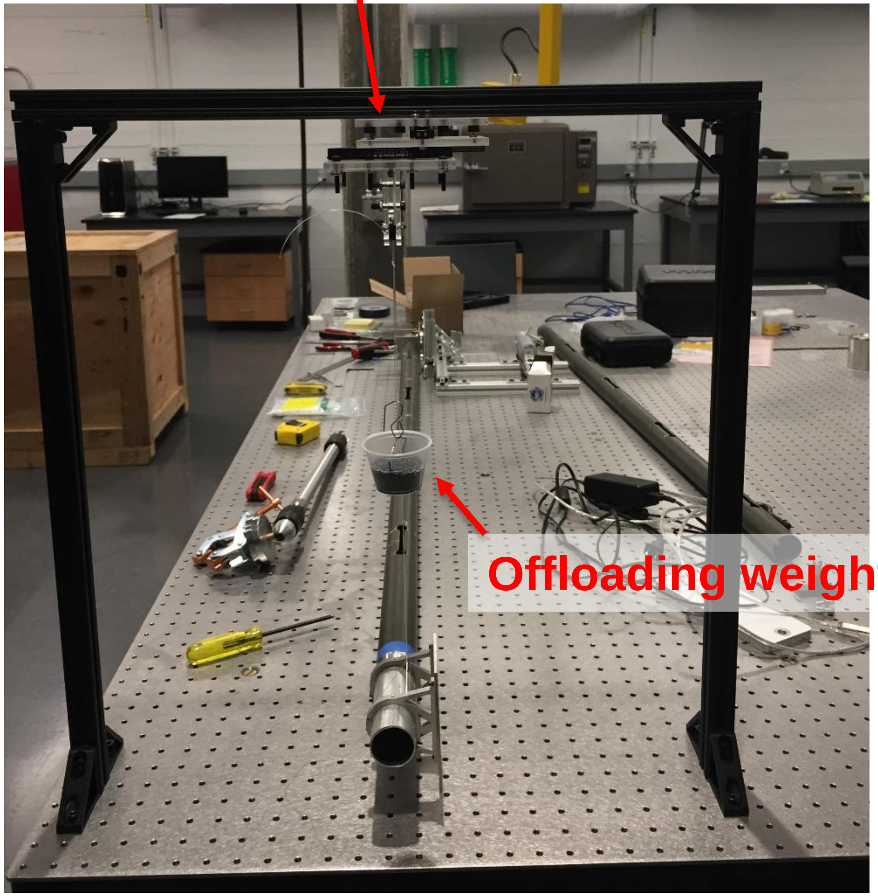
# Boom Offloading Rig



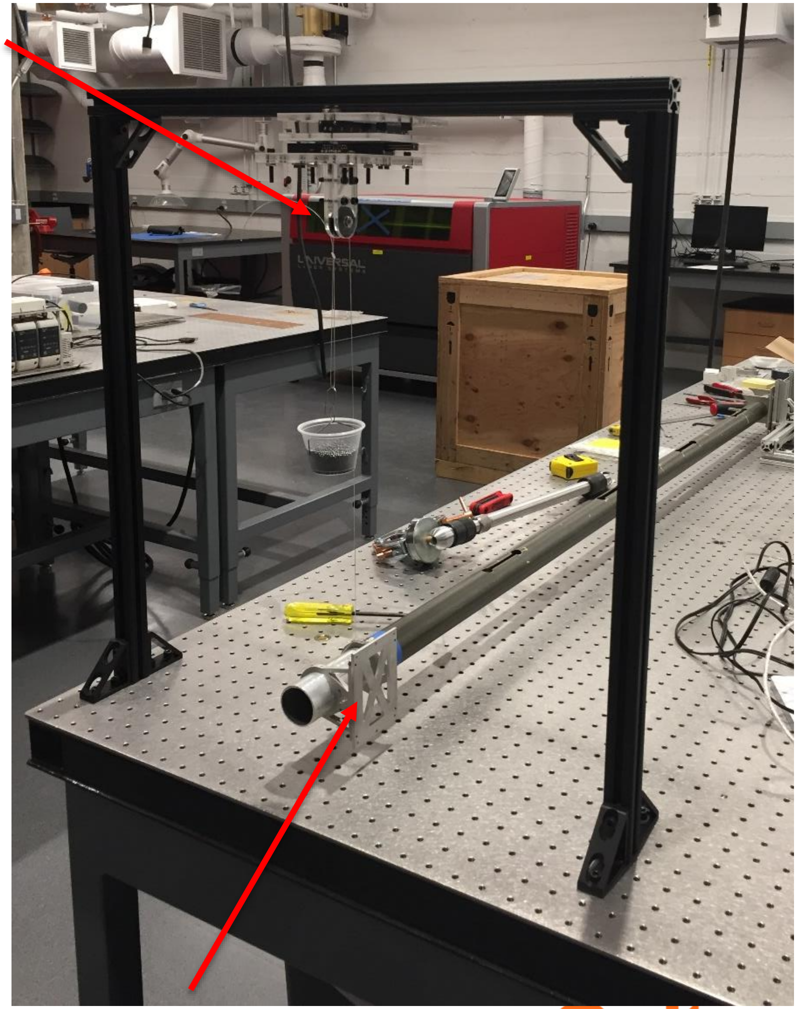
# Offloading Jig

2-axis sliding plateform



Offloading weight

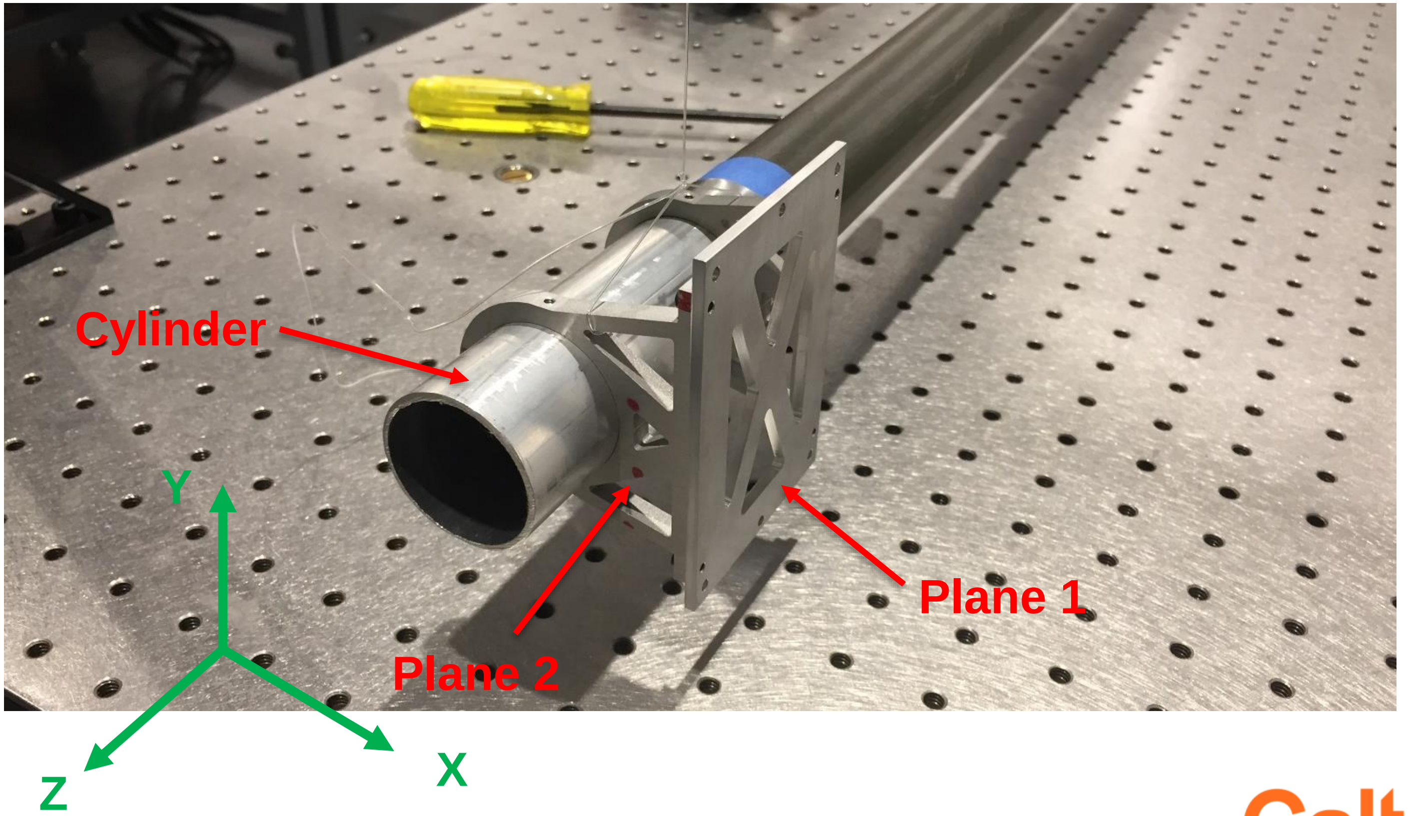
Pulley



Camera interface

# Offloading Jig

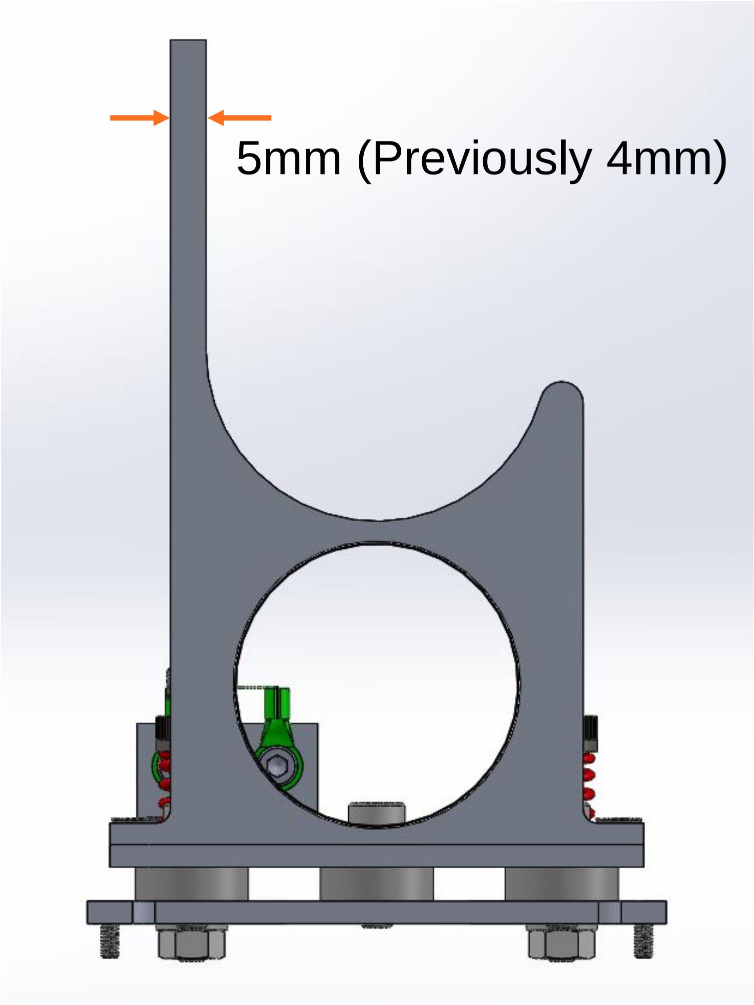
- Measure planes 1 and 2, and cylinder with the Faro arm scanner
- Clean point clouds and fit planes and cylinder
- Project cylinder axis on plane 2 to obtain an origin
- Use plane 1 normal as the rotational orientation

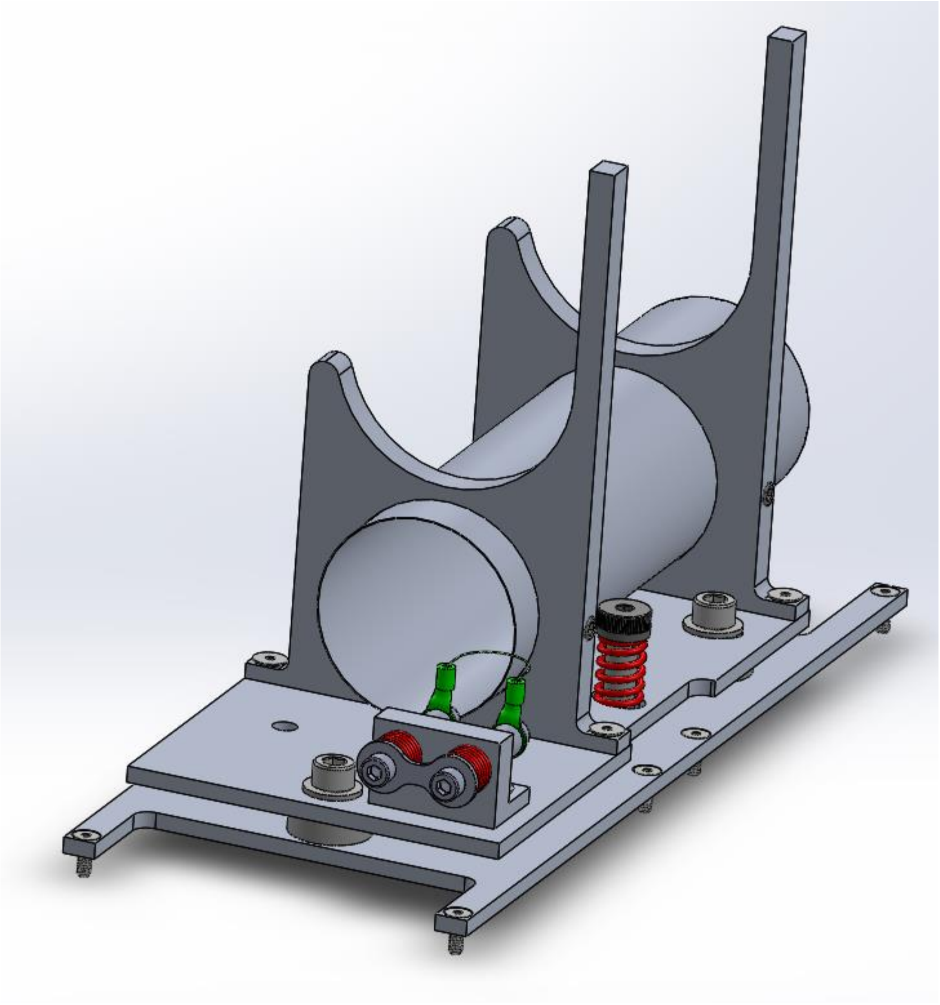


# New Kinematic Mount Design

- **Problem:**
  - When folded, boom cross-section width increase
  - Aging seems to amplify this phenomenon
  - Therefor, the boom can be stuck inside the collar mounts
- **Objective:**
  - Ensure reliable boom deployment even if boom change cross-section due to aging
- **Modifications:**
  - Removed one side of the collar mount
  - Increased size of remaining support
  - Changed Vectran cable path

# New Kinematic Mount Design





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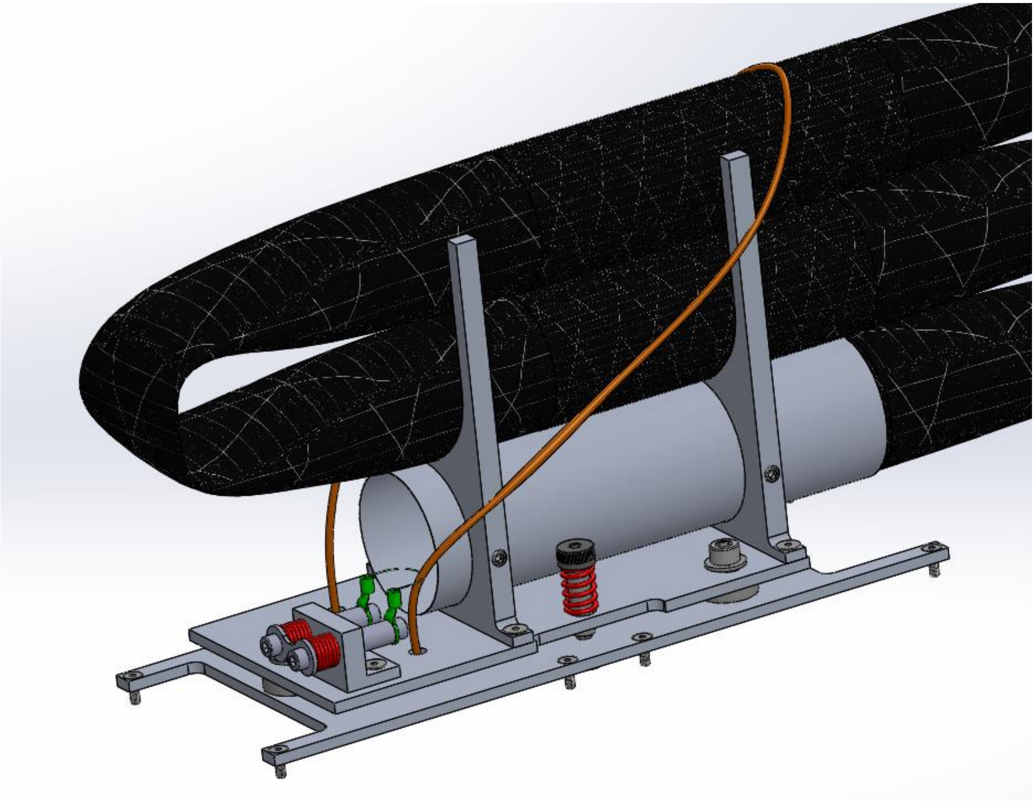
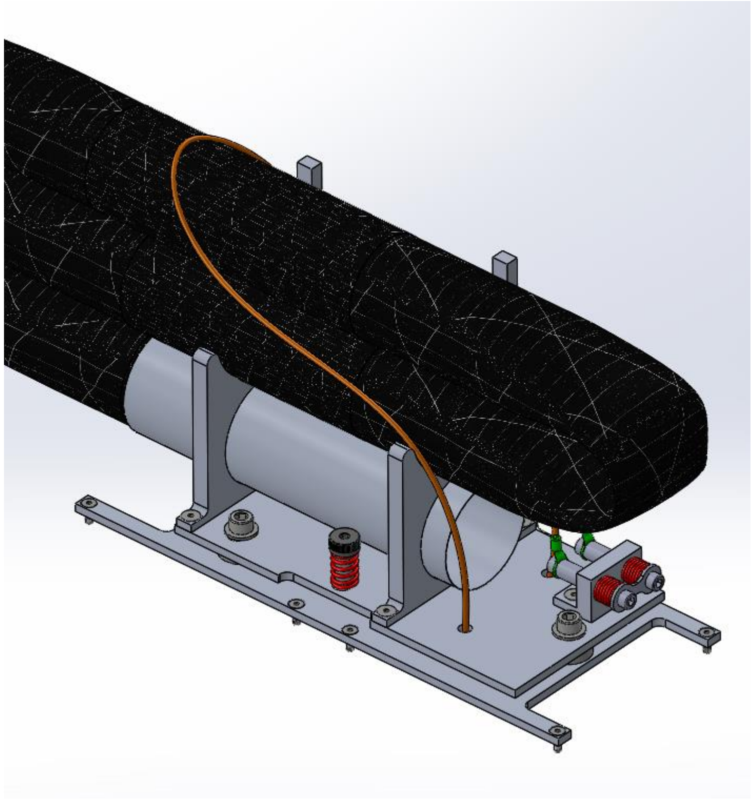
# New Kinematic Mount Design





# Summary

- We completed the design of the boom subsystem
- We studied the viscoelastic behavior of the composite boom
- We successfully performed:
  - Vibration testing
  - Deployment testing (both stages)
  - Accuracy testing following aging

# Future Work

- Anodize kinematic mount parts
- Cut the boom to final length
- Vibration of full folded boom