# Review Outline

1:00 pm: Introduction & Welcome (Pellegrino)
1:05 pm: Mission Overview (Baker & Arya)
1:20 pm: AAReST Spacecraft Bus (Underwood & Bridges)
2:30 pm: AAReST Telescope Payload

a) Optical System (Jackson)
b) Mirrors (Bongiorno)
c) Mirror Box (Wilson)
d) Boom (Bosi)
e) Camera (Sakovsky)
f) Electronics (Lee)
g) Calibration Algorithms (Talon)
h) Telescope Software (Wei)

5:45 pm: Discussion & Drinks at the Rath

Meeting Objective: *To determine if the design is appropriately mature to continue with the final design and fabrication and test phase.*

# AAReST History

2008 November: Large Space Apertures KISS workshop
2010 June: Ae105
- Initial mission design; mission requirement definition

2011 June: Ae105
- Spacecraft configuration revision: prime focus design
- Docking testbed commissioning

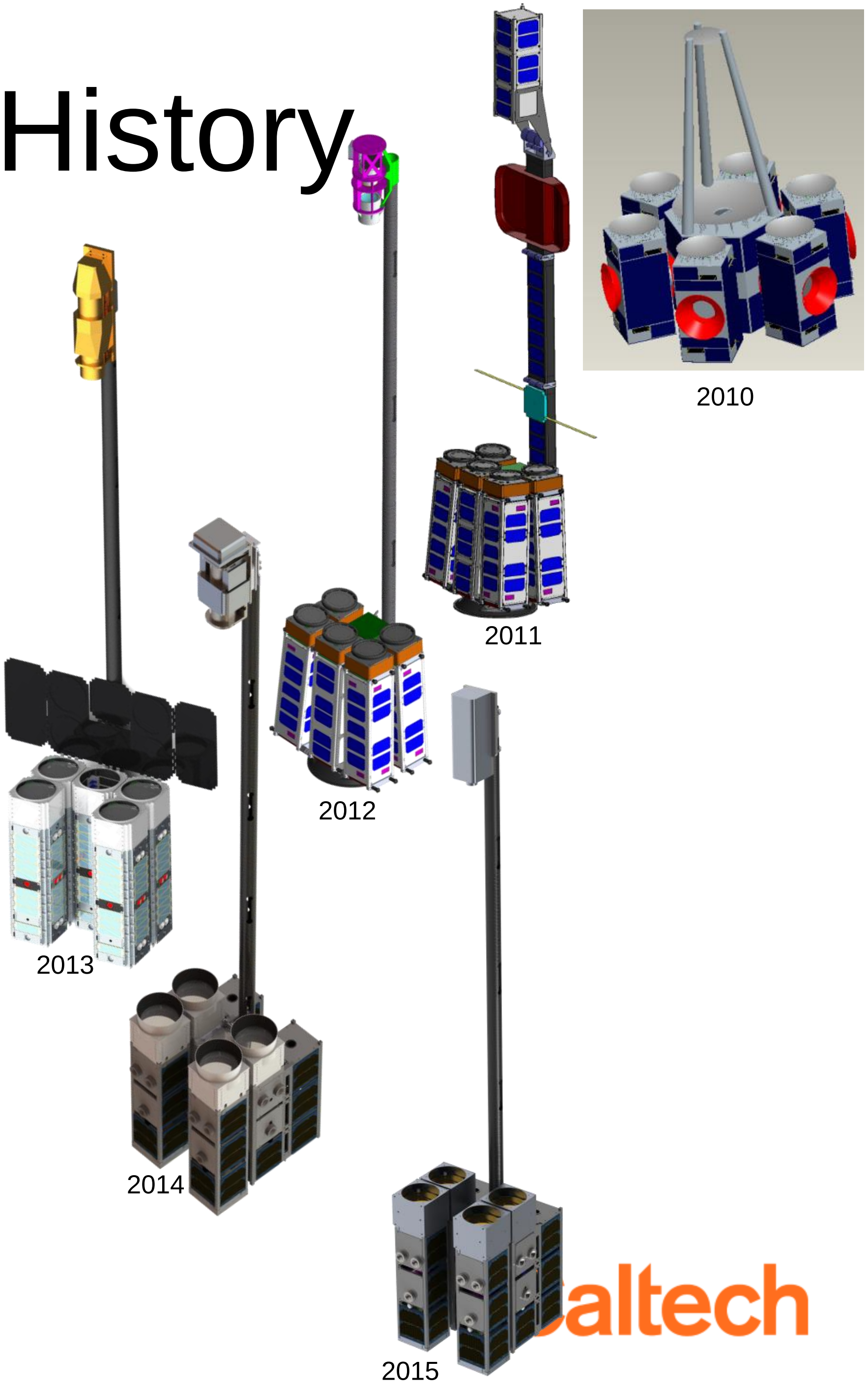
2012 June: Ae105
- Composite boom design and experiments
- Reconfiguration and docking experiments

**2012 September: Mission Concept Review**
2012 October: Division of responsibilities
- Surrey: Reconfiguration and docking
- Caltech: Deformable mirror and telescope payload

2013 June: Ae105
- Detailed camera design
- Thermal modeling

**2013 September: Preliminary Design Review**
2014 June: Ae105
- Camera opto-mechanical prototype
- Boom gravity offload deployment testing
- Mirror vibro-acoustic experiments
- TVAC chamber commissioning
- Telescope testbed commissioning

**2014 September: Detailed Design Review**
2015 June: Ae105
- Engineering models/prototypes of boom, camera
- Mirror thermal characterization
- Software and algorithms prototyping and testing



# Team Responsibilities

- University of Surrey
  - NanoSat and MirrorCraft
  - Docking system
  - Integrated spacecraft and mission ops
- Caltech
  - Deformable mirrors
  - Telescope system
  - Optical focus algorithm
  - Boom
- JPL
  - Class instructors
  - Project management
  - Manufacturing facilities

# Caltech Team

- Ae105 class designs, builds, analyzes, tests components
- Ae205 class provides mentorship and guidance
- JPL class instructors, project manager
- JPL provides mirror manufacturing facilities
- Postdocs, upper-year grad students, SURF students provide focused support

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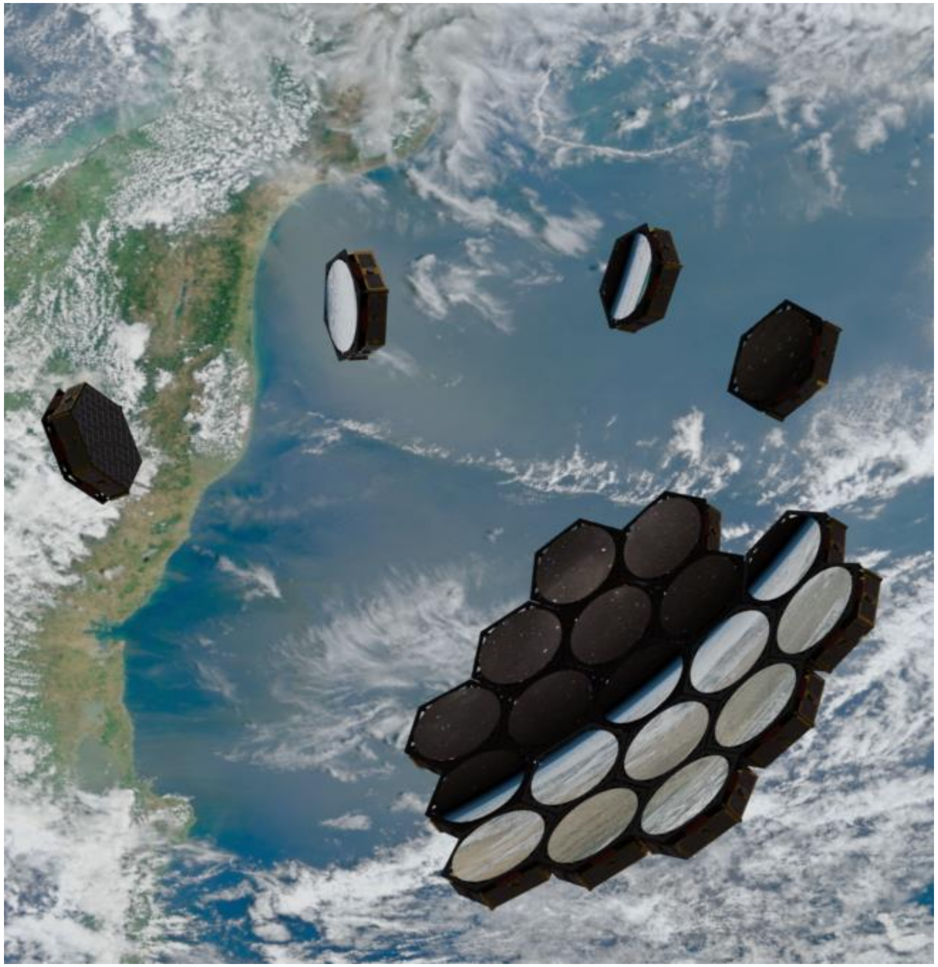
# Mission Overview

Manan Arya

# Motivation: Building Large Space Telescopes

- Mirror dia. of current and planned space telescopes limited by constraints of a single launch
  - Hubble (1990): Ø 2.4 m
  - JWST (2018): Ø 6.5 m
  - HDST (2030+): Ø 11.7 m
- New paradigms needed for Ø 30 m+ segmented primary:
  - Autonomous assembly in orbit
  - Active ultralight mirror segments
- Active mirrors relax tolerances for assembly and manufacturing, correct thermal distortions
- Modular, robust, low-cost architecture





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JWST

HDST

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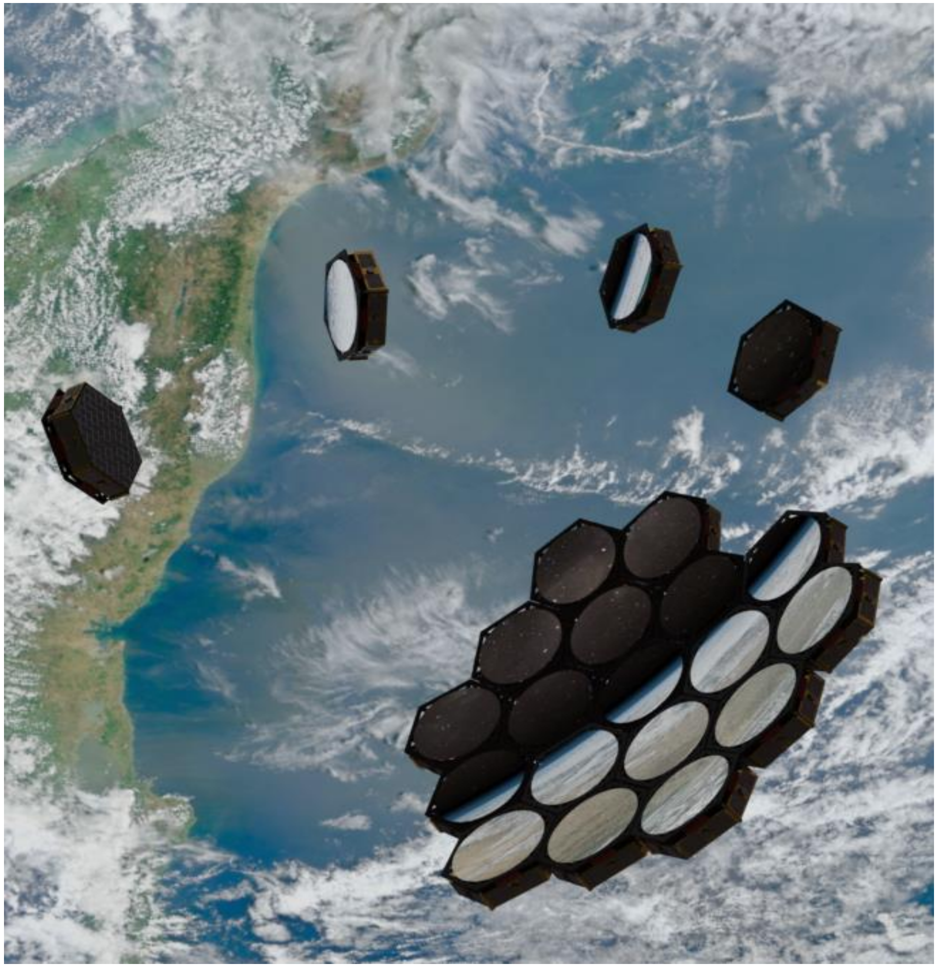



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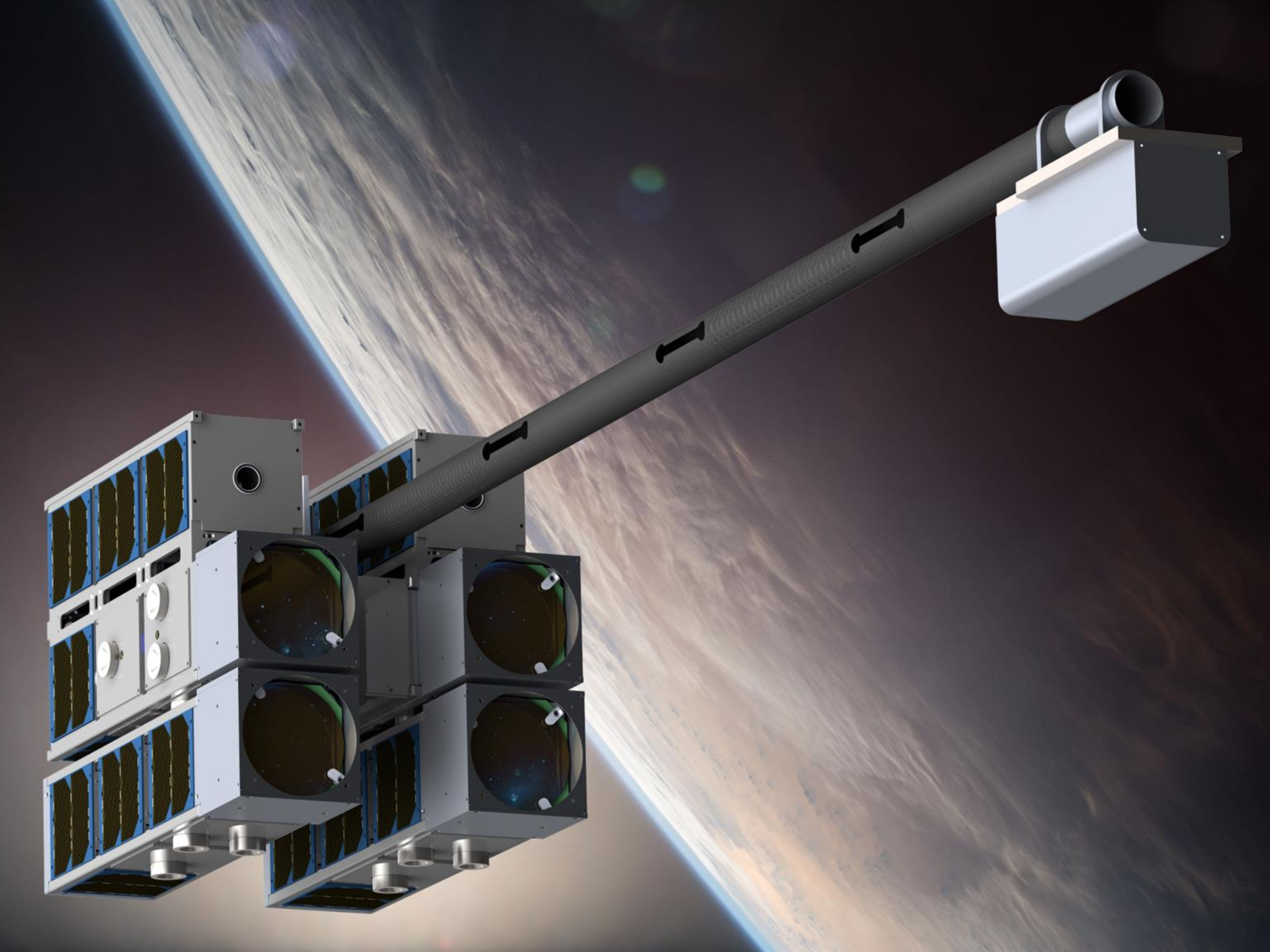
# AAReST Objectives

- Demonstrate key technologies:
  - Autonomous assembly and reconfiguration of modular spacecraft carrying mirror segments
  - Active, lightweight deformable mirrors operating as segments in a primary
- Operate for as long as necessary to accomplish the objectives (~90 days)
- Gather engineering data to enable development of the next system



# AAReST Spacecraft

# AAReST Spacecraft

CoreSat
Power, Comm., Telescope ADCS
*U. of Surrey*



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# AAReST Spacecraft




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# AAReST Spacecraft

**MirrorSat (×2)**
Reconfigurable free-flyers
*U. of Surrey*

**CoreSat**
Power, Comm., Telescope ADCS
*U. of Surrey*

**Deformable Mirrors (×2)**
Active mirror segments
*Caltech*

# AAReST Spacecraft

**MirrorSat (×2)**
Reconfigurable free-flyers
*U. of Surrey*

**CoreSat**
Power, Comm., Telescope ADCS
*U. of Surrey*

**Reference Mirrors (×2)**
Fixed figure mirror segments
*Caltech*

**Deformable Mirrors (×2)**
Active mirror segments
*Caltech*



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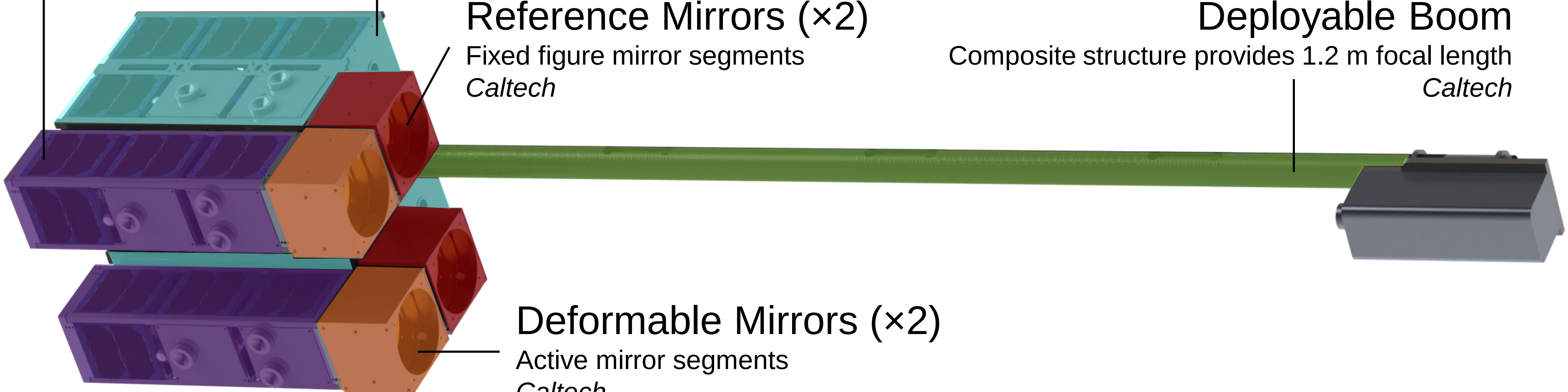
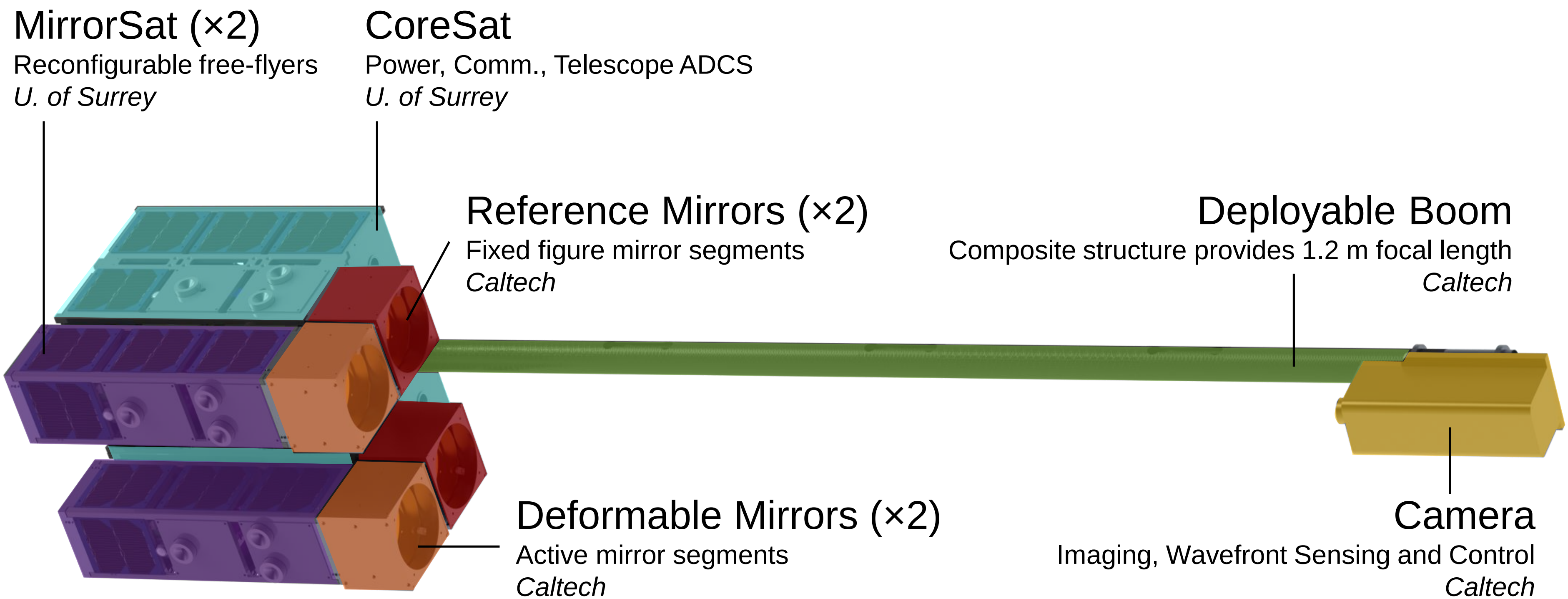
# AAReST Spacecraft



# AAReST Spacecraft



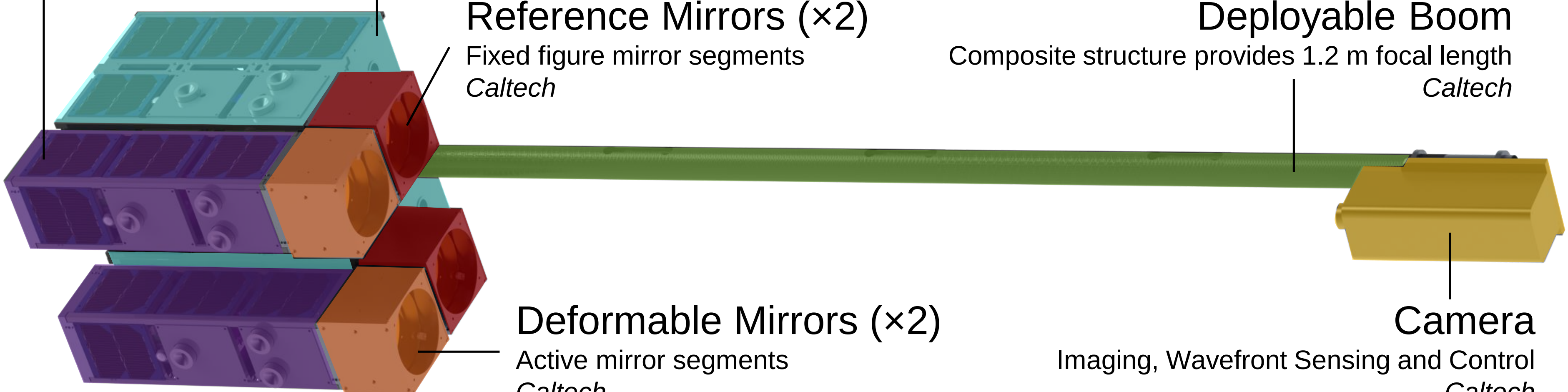
# AAReST Spacecraft

**MirrorSat (×2)**
Reconfigurable free-flyers
*U. of Surrey*

**CoreSat**
Power, Comm., Telescope ADCS
*U. of Surrey*

**Reference Mirrors (×2)**
Fixed figure mirror segments
*Caltech*

**Deployable Boom**
Composite structure provides 1.2 m focal length
*Caltech*



**Deformable Mirrors (×2)**
Active mirror segments
*Caltech*

**Camera**
Imaging, Wavefront Sensing and Control
*Caltech*

| | | | |
|---|---|---|---|
| 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.) |



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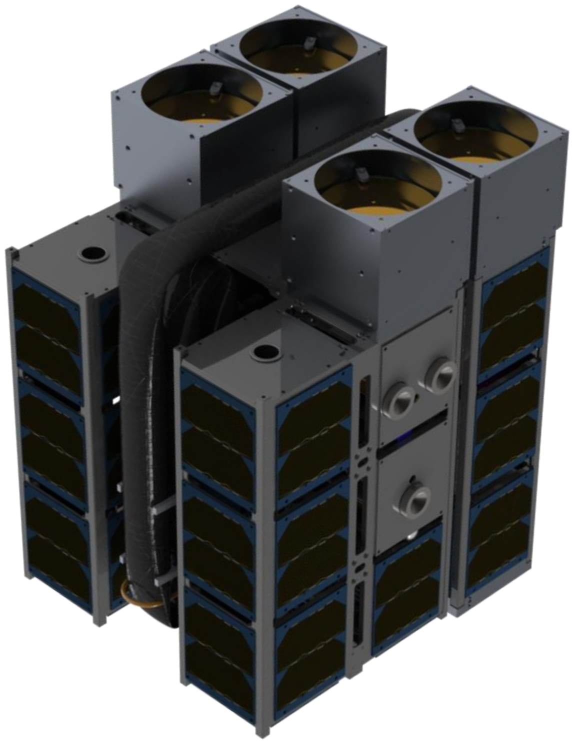
# Concept of Operations

| 1. Launch | 2. Telescope Deployment | 3. Telescope Calibration & Imaging | 4. Reconfiguration | 5. Telescope Recalibration & Imaging | 6. Extended Mission |
|---|---|---|---|---|---|



Launch in a compact, stowed volume
- 46 cm × 34 cm × 30 cm



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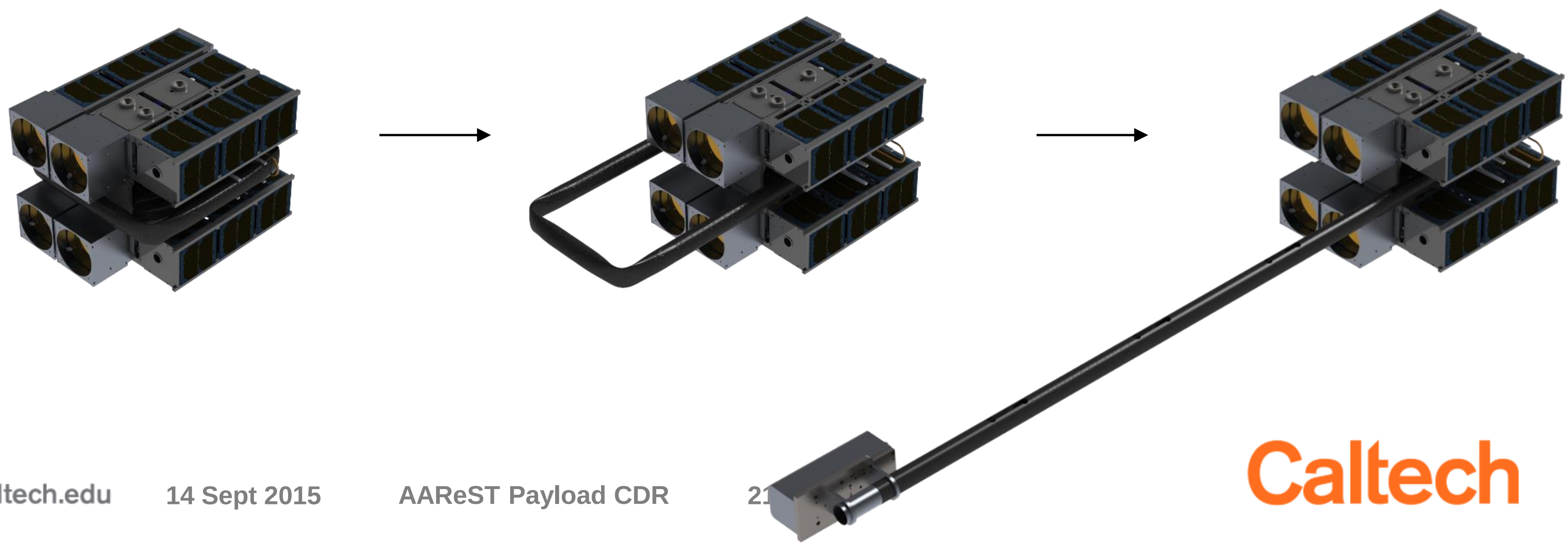
# Concept of Operations

| 1. Launch | 2. Telescope Deployment | 3. Telescope Calibration & Imaging | 4. Reconfiguration | 5. Telescope Recalibration & Imaging | 6. Extended Mission |
|---|---|---|---|---|---|

- Turn on, verify satellite components
- Stabilize attitude, temperature

- Deploy boom in two stages:
  1. Boom segments unfold
  2. Camera is released
- Uncage deformable mirrors



# Concept of Operations

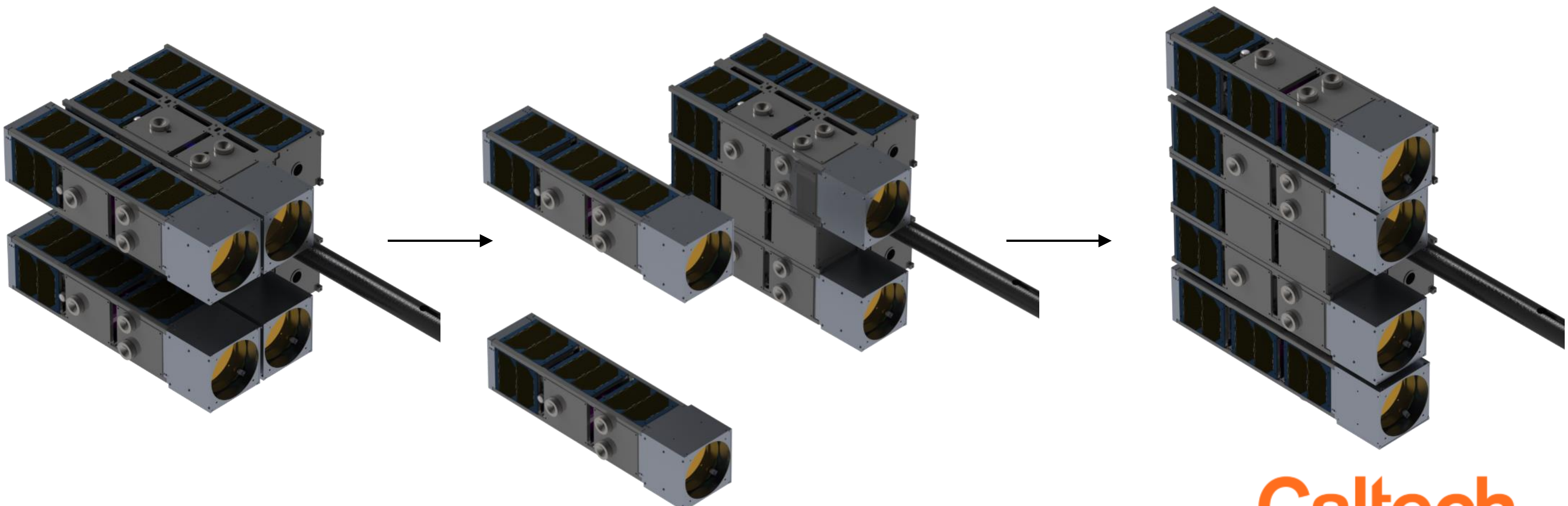
| 1. Launch | 2. Telescope Deployment | 3. Telescope Calibration & Imaging | 4. Reconfiguration | 5. Telescope Recalibration & Imaging | 6. Extended Mission |
|---|---|---|---|---|---|

- Telescope points to a bright reference star
- Calibrate:
  - Segment tip/tilt/piston
  - Deformable mirror surface figure
- Camera provides feedback for segment calibration

# Concept of Operations

| 1. | 2. | 3. | 4. | 5. | 6. |
|---|---|---|---|---|---|
| Launch | Telescope Deployment | Telescope Calibration & Imaging | Reconfiguration | Telescope Recalibration & Imaging | Extended Mission |

- MirrorSats release from CoreSat (one at a time)
- Fly out ~1 m
- Re-dock into “wide” configuration

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# Concept of Operations

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# Concept of Operations

| 1. Launch | 2. Telescope Deployment | 3. Telescope Calibration & Imaging | 4. Reconfiguration | 5. Telescope Recalibration & Imaging | 6. Extended Mission |
|---|---|---|---|---|---|

- Co-align star images from different segments to improve SNR
  - Pre-cursor to co-phasing
- Produce images of extended sources (e.g. Moon, Earth) for outreach



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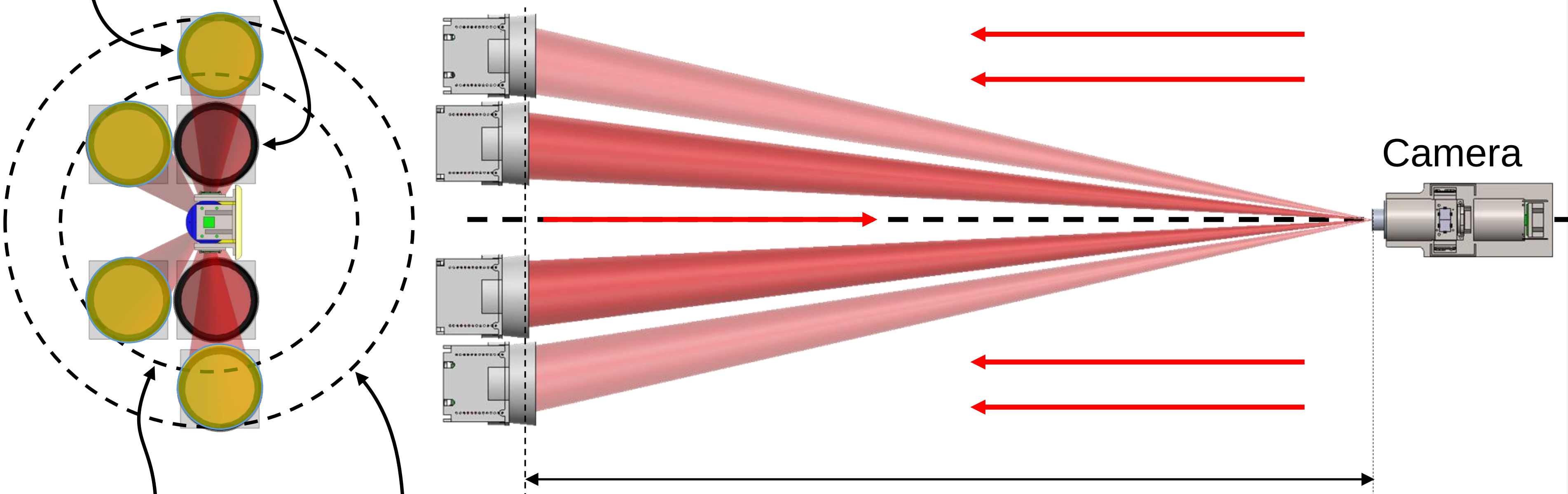
# Mission Requirements

- Minimum mission
  1. Produce one focused image from a deformable mirror
     - 80% encircled energy radius from point source < 25 μm
  2. Perform at least one in-flight autonomous spacecraft reconfiguration maneuver to demonstrate space assembly capability
- Extended mission
  1. Produce one focused image from a deformable mirror after reconfiguration
  2. Coalign images to improve SNR and demonstrate precursor to co-phasing
  3. Produce at least two images of other sources (e.g. Earth and Moon) for outreach purposes

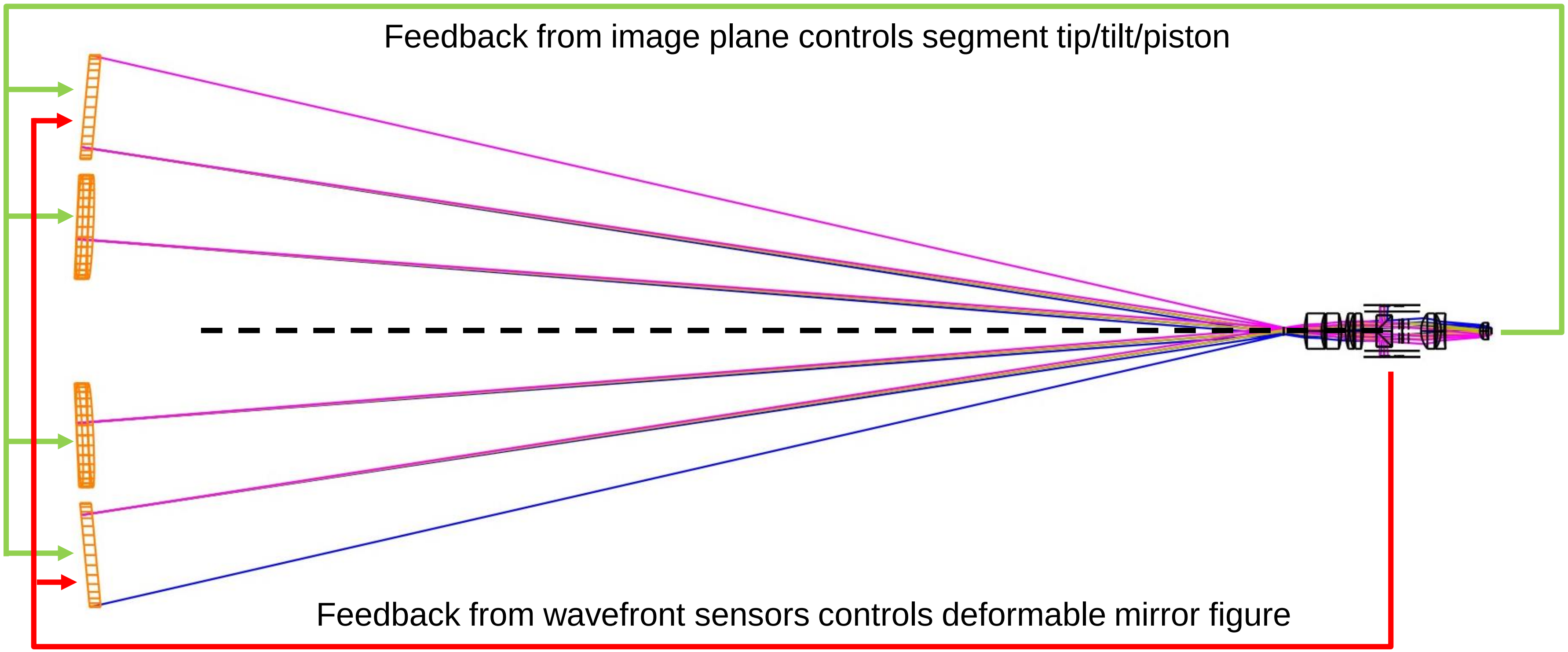
# AAReST Optical Overview



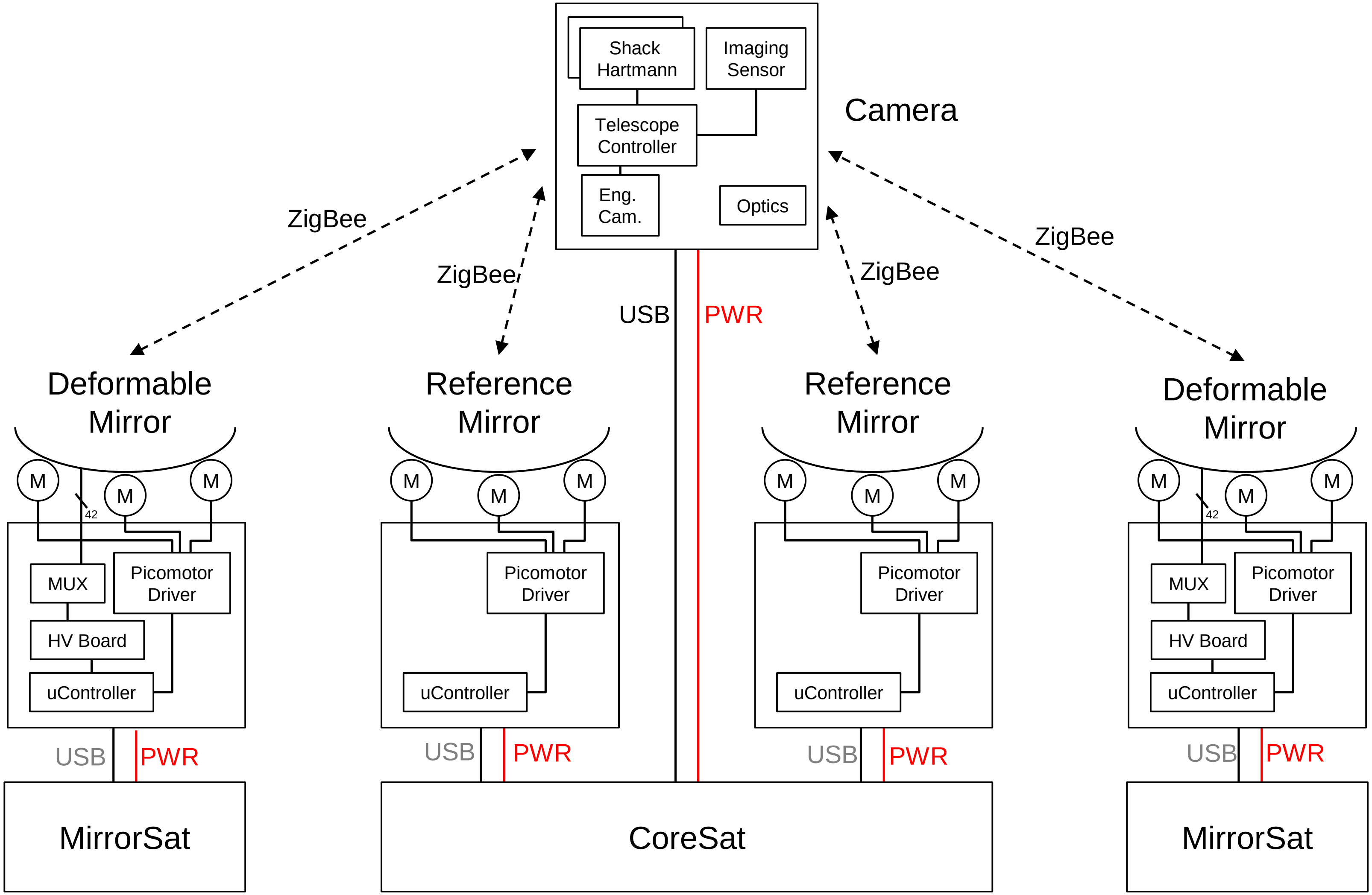

- Field of View : 0.34°
- Optical bandwidth: 465-615 nm (540 nm center)

# Telescope Alignment and Control

- Automatically correct for deployment errors, manufacturing errors and thermal disturbances with active calibration in-flight
- Actuators:
  - 3 rigid body motion (RBM) actuators per segment
  - 41 piezoelectric actuators per deformable mirror
- Sensors:
  - Image plane camera
  - Shack-Hartmann Wavefront Sensors (SHWS)



# AAReST Payload Block Diagram



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# 2015 Payload Accomplishments

- Produced deformable mirrors using spherically curved substrates
  - Previous DMs were flat
- Demonstrated actuation of DM using proto-flight high-voltage (HV) supply electronics
  - Previous DM actuation used benchtop HV supplies
- Constructed a camera mechanical prototype with integrated optics and detectors
- Validated telescope alignment algorithms on telescope testbed with the camera prototype
- Successfully interfaced image sensors and telescope CPU
- Produced in-house full-length composite booms free from defects
- Built boom fixture prototype, and tested boom deployment stage 1
- Wrote and tested telescope autonomy software on flight CPU
- Designed and tested piezomotor driving electronics



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# Optical System

Kathryn Jackson

caltech.edu

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# Outline

- Optical System Overview
- Baseline Optical Requirement
- Rigid Mirrors
- Deformable Mirrors
  - Performance Requirements
  - System Model
  - Monte Carlo Optical Tolerance Simulations
- Pointing and Attitude Stability
- Signal to Noise Ratio
  - Science Detector
  - Wavefront Sensors
- Summary



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# Optical System Overview

- AAReST has been designed to meet its Baseline Requirement of 80% encircled energy from each individual mirror segment within a 25μm radius at all points within the 0.34$^{o}$ Field of View.
- Given the optical system design, key system elements have been identified, and their impact on optical performance assessed.



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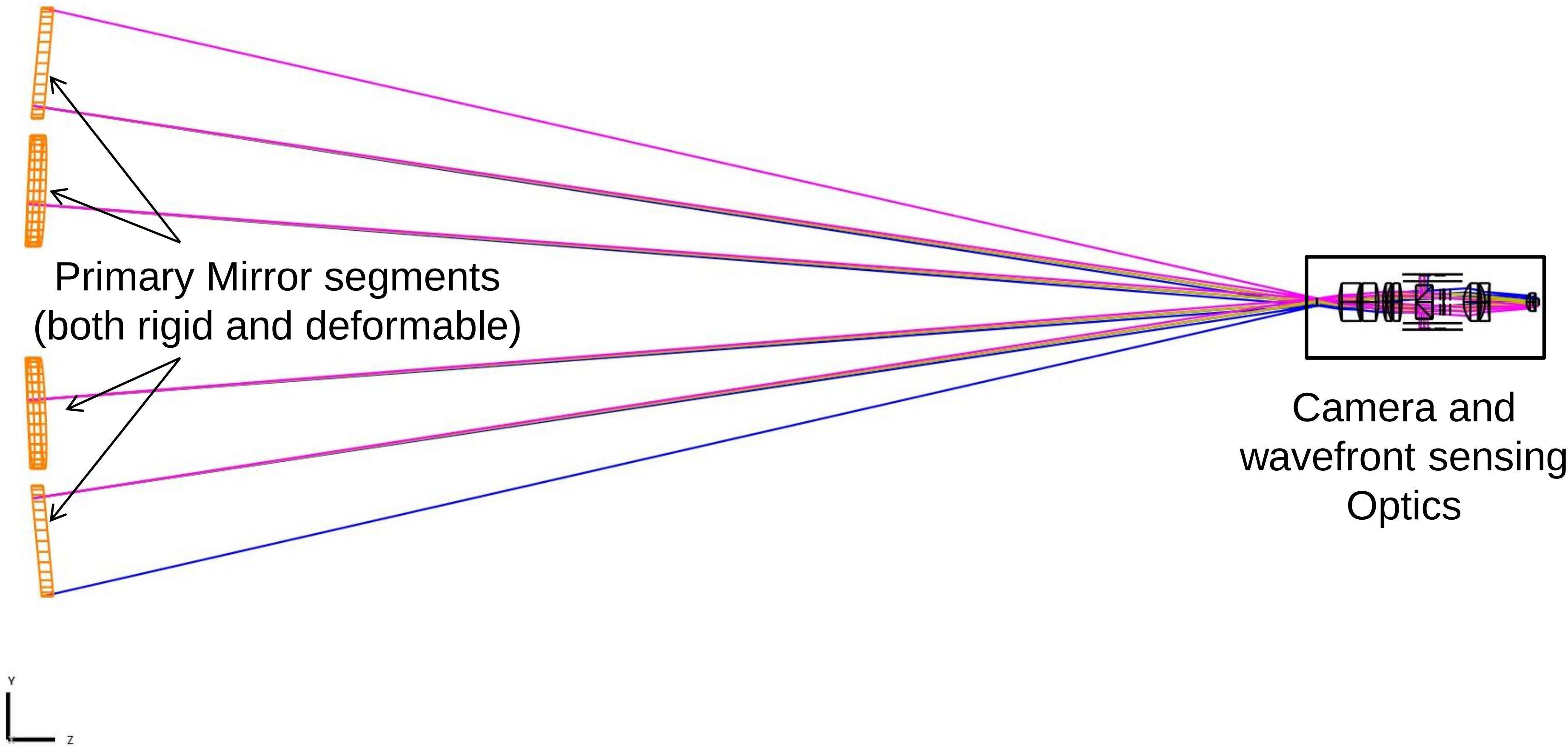
# Optical System Overview



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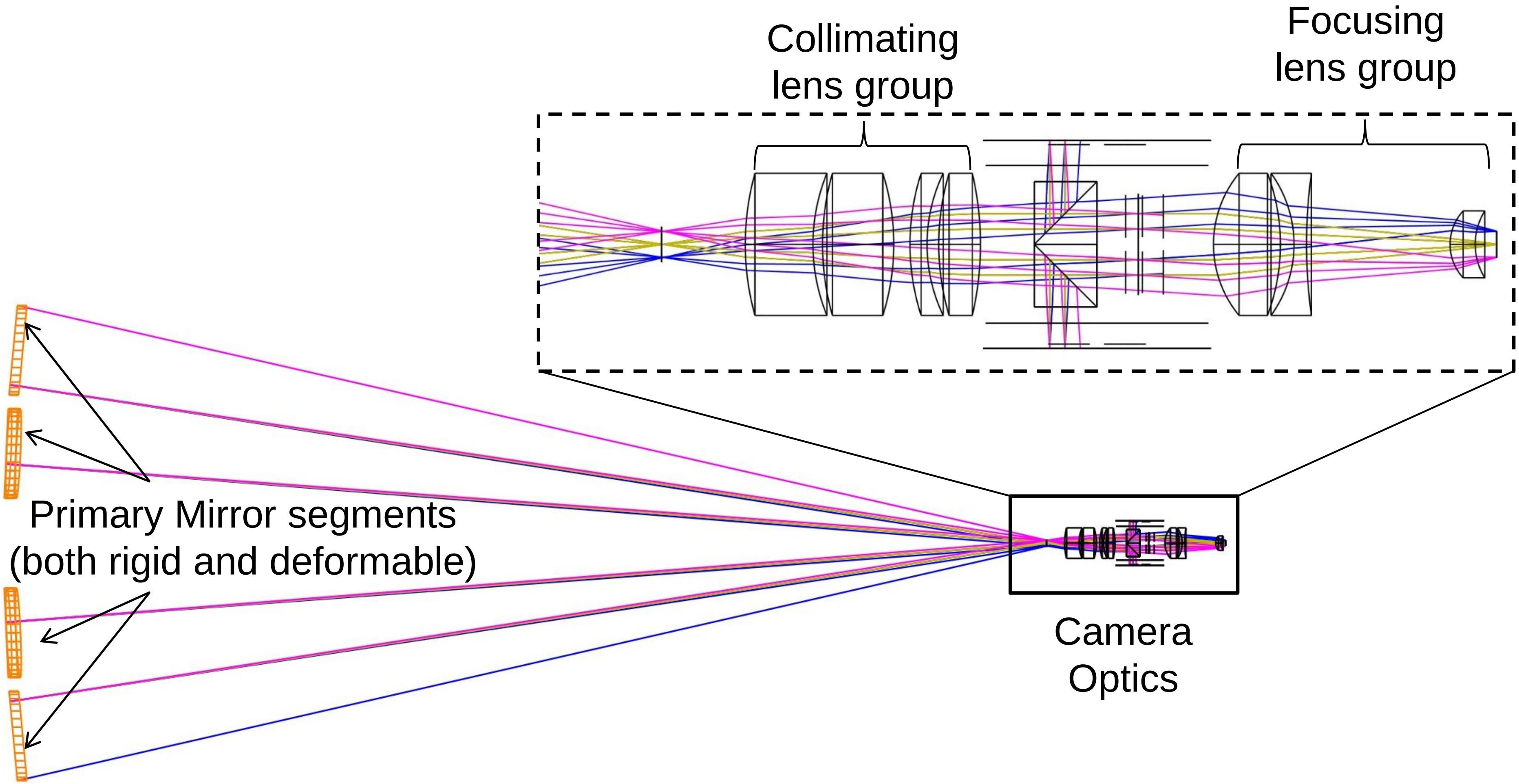
# Optical System Overview



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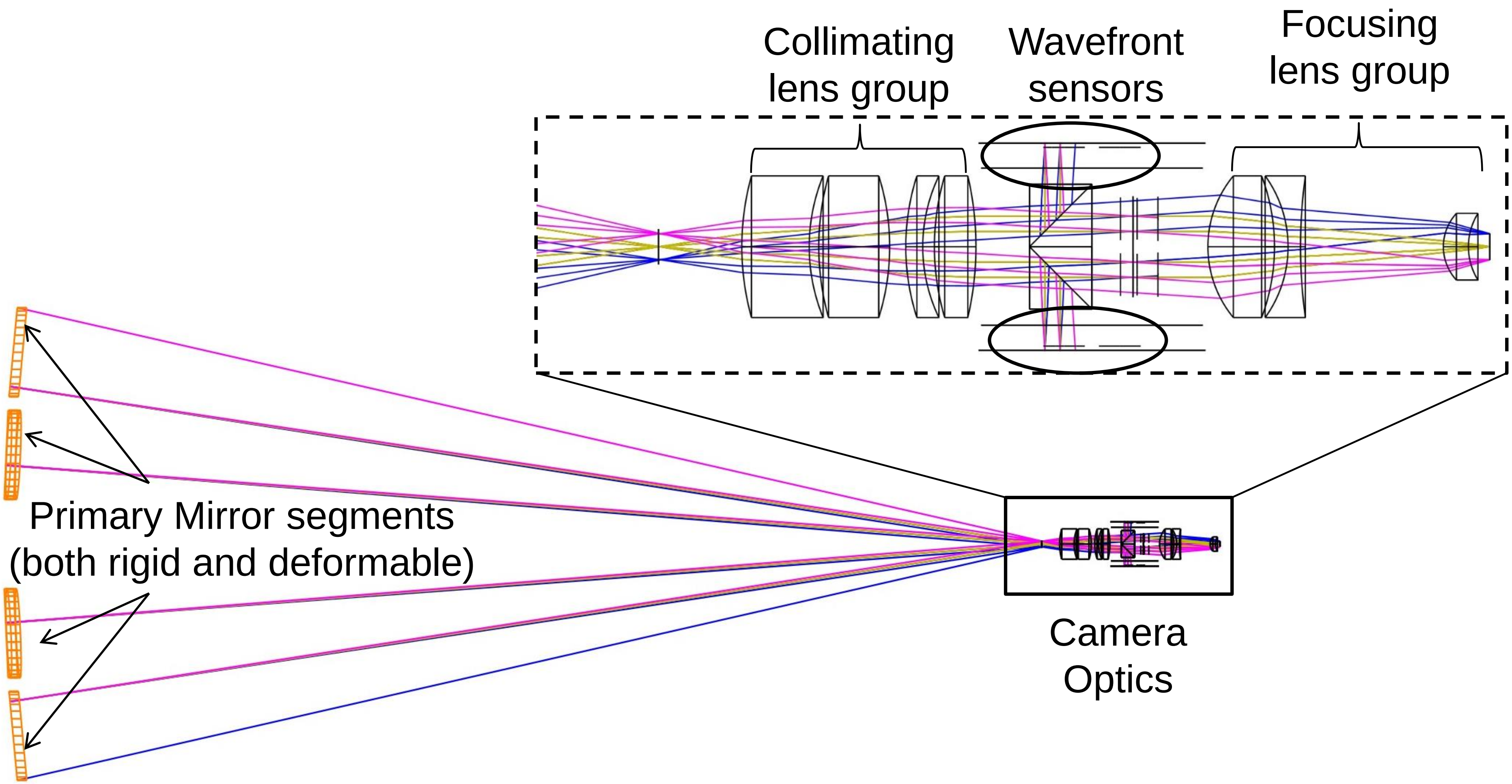
# Optical System Overview



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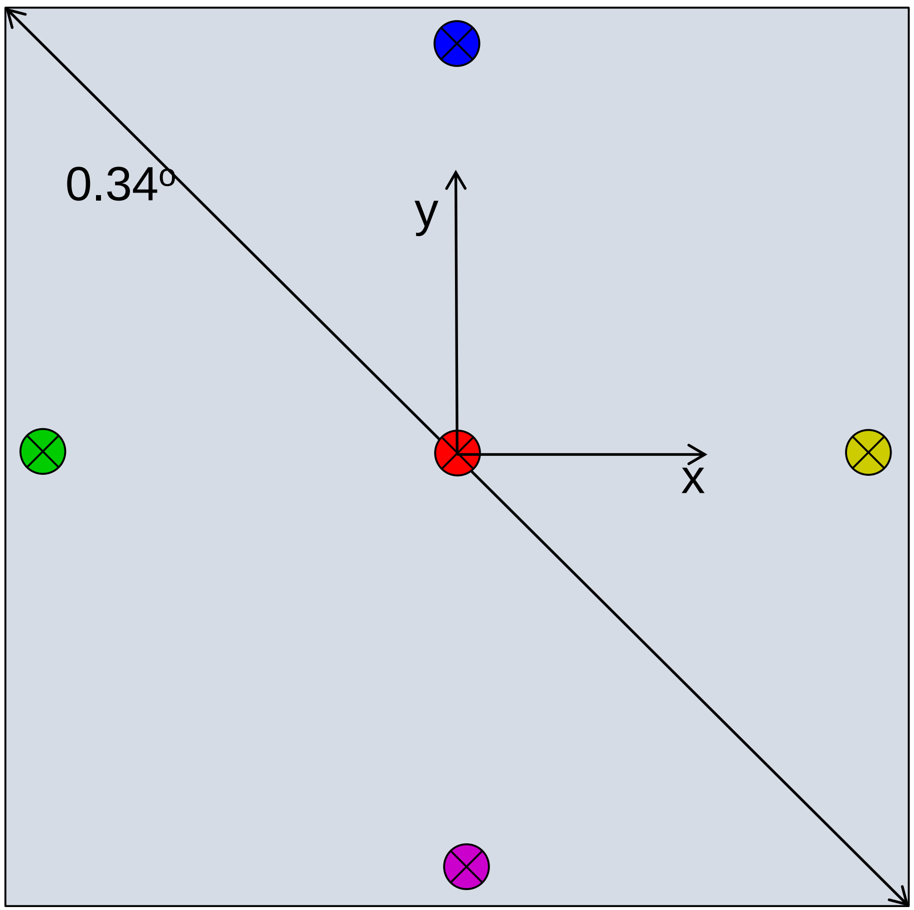
# Baseline Requirement

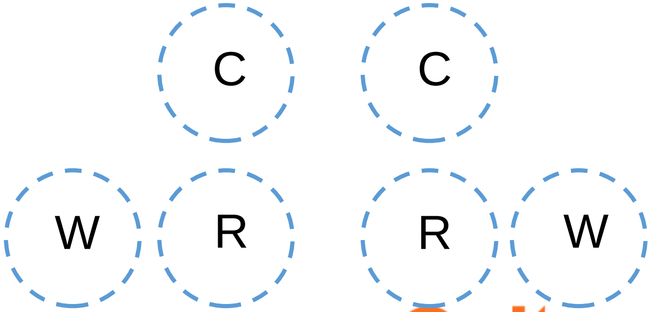



Detector

Expected Encircled Energy of system "as designed" simulated on axis and at largest field angles using Zemax.

Simulations were done for individual mirror segments at each of three segment locations:

| | |
|---|---|
| Reference | (R) |
| Compact | (C) |
| Wide | (W) |



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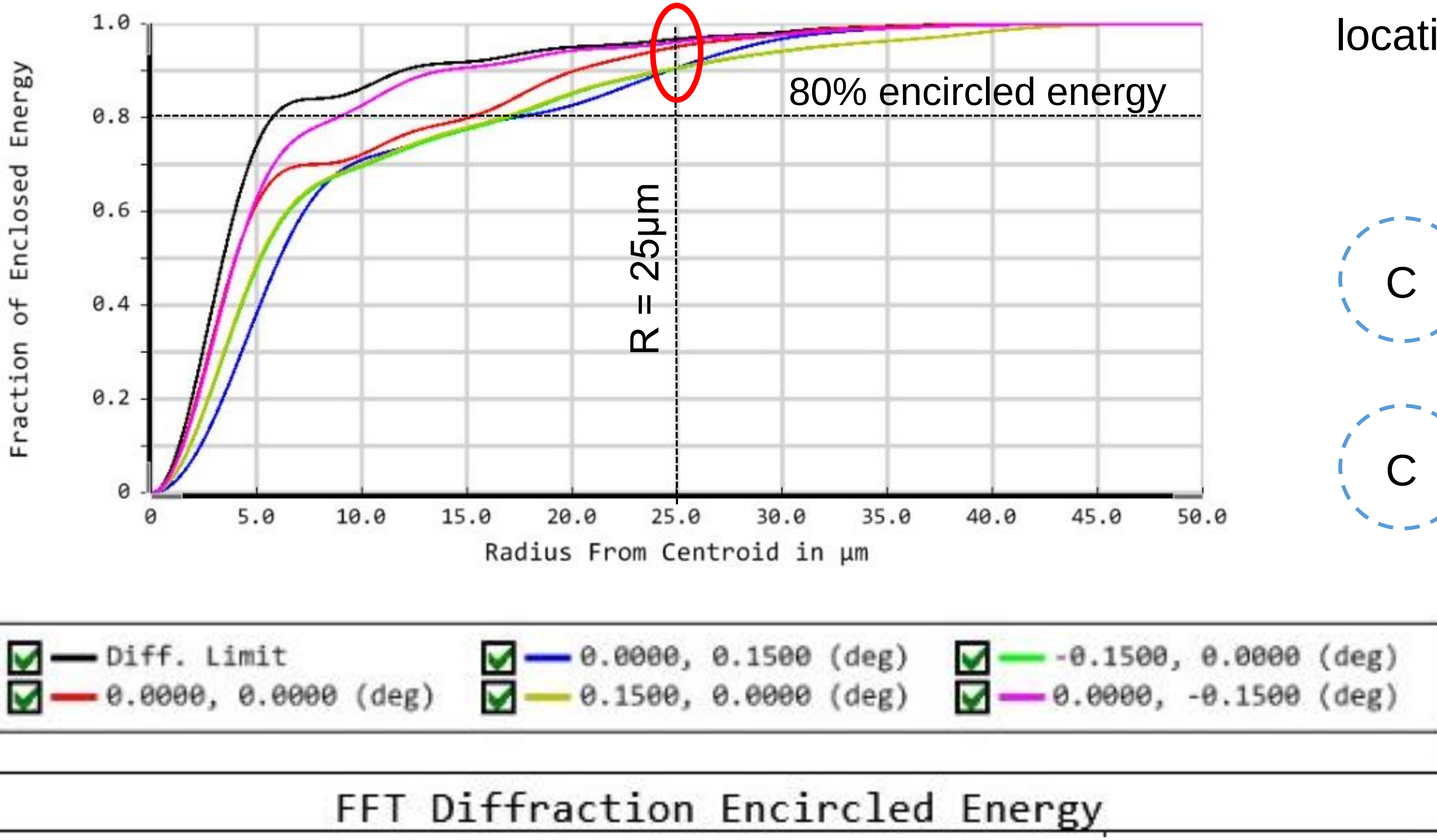
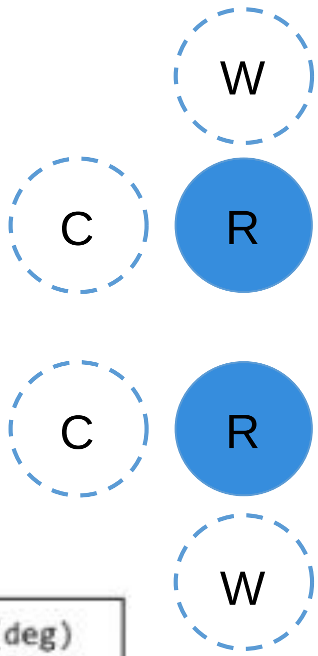
# Baseline Requirement:

80% encircled energy within 25μm radius for each segment over entire FoV




Reference Mirror location:



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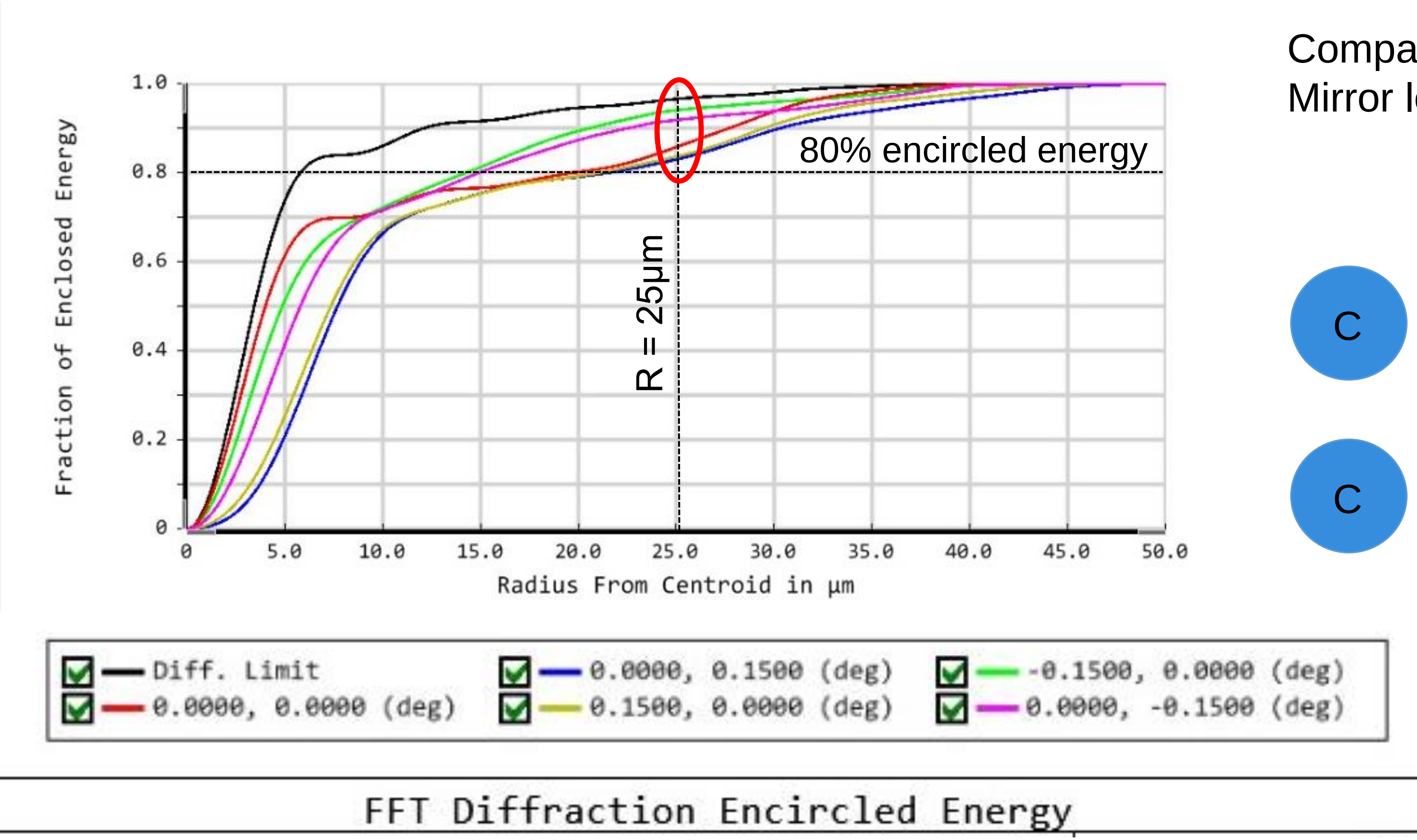
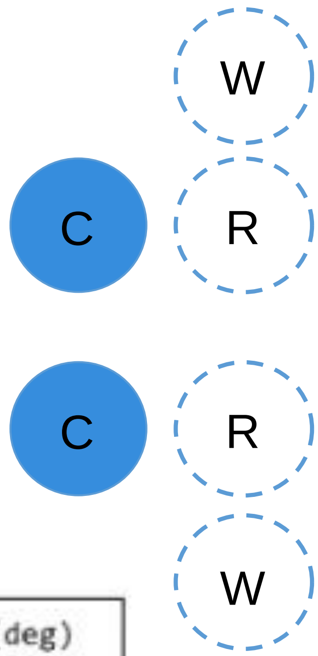



Compact/Narrow Mirror location:



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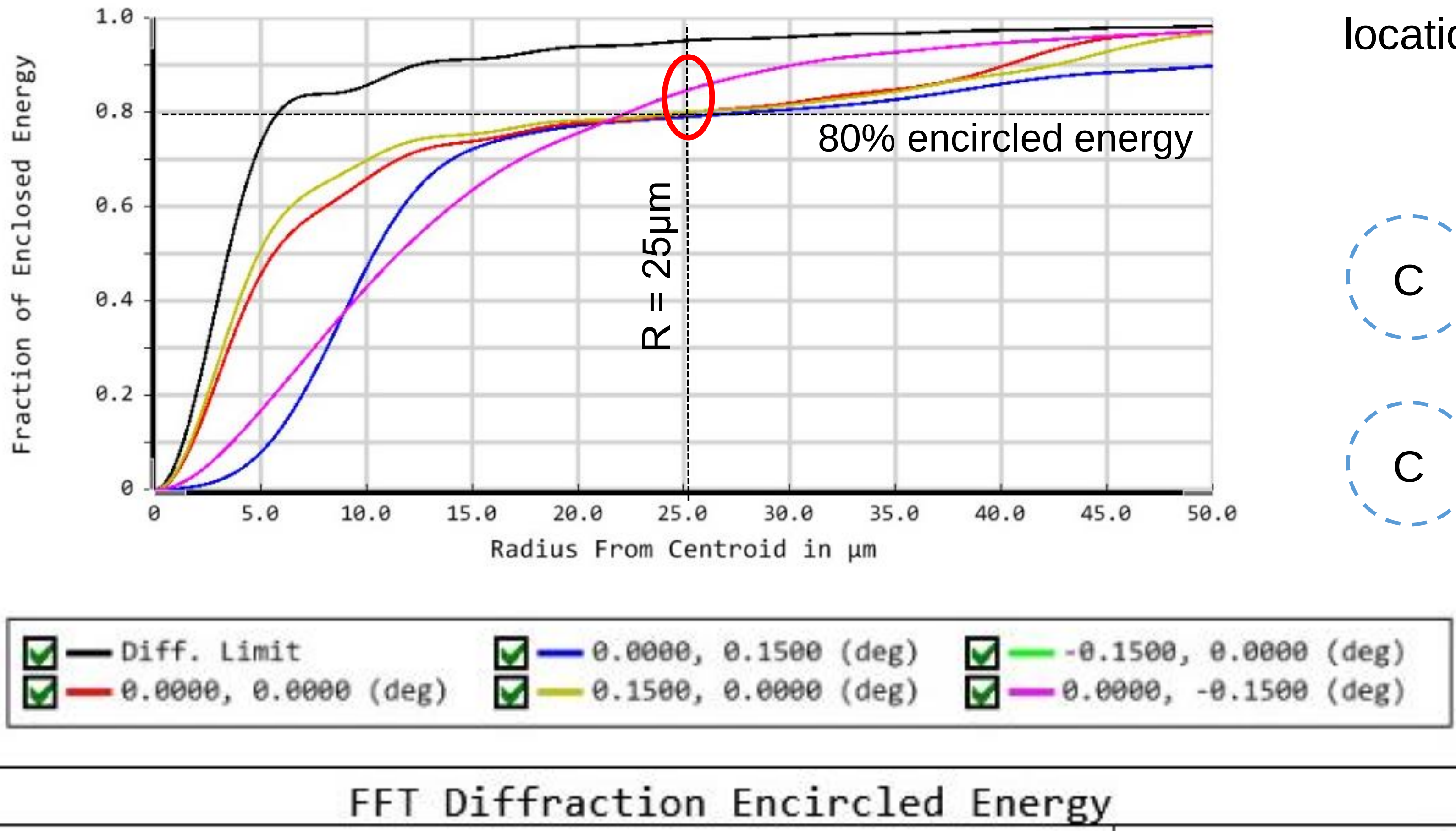
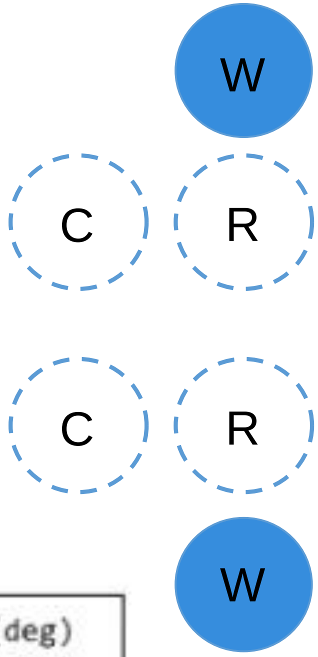
# Baseline Requirement:

80% encircled energy within 25µm radius for each segment over entire FoV




Wide Mirror location:



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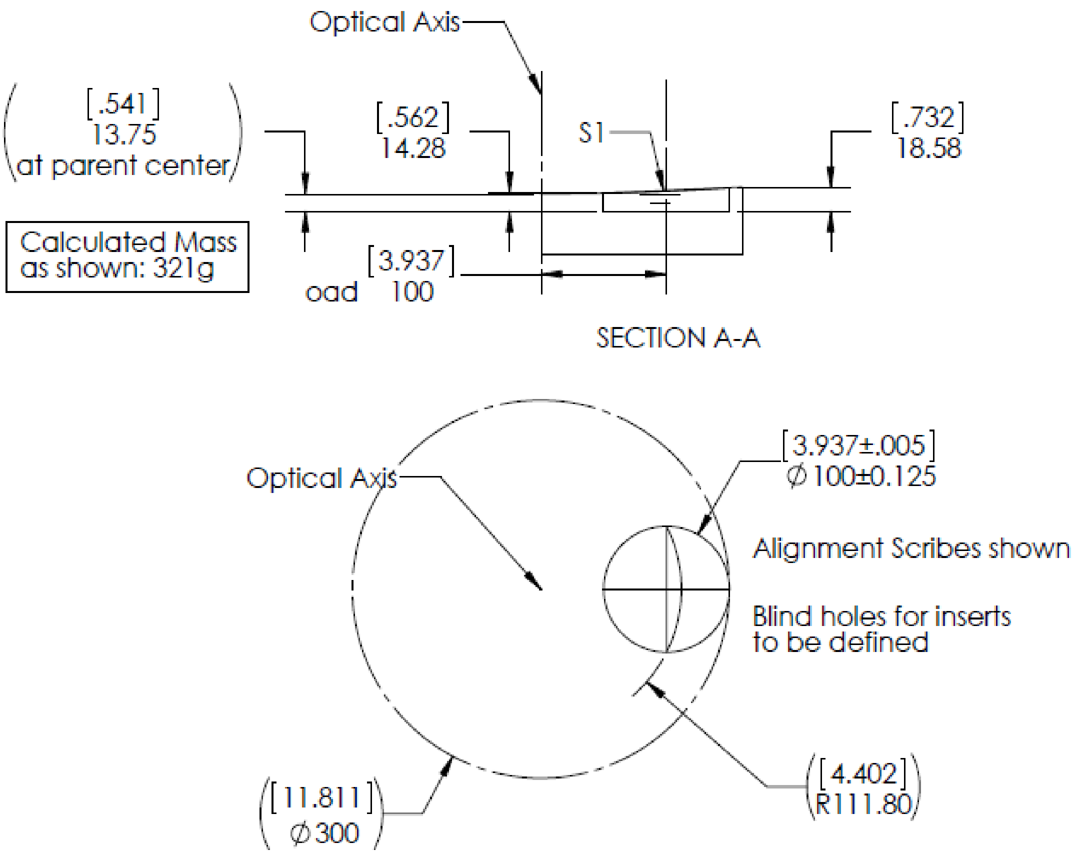
# Rigid Mirrors



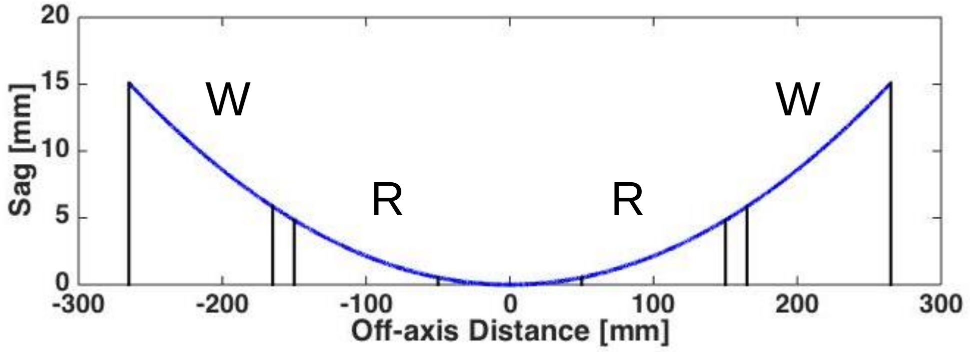

- Procurement process initiated for 5 off-axis hyperboloidal mirrors cored from single parent.

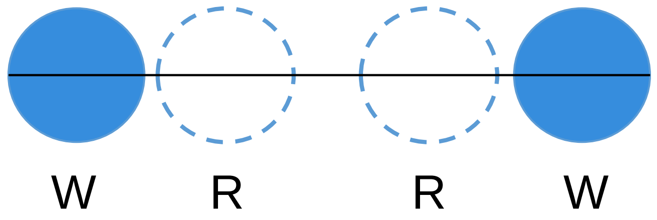
- Delivery: October 2015.
- Material: Zerodur
- Mass: 321g
- Surface quality: λ/10 PV at 630nm.

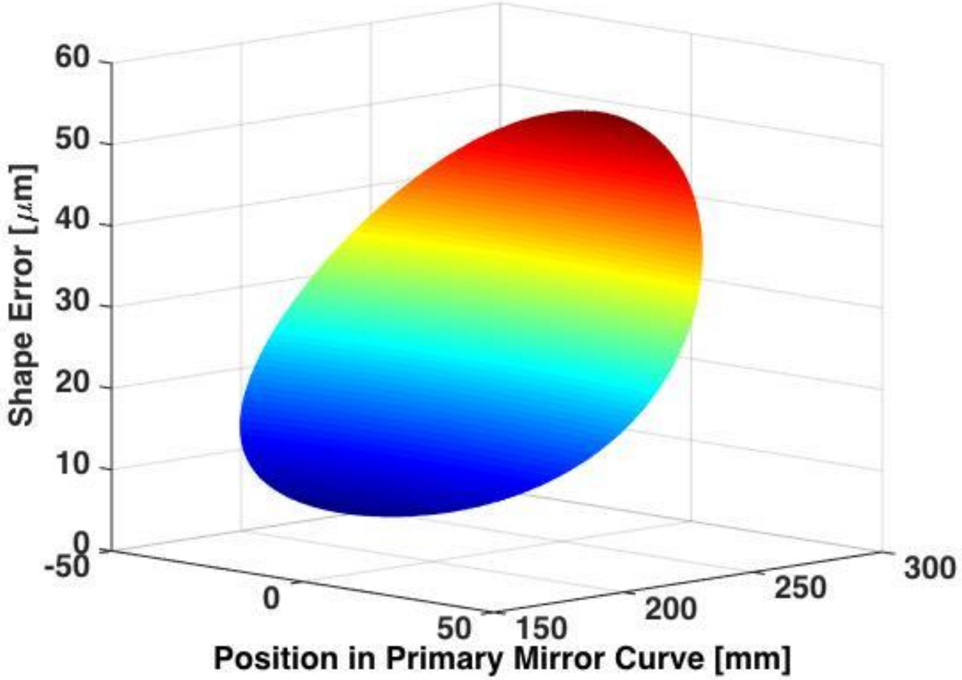
- To be used in optical test bed for assessment of other prototyped opto-mechanical components.
- To be assessed for flight readiness.

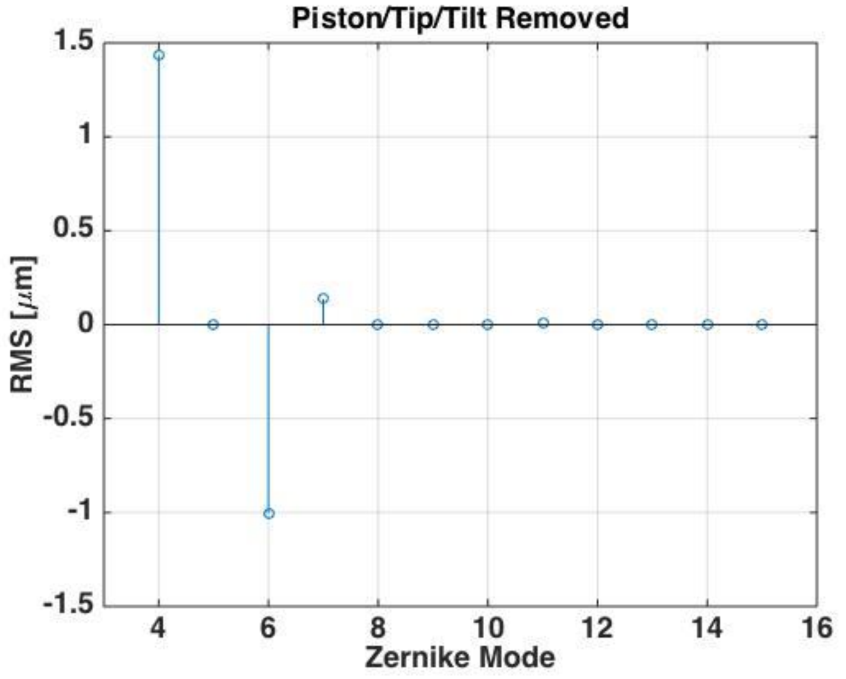
# Deformable Mirrors:

Must change from manufactured resting shape to that required by their positions in the primary mirror



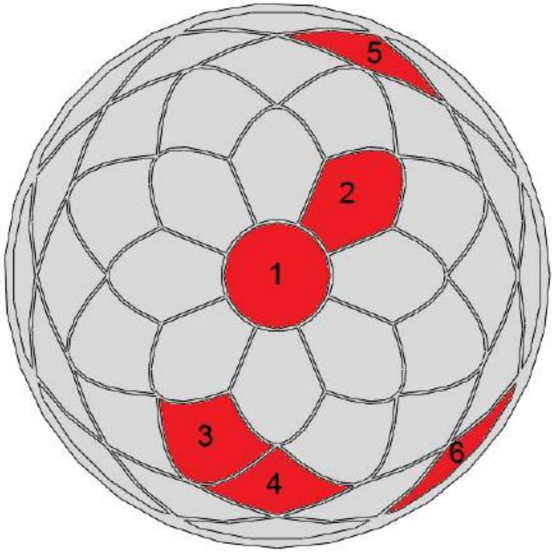



# Deformable Mirror Simulations

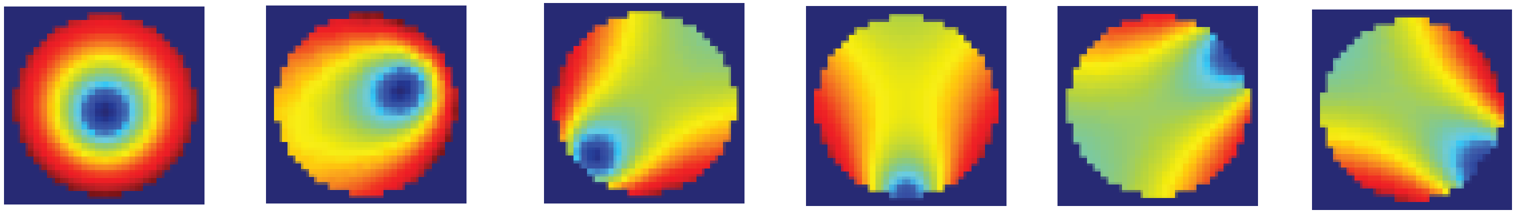
- Goal:

  To ensure DMs can be driven in closed loop to required shape under various initial and transient error conditions, given available actuation.

- Key Inputs to Optical System Model:
  – Simulated DM influence functions
  – Measured resting shape of current DM
  – +/- 500 V actuator command limits
  – As delivered camera lens elements
  – thermal effects on opto-mechanical elements and DM actuation response.
  – boom deflection

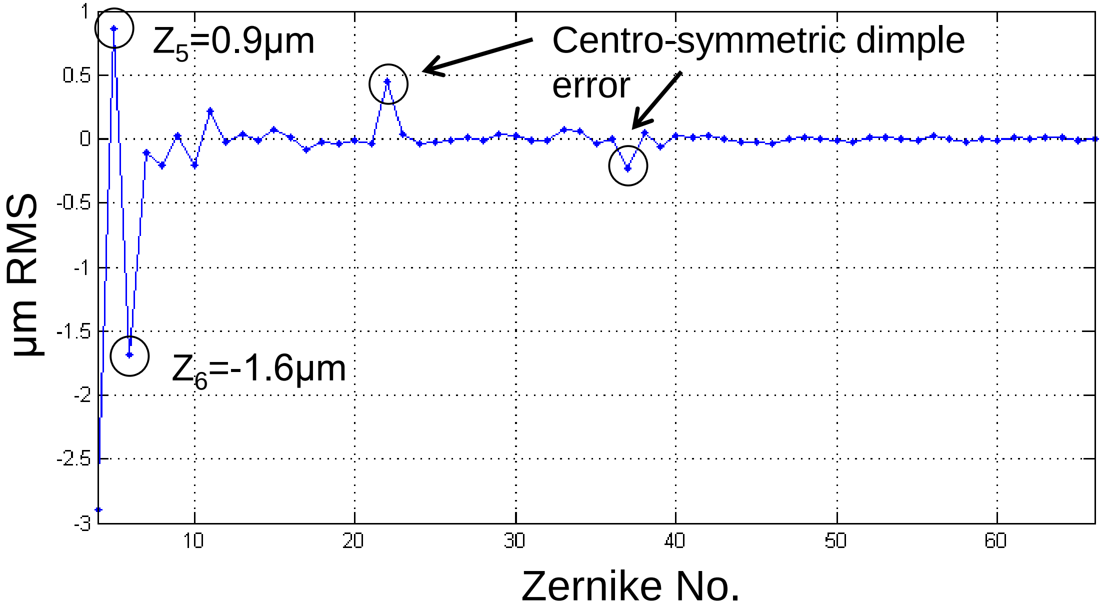



The 41 actuator electrode pattern has been optimized to correct astigmatism (“Notre Dame” pattern).



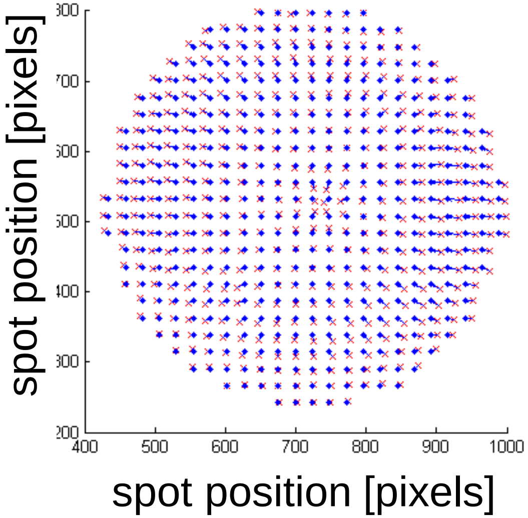
Simulated Influence functions for actuator types 1 – 6 (left to right)

# Unactuated DM shape

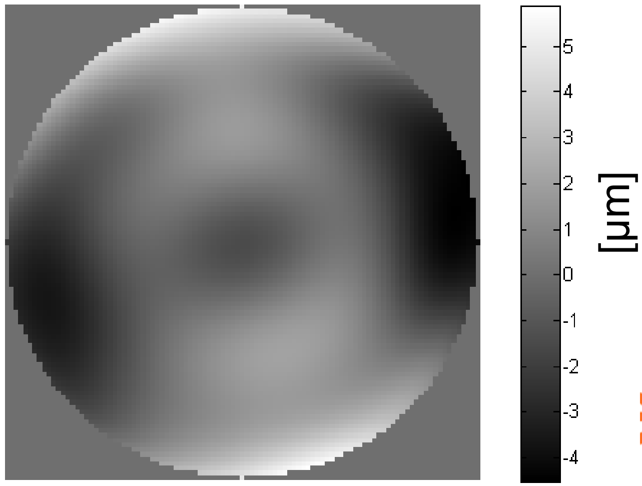



- Use a Reverse Hartmann optical test bed to measure mirror surface error.
- Project RH spot displacements onto Zernike modes.
- T/T removed RMS Surface error: 1.75µm
- Relatively large astigmatism

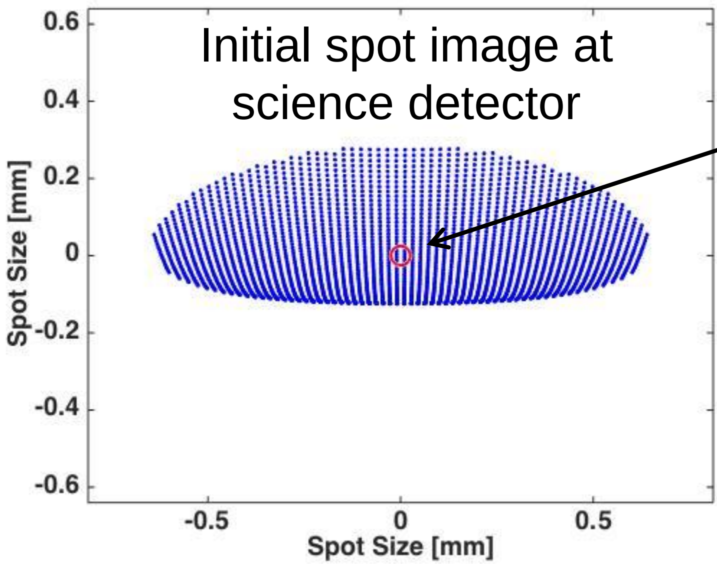
Reverse Hartmann spots

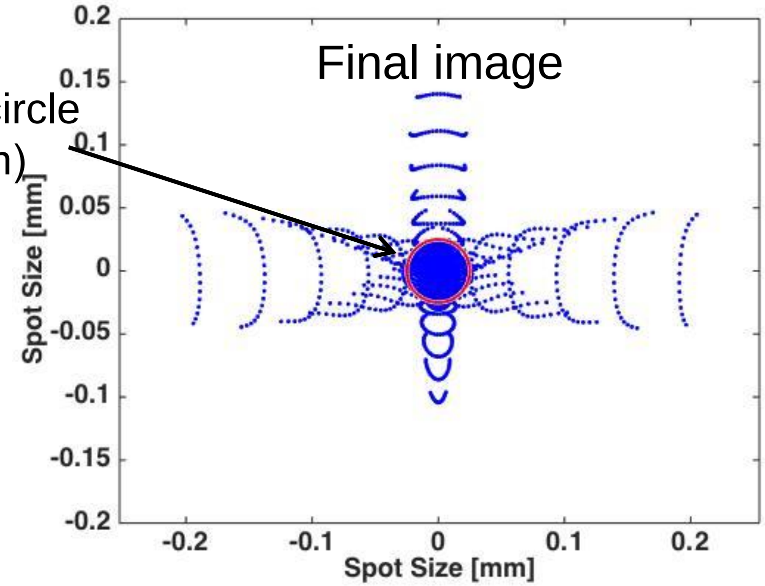


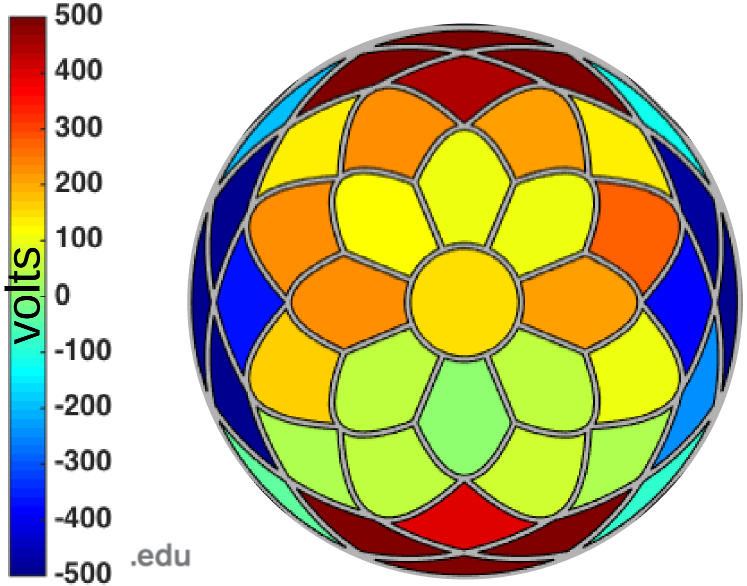

Reconstructed Surface Phase



# Current DM initial shape




Top Left:

- Initial geometric spot at the image plane for conservative initial shape: 2μm RMS of Astigmatism.

Top Right:

- Best spot image after closing the loop with the DM: 80% encircled energy radius = 23.5μm

Bottom Left:

- DM actuator voltage commands to achieve best spot image.
- 11 saturated actuators

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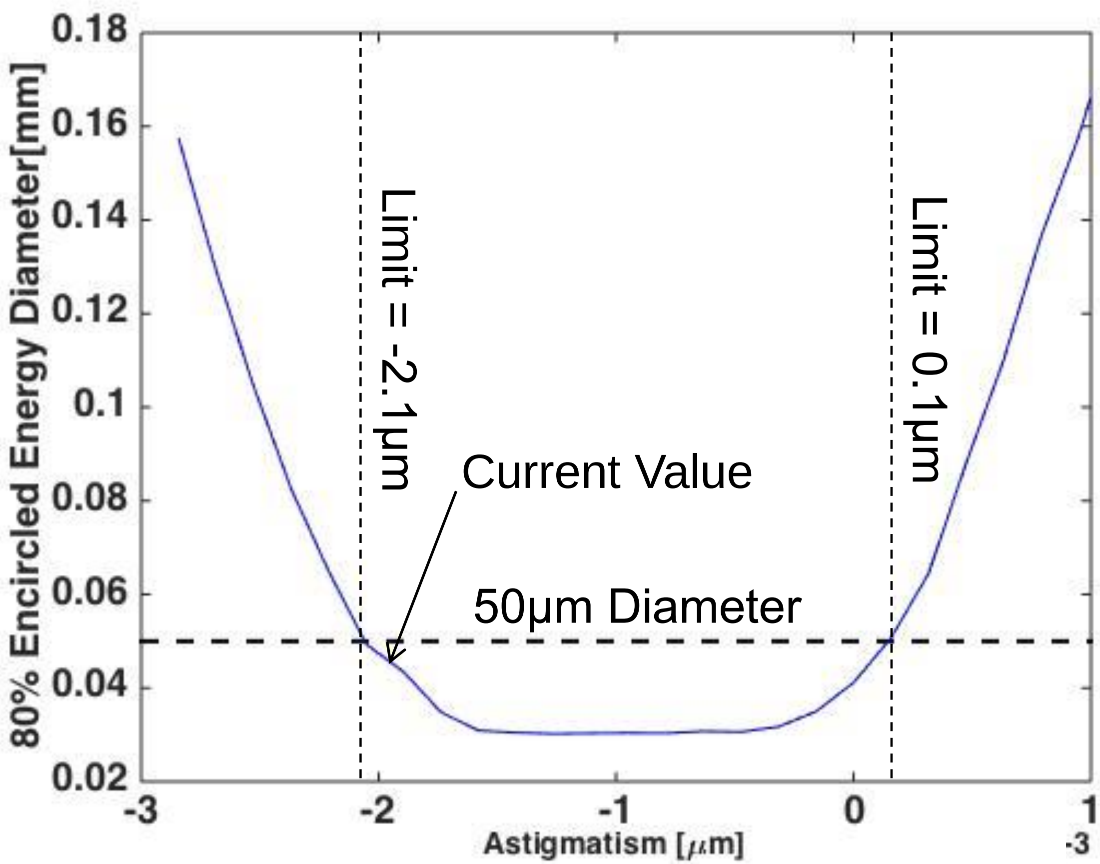
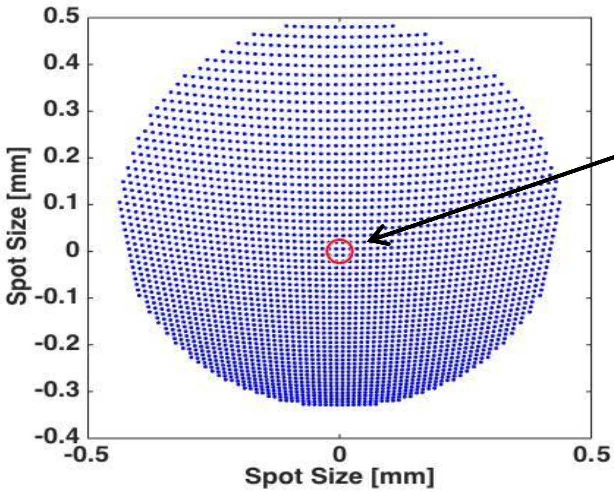
# Optimal Initial Astigmatism



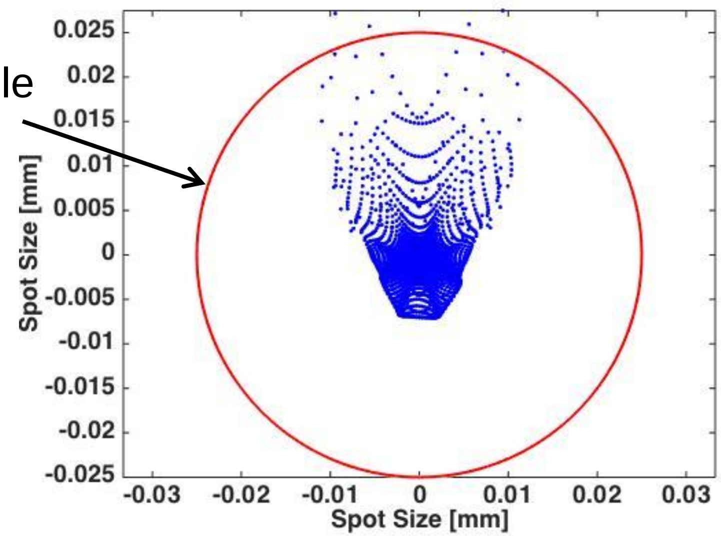

Optimal range:
-1.5µm < Astig < -0.5µm

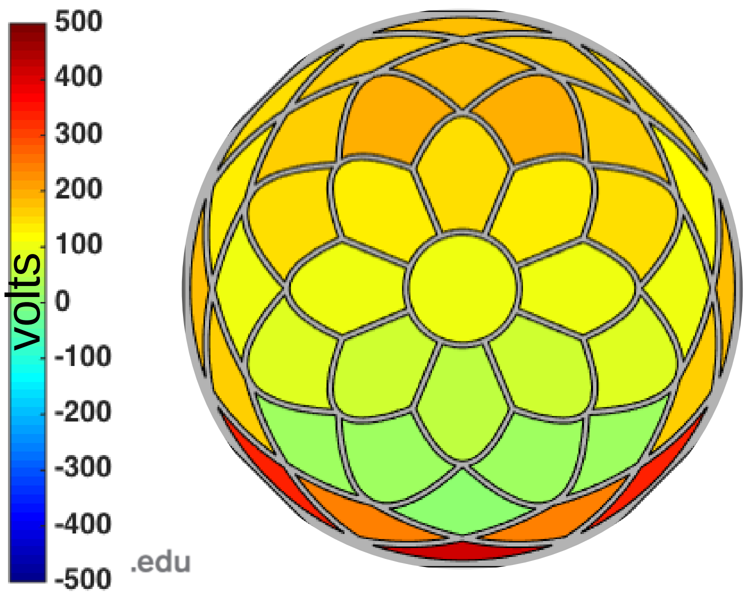
- Best performance achieved when astigmatism is aligned with primary mirror radial ray.
- Sign is equivalent to $90^o$ rotation.
- A range of values give similar encircled energy performance, however the centre of the range (-1µm) requires the least amount of DM stroke, leaving the most dynamic range for correction of other errors.

# Optimal Initial Astigmatism




Reference circle
(r = 25μm)




Top Left:

- Initial geometric spot at the image plane for conservative initial shape: 1μm RMS of Astigmatism.

Top Right:

- Best spot image after closing the loop with the DM: 80% encircled energy radius = 15μm

Bottom Left:

- DM actuator voltage commands to achieve best spot image.
- 0 saturated actuators

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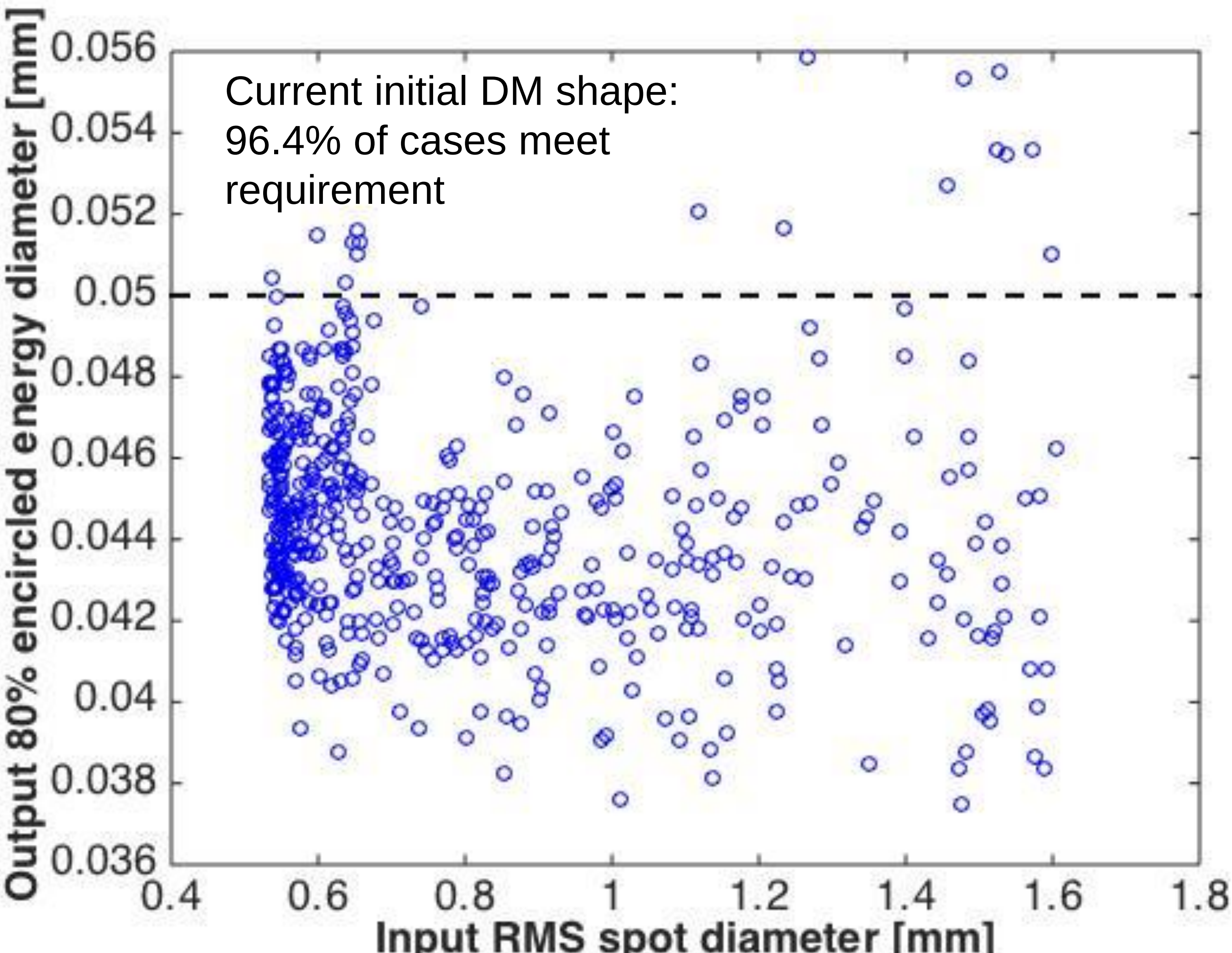
# Monte Carlo simulation

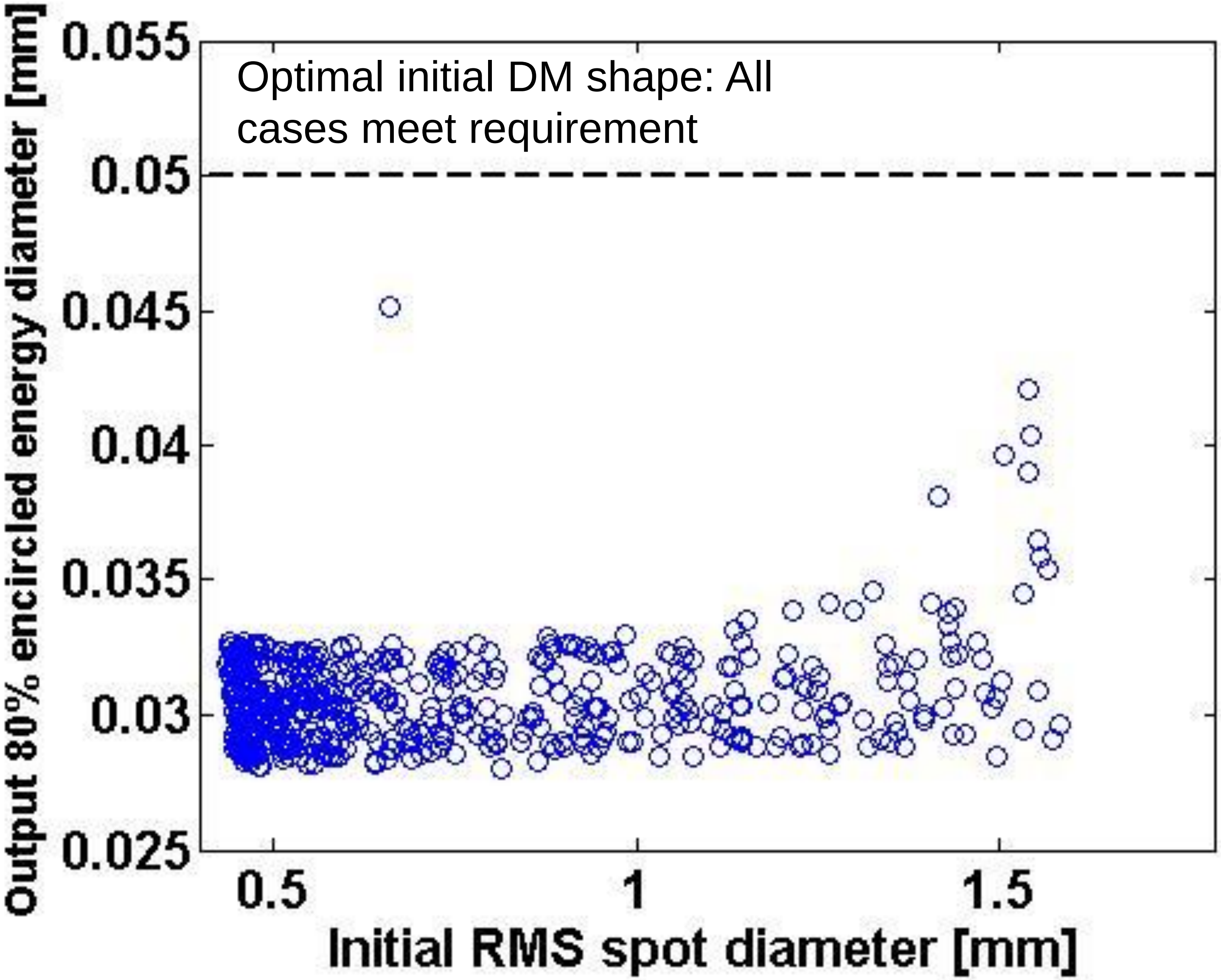
- 500 iteration Monte Carlo simulation.
- Initial conditions: current DM resting shape and measured camera lens specifications.

| Error source | Min | Max |
|---|---|---|
| **Temperature (°C)** | | |
| Mirror | -20 | +20 |
| Camera | -20 | +20 |
| **Boom deflection: translation (mm)** | | |
| x translation | -0.625 | +0.625 |
| y translation | -0.625 | +0.625 |
| z translation | -0.127 | +0.127 |
| **Boom deflection: rotation (°)** | | |
| Tip | -0.04 | +0.04 |
| Tilt | -0.04 | +0.04 |

# Monte Carlo simulation



# Monte Carlo simulation



# System requirement: Telescope Pointing

| System Element | Requirement | Expected Performance |
|---|---|---|
| Pointing | <360" (+/-180") | At 0º pointing angles +/-18"(roll, pitch) +/-108" (yaw) |
| Attitude Stability | <3.6"/s | <1.8"/s |

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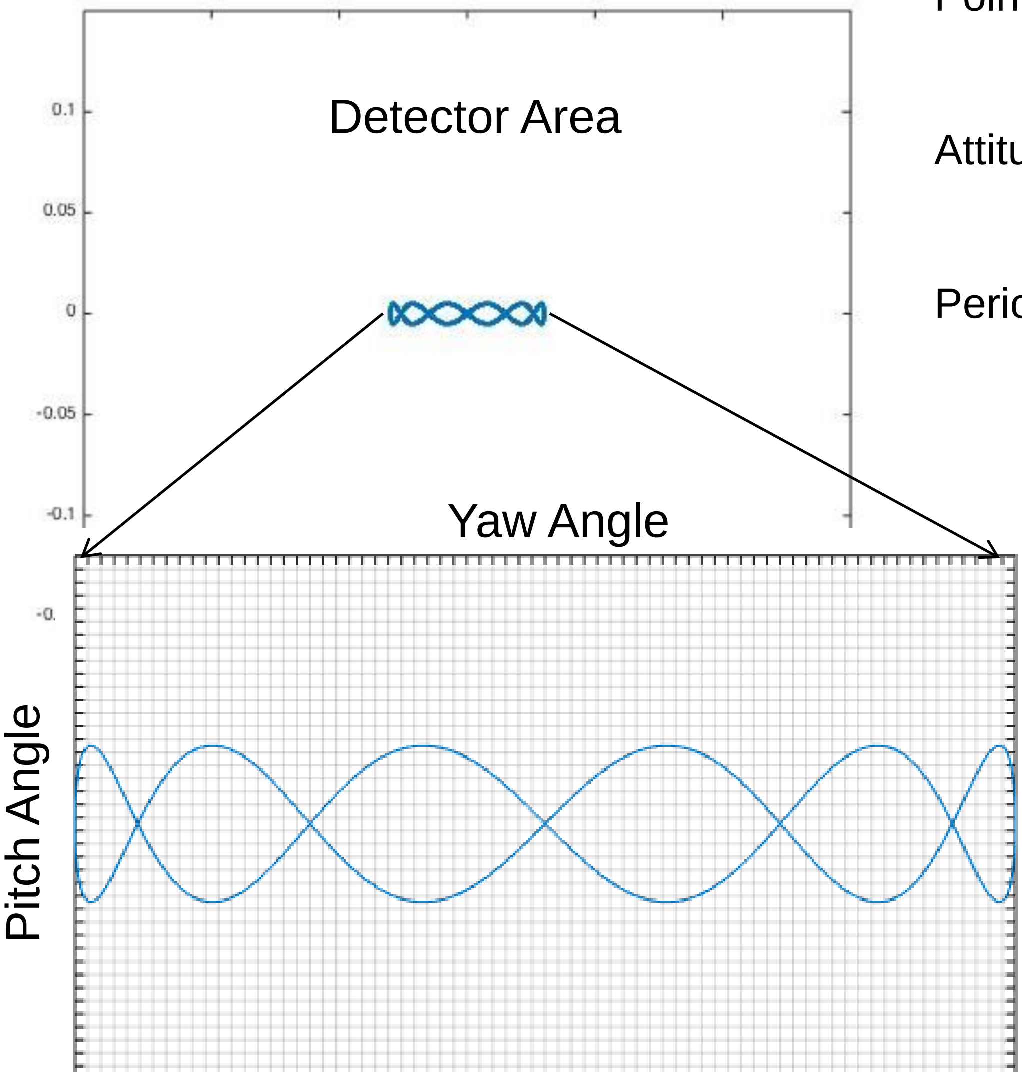
# Science Image Motion




Pointing:

Pitch = +/- 18".

Yaw = +/- 108".

Attitude Stability:

Pitch = 1.8"/s

Yaw = 1.8"/s

Period for full excursion:

Pitch = 72"/1.8"/s = 40s

Yaw = 432"/1.8"/s = 240s

(Motion on detector approximated by sinusoids)

Airy Disc diameter for a single segment:

$$A_D = \frac{2.44\lambda f}{D_{seg}}$$

$$= \frac{2.44(0.54\,\mu m)(1163.05\times 10^3\,\mu m)}{100\times 10^3\,\mu m}$$

$$= 15.32\,\mu m$$

One square represents the size of a mirror segment Airy Disc.
With a 2.2μm pixel pitch, this is 7x7 pixels.

# Science Exposure Time

- Rate of motion: 1.8”/s in both pitch and yaw giving 2.55”/s total speed (from $[\text{pitch}^2+\text{yaw}^2]^{1/2}$)
- Plate scale of science detector = 0.38”/pixel

$$\frac{0.38''/\,pix}{2.55''/\,s} = 149\,ms\,/\,pix$$

- 149ms exposures will limit smearing of image to one pixel.
- Effect of Roll has not yet been considered.



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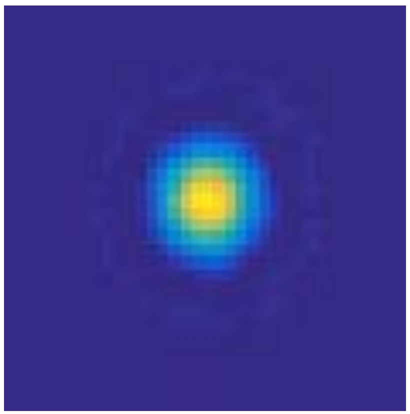
# Science SNR for a 150ms exposure for a single mirror segment (goal is 100)

- With 2.2micron pixels, a diffraction limited segment image is 7x7 pixels



- $n_{pix}$~45 illuminated pixels.
- From camera specs:

  $n_{RON}$ = 2.6e⁻/pix
  QE = 0.62@482nm
- Read noise adds in quadrature:

$$N_{RON} = \sqrt{(n_{RON})^2 n_{pix}} = 17.5e^-$$

Observing targets: stars $m_v$ = 1 to 2
F = 3.4x10$^6$ photons/cm$^2$/s:
S = signal,
Nρ = photon noise = √S,
$T_s$ = integration time,
A = segment area,
η = throughput,

$$SNR = \frac{S}{N_{RON} + N_r} \qquad S = F \times T_s \times \eta \times \frac{A}{n_{pix}}$$

$$S = 3.4 \times 10^6 \frac{\nu}{cm^2 s} \times 150 \times 10^{-3} s \times \eta \times \frac{63.6 cm^2}{45}$$

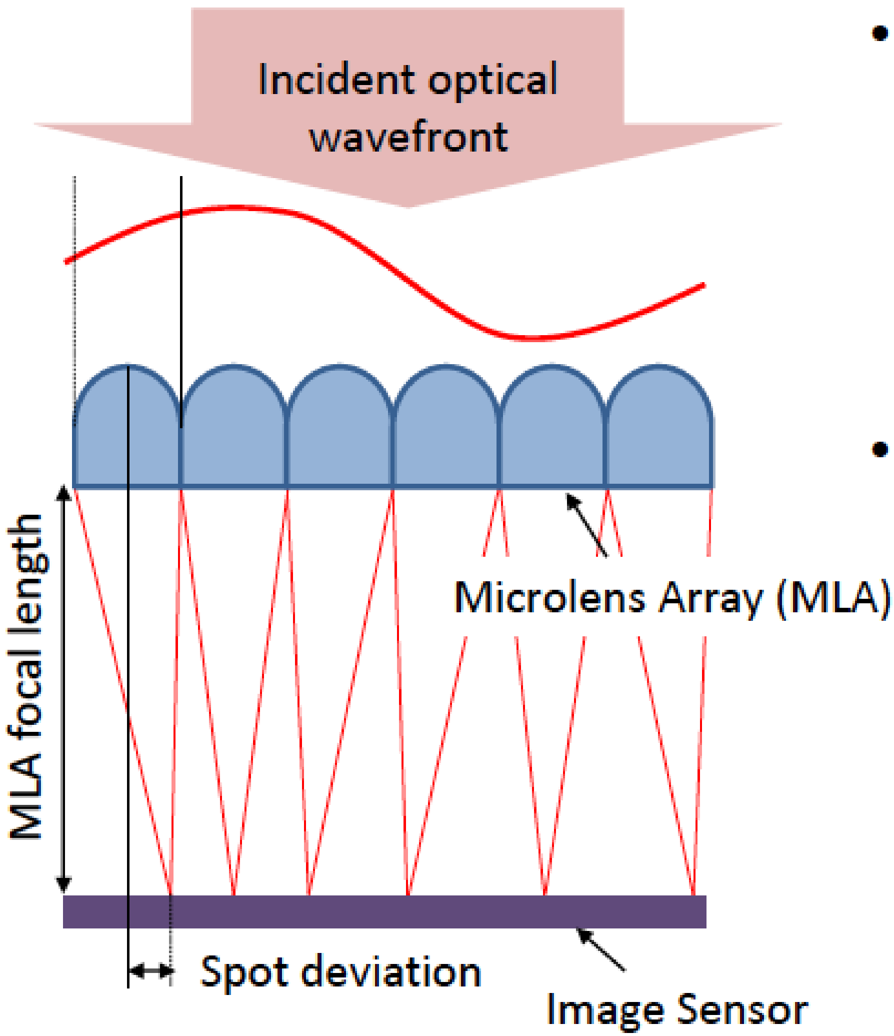
$$\eta = \eta_{mirror} \eta_{lens}^7 \eta_{BS} QE \sim 0.05 \frac{e^-}{\nu}$$

$$\eta_{BS} = 0.1$$

$$S = 3.6 \times 10^4$$

$$SNR = \frac{3.6 \times 10^4}{2.6 + 189} = 187 / pixel.$$

# Shack-Hartmann Wavefront Sensor




- MLA: EO #64-476
  - 10 × 10 mm, 300 µm pitch
  - 5.1 mm focal length
  - ~177 WF slope samples per segment
- Image sensor: CMOSIS CMV4000
  - CMOS imager
  - 11.26 × 11.26 mm active area
  - 5.5 µm pixel pitch
  - 2048 × 2048 pixels, 4.2 Mp
  - $(QE)_{peak}$ = 0.57 at 537 nm



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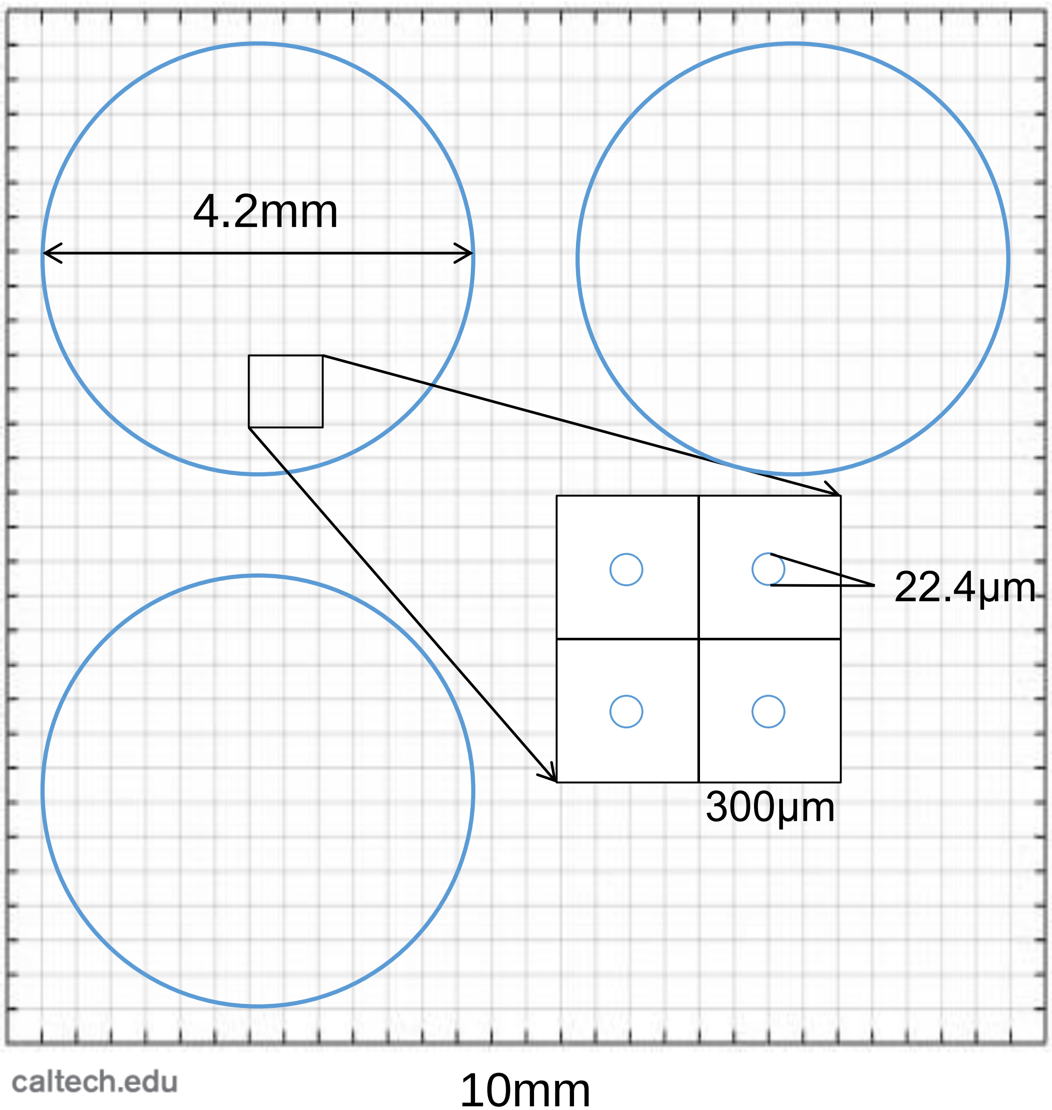
# WFS Geometry




- Lenslet Array = 10x10mm
- lenslet pitch = 300μm
- 33x33 lenslets in total

- Beam footprint diameter = 4.2mm
- 14x14 lenslets per segment pupil

- Detector pixel size = 5.5μm
- 300μm/5.5μm = 55x55 pixels per subaperture
- Spot size:

$$A_D = 2.44\frac{\lambda f_l}{D_l}$$

$$A_D = 2.44\frac{(0.54\mu m)(5.1mm)}{300\mu m} = 22.4\mu m$$

$$22.4\mu m / 5.5\mu m = 4 \times 4\, pixels$$

# WFS SNR for a 50ms exposure for a single mirror segment

Signal to noise for given flux
F = 3.4x10$^6$ photons/cm$^2$:
S = signal
Nρ = photon noise
$N_{RON}$= Read out noise
$T_s$ = integration time = 50ms
A = segment area = π(4.5cm)$^2$
η = throughput = 0.5e$^-$/photon
$n_{pix}$ = number of pixels/spot = 12
$n_l$= number of lenslets/segment = 177

$$SNR = \frac{S}{N_{RON} + N_r}$$

$$N_{RON} = 13e^-$$

$$N_r = \sqrt{S}$$

$$S = F \times T_s \times \eta \times \frac{A}{n_{pix} n_l}$$

$$S = 3.4 \times 10^6 \frac{\eta}{cm^2 s} \times 50 \times 10^{-3} s \times \eta \times \frac{63.6cm^2}{12 * 177}$$

$$\eta = \eta_{mirror} \eta_{lens}^4 \eta_{BS} QE \sim 0.5 \frac{e^-}{\eta}$$

$$QE = 0.57 @ 540nm, \eta_{BS} = 0.9$$

$$S = 2545, \sqrt{S} = 50.4$$

$$SNR = \frac{2.5 \times 10^3}{13 + 50.4} = 40 / pixel = 138 / lenslet.$$



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# Summary

- Given current optical system elements, including DM and Camera lenses, AAReST is able to meet its science requirement of 80% encircled energy in a 25μm radius under most tested error conditions.
- With some improvement to the DM initial shape, the science requirement can be met for all tested error conditions.
- For the selected target type (stars brighter than magnitude 2) both the WFSs and science detector will attain sufficient SNR within the time limits imposed by attitude stability.
- Additional information regarding pointing and attitude stability will ensure requirements are met.

# Mirrors

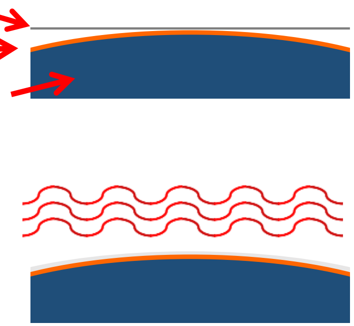
Stephen Bongiorno

# Deformable Mirror (DM) Overview

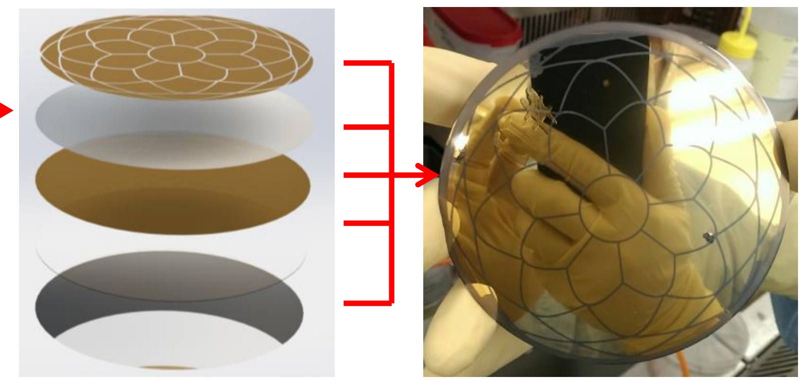
## GSFC

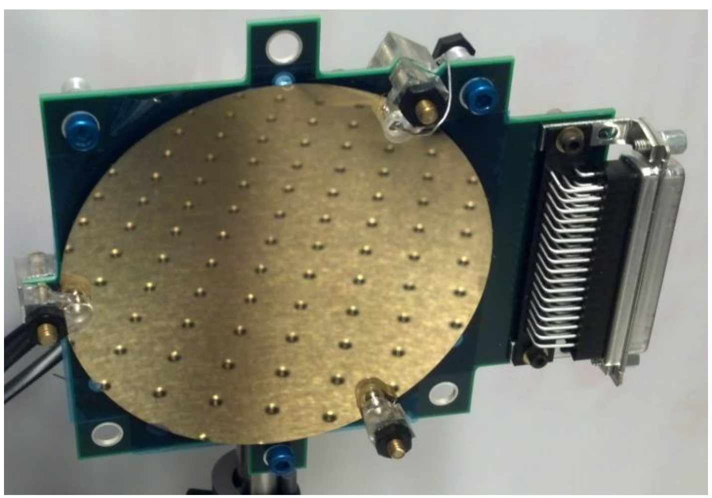
- Schott D263 sheet
- BN release layer
- Fused silica mandrel

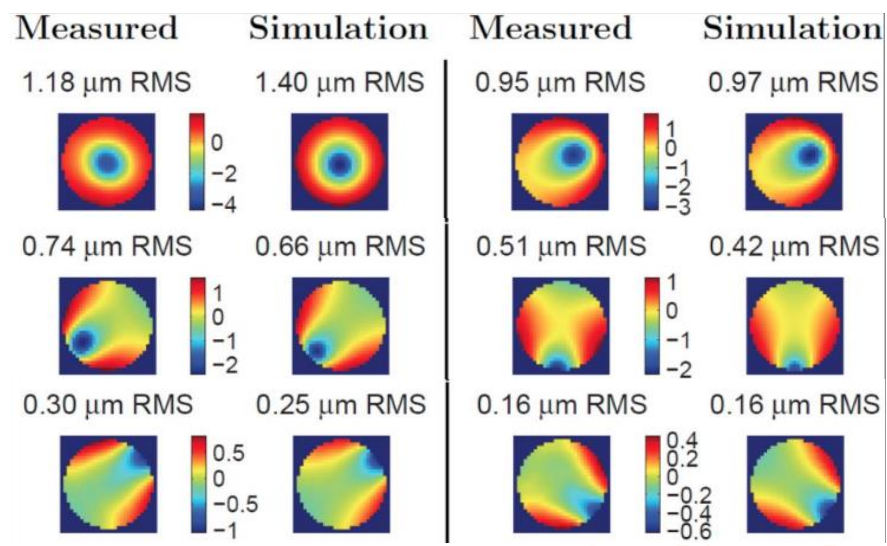
- Heat in clean furnace
- Glass slumps to shape of mandrel



## Caltech



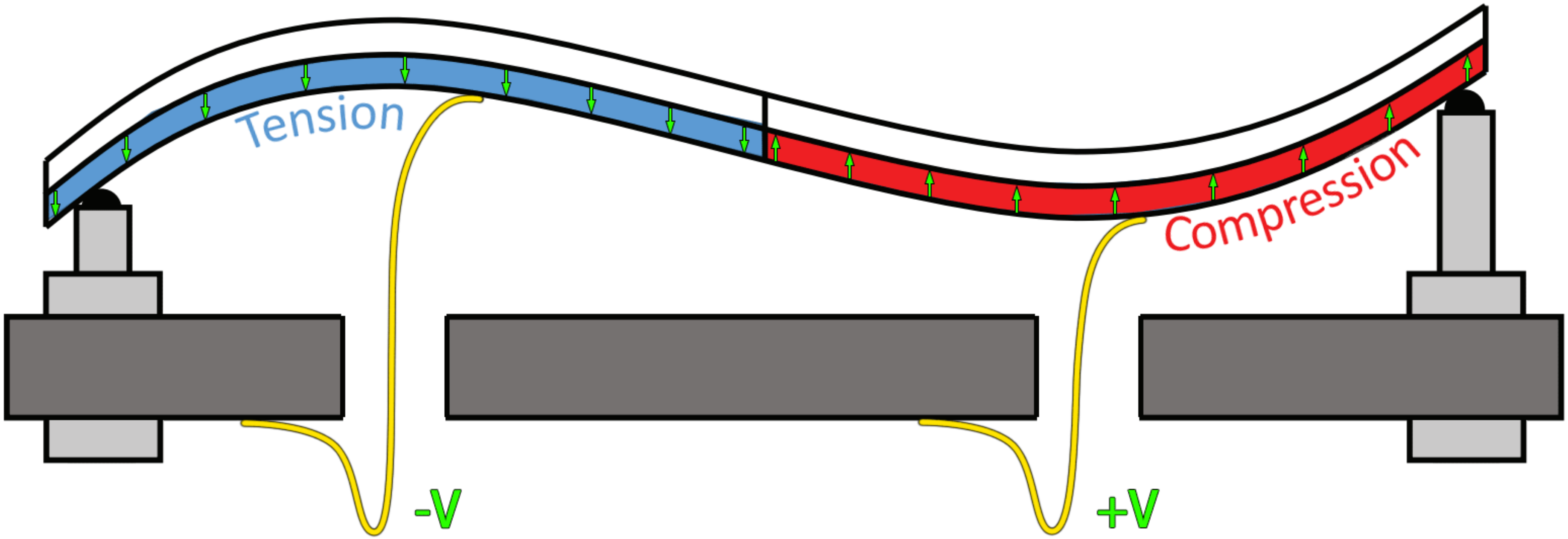




# Driving requirements

- Optics must focus 80% of point source energy to <50 μm diameter spot at focal plane.
  - Desired mirror shape + initial shape error must be within stroke limits of actuators.

# DM theory of operation




- Piezo depoles at 25 V/micron
- Dielectric breakdown at 75 V/micron

# Slumped glass substrates

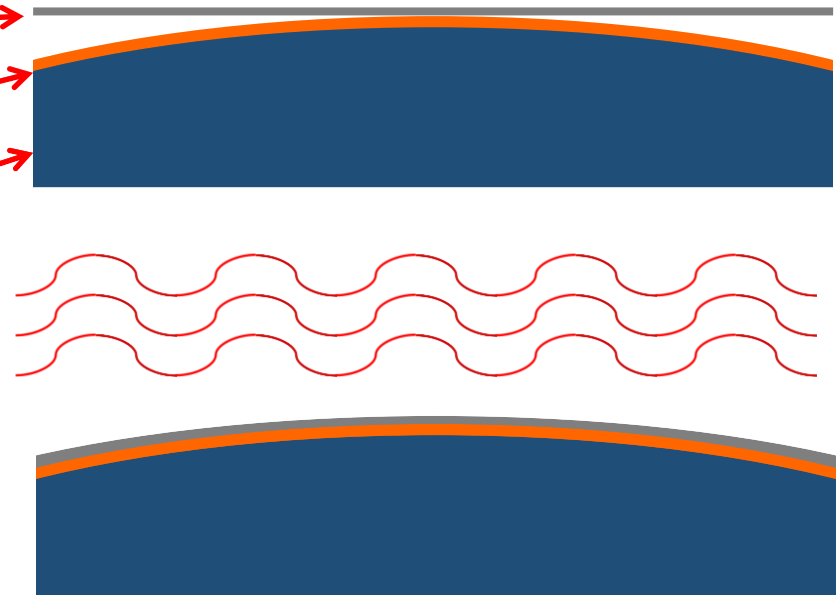
Schott D263 sheet

BN release layer

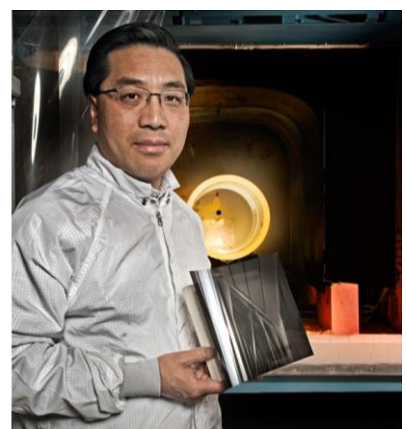
Fused silica mandrel

Heating in clean furnace

Glass slumped to shape of mandrel



RAYOTEK scientific inc THE CLEAR SOLUTION



Goddard SPACE FLIGHT CENTER

# Fabricating deformable mirrors

ND pattern electrodes
(100 nm Au evaporated)

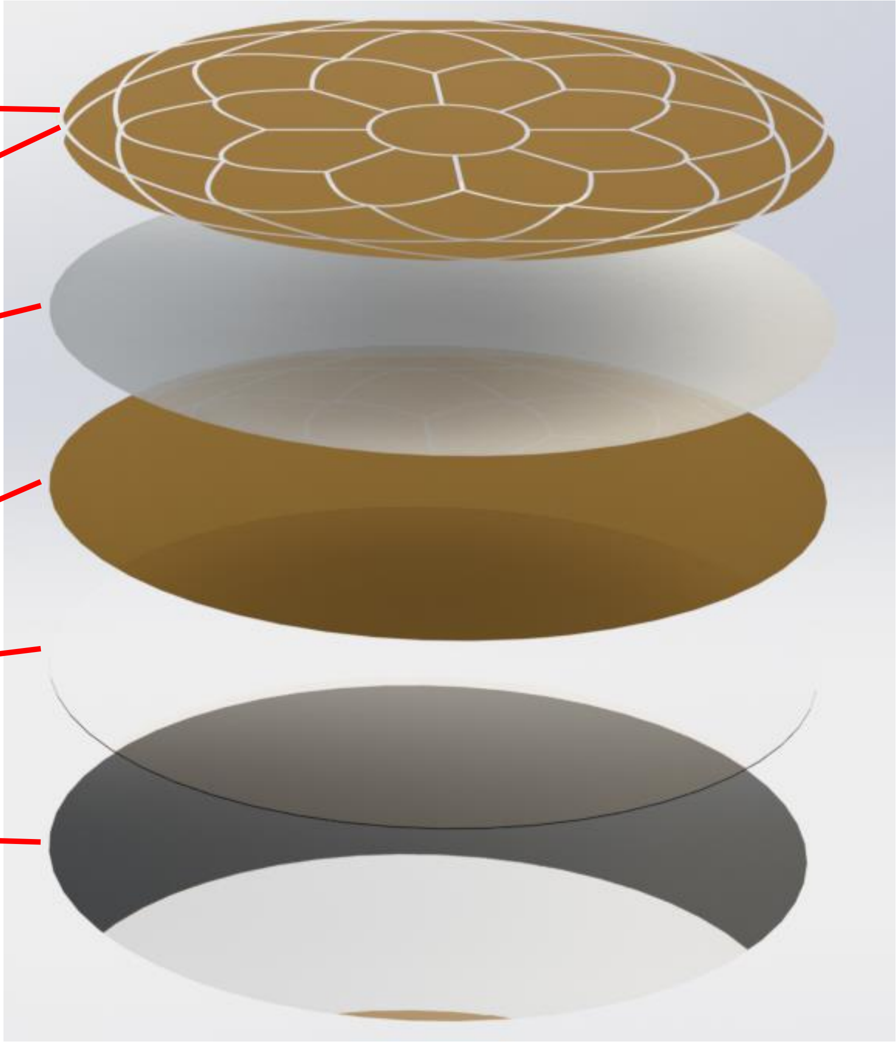
Poling electrode
(10/20 nm sputtered Ti/Au)

PVDF-TrFE
(20 μm spin coated)

Ground electrode
(10/50/20 nm sputtered Ti/Au/Ti)

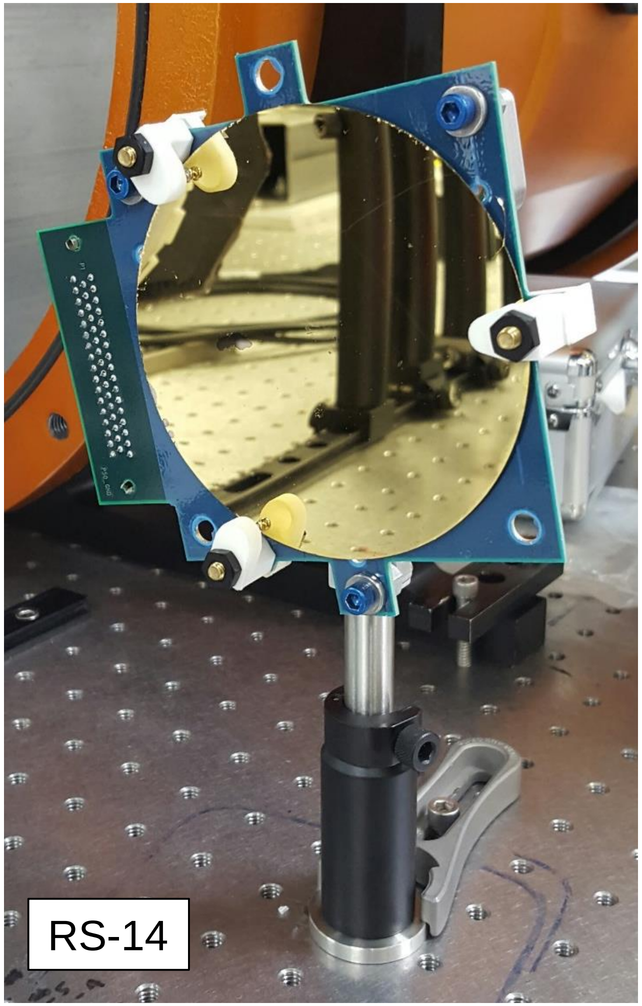
Slumped glass
(200 μm Schott D263)

Reflective layer
(5.445 μm evaporated Al/Cr)



# Mirror fabrication status

- Deformable Mirrors:
  - Initial shape test GS-12
  - Thermal test mirror GS-13
  - ND electrode mirror RS-14
- Reference Mirrors:
  - Ordered from NU-TEK
  - Expected delivery Oct.2015



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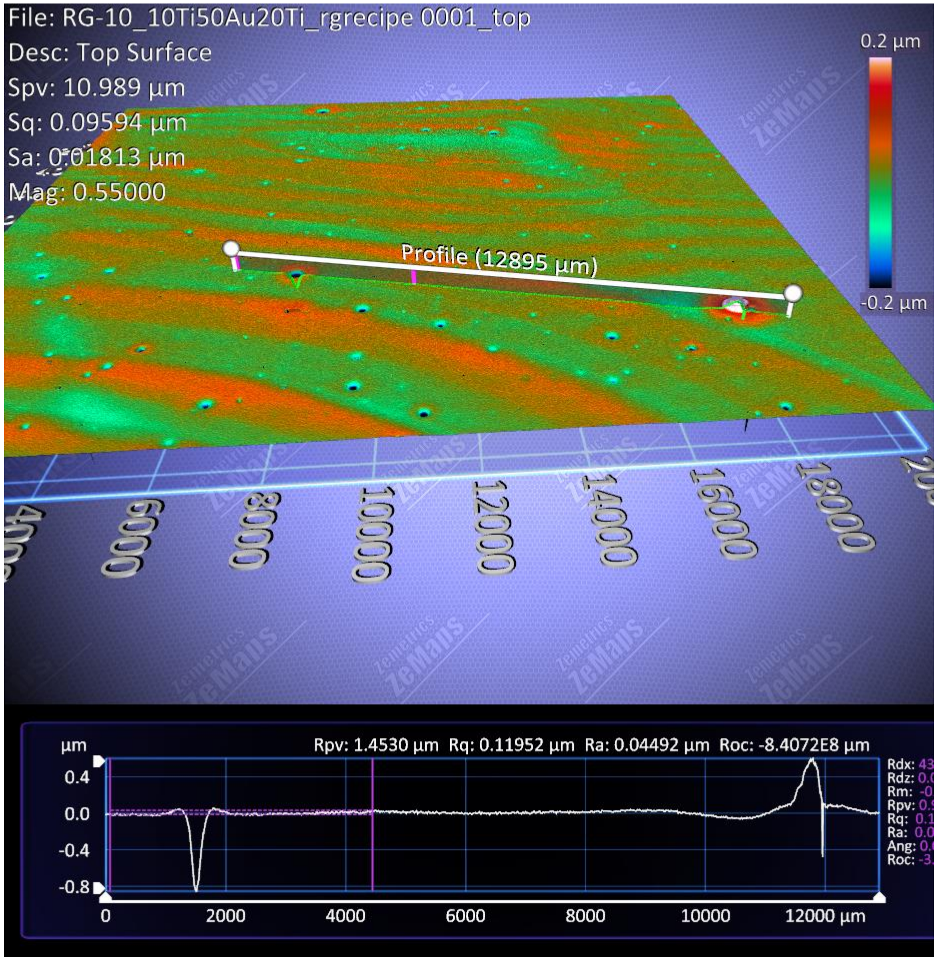
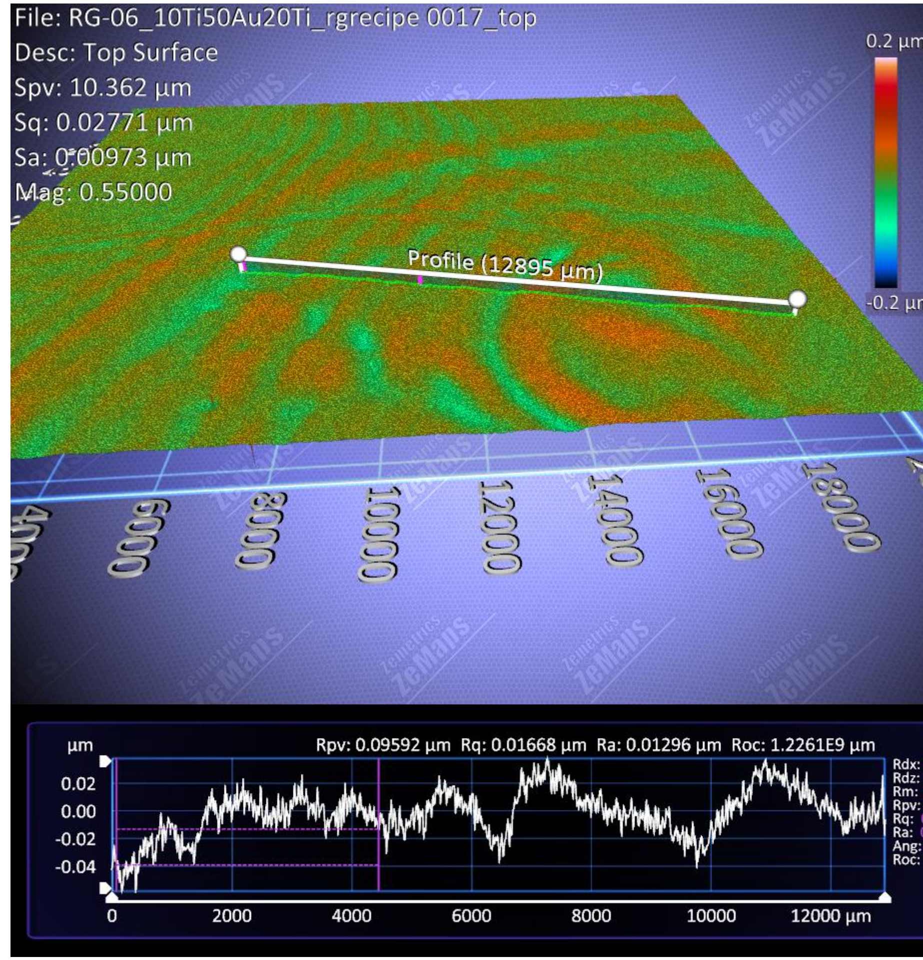
# DM process Improvements

## Resin vacuum degassing




## Resin centrifugation



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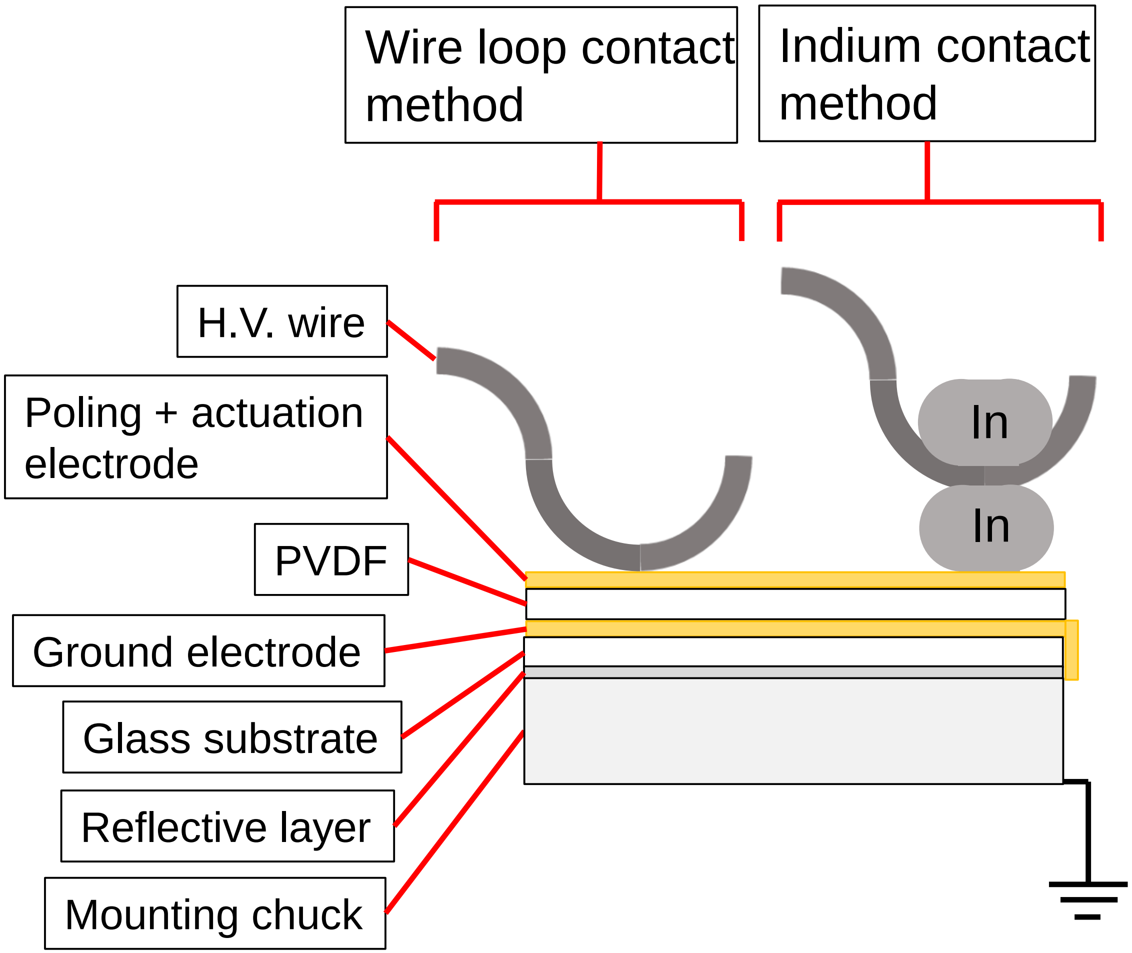
# DM process Improvements



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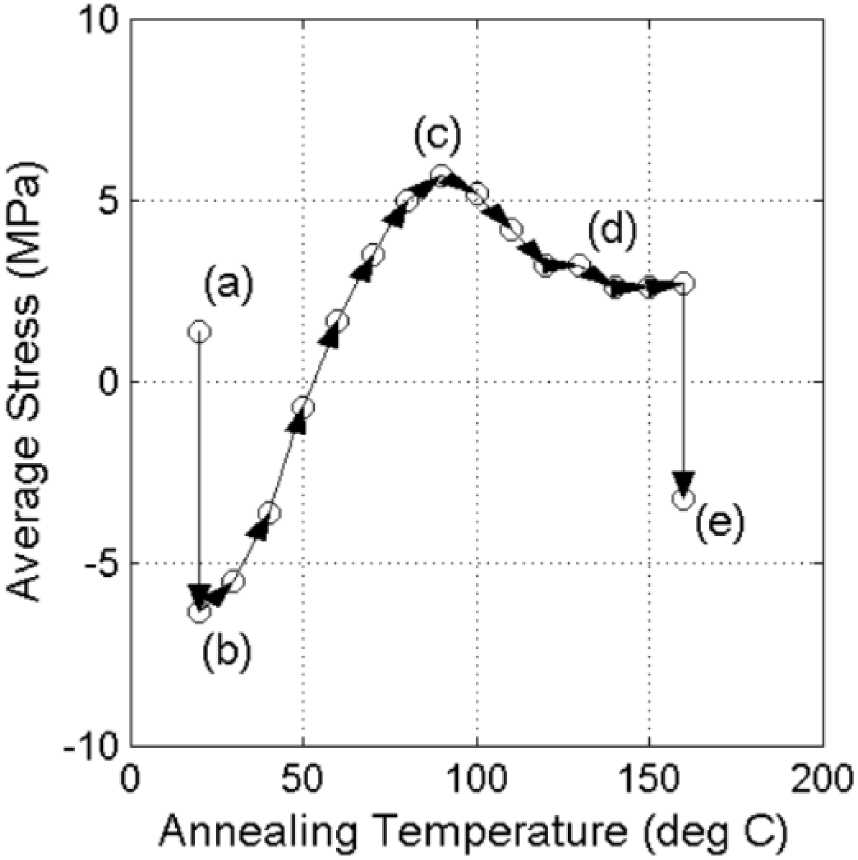
# DM process Improvements

- PVDF-TrFE Annealing
  - Simulation predicts loop can close on +54 to -18mm CoF shift.
  - Worst-case high-temp. anneal will cause +19mm CoF shift.
- Heated poling



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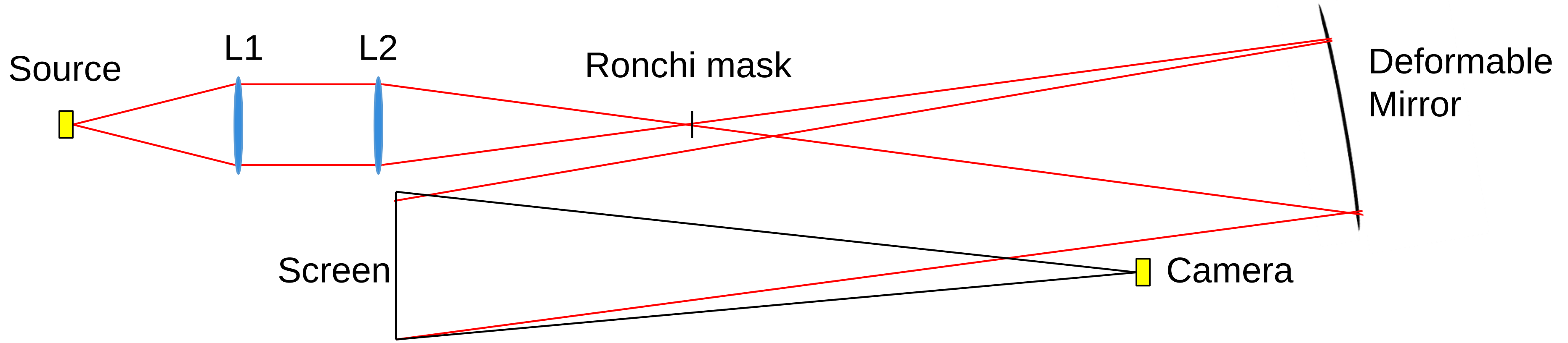
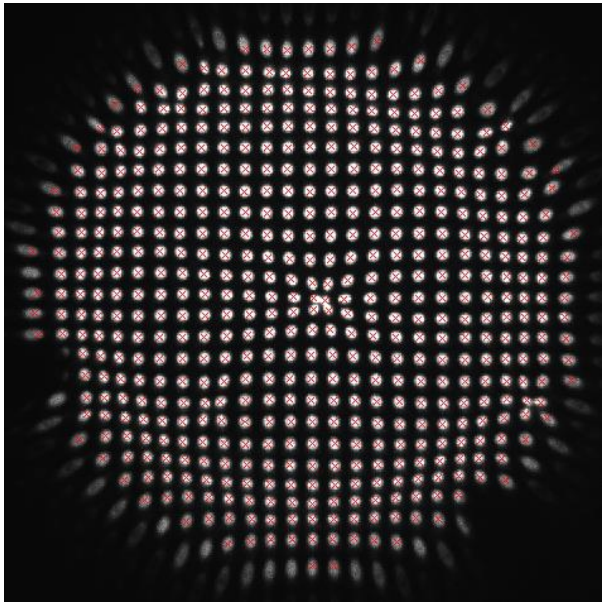
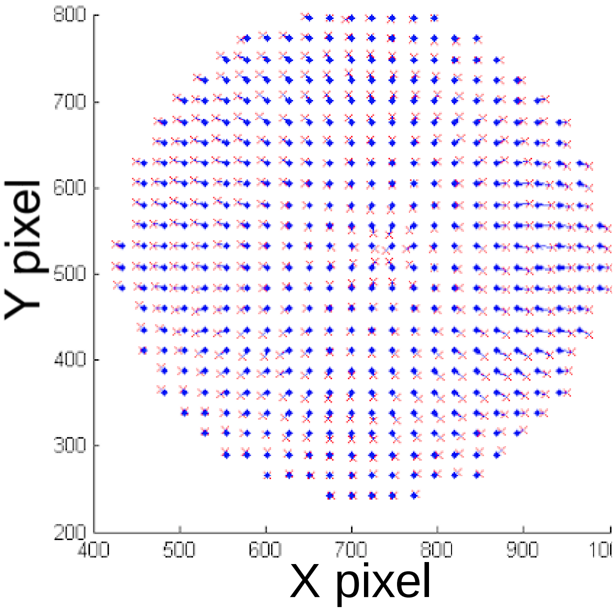
# Reverse Hartmann test-bed

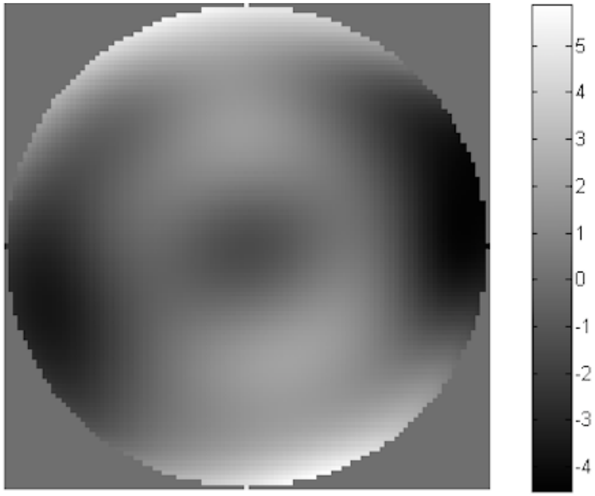


Spot displacements




GS-12 reconstructed surface
1.75 μm RMS < 2.0 μm RMS req.



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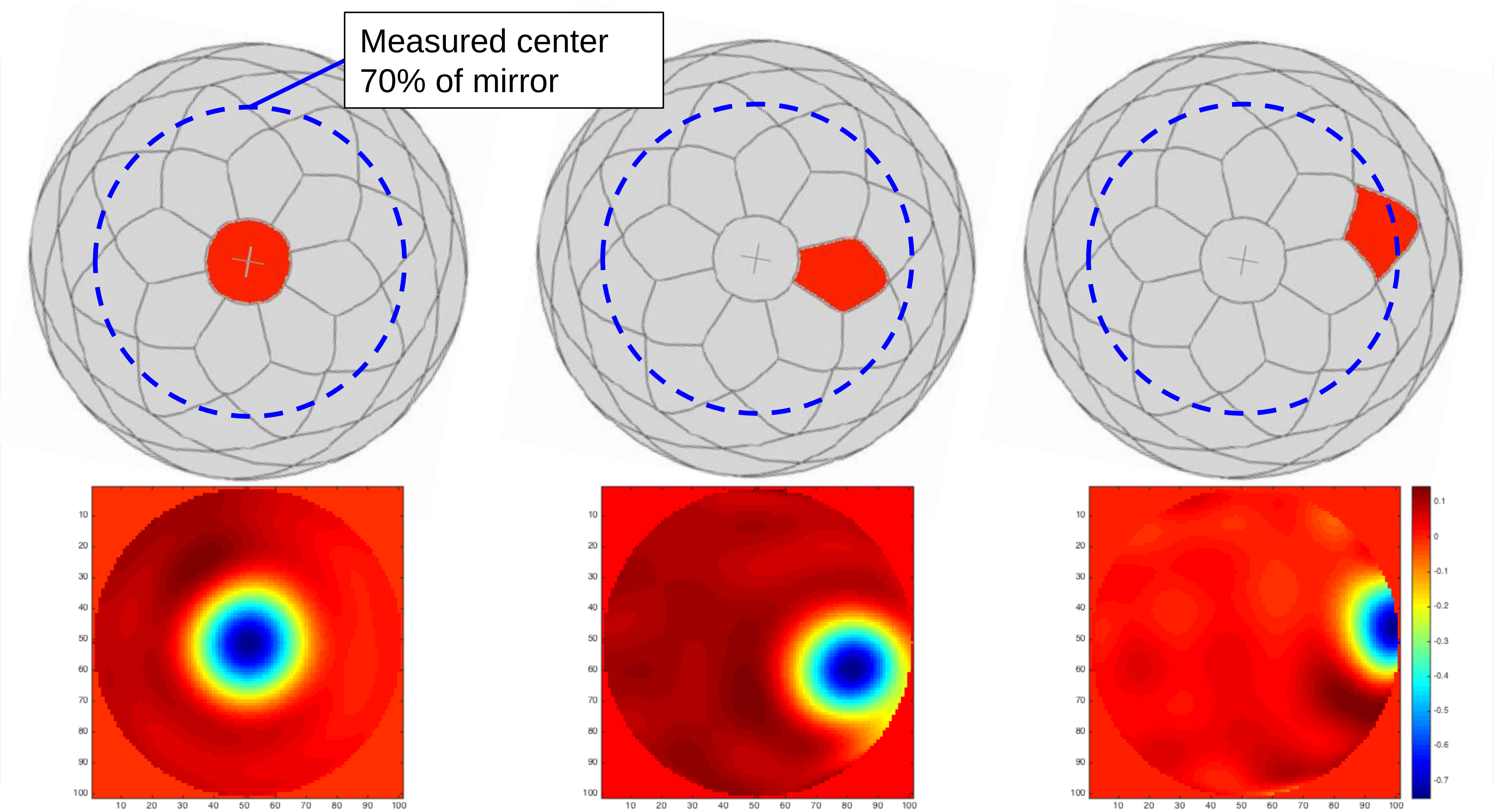
# RS-14 influence functions



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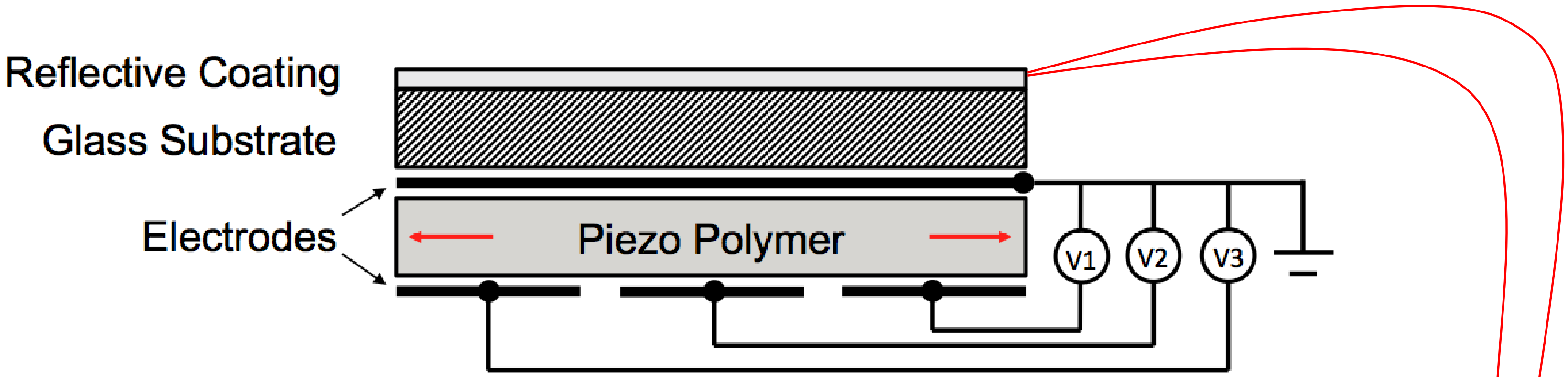
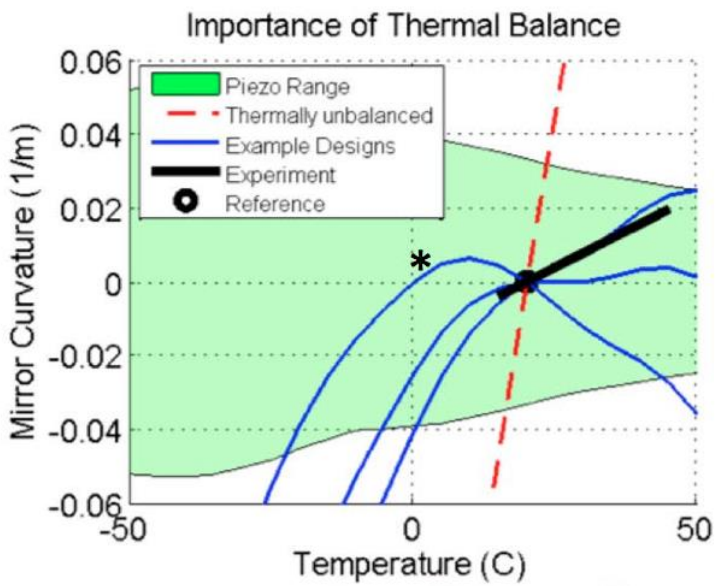
# Thermally balanced reflective layer



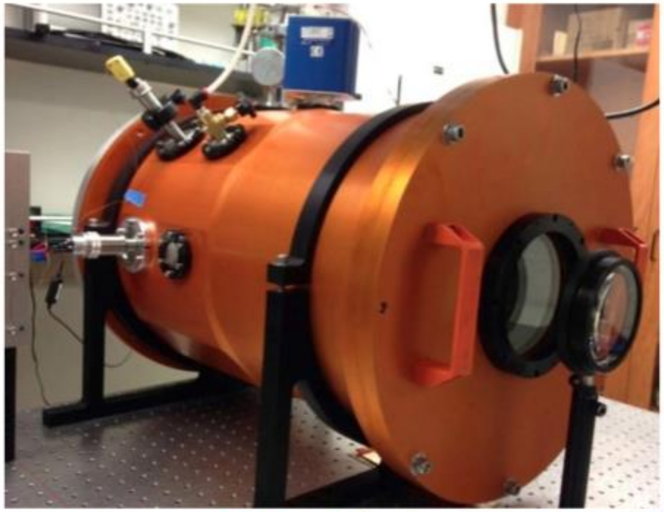



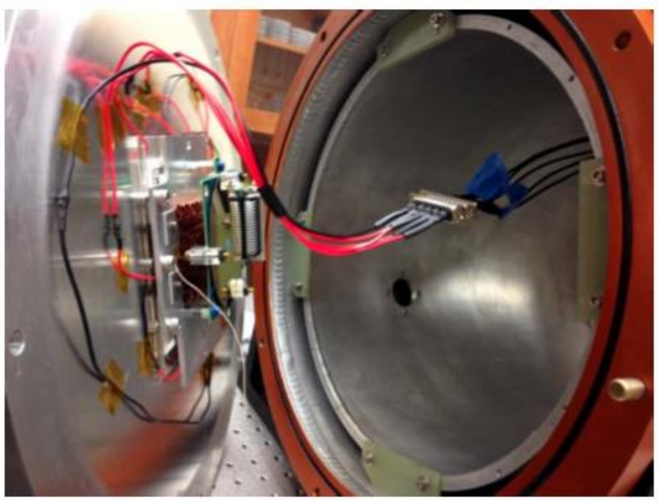

1/3 scale mirror

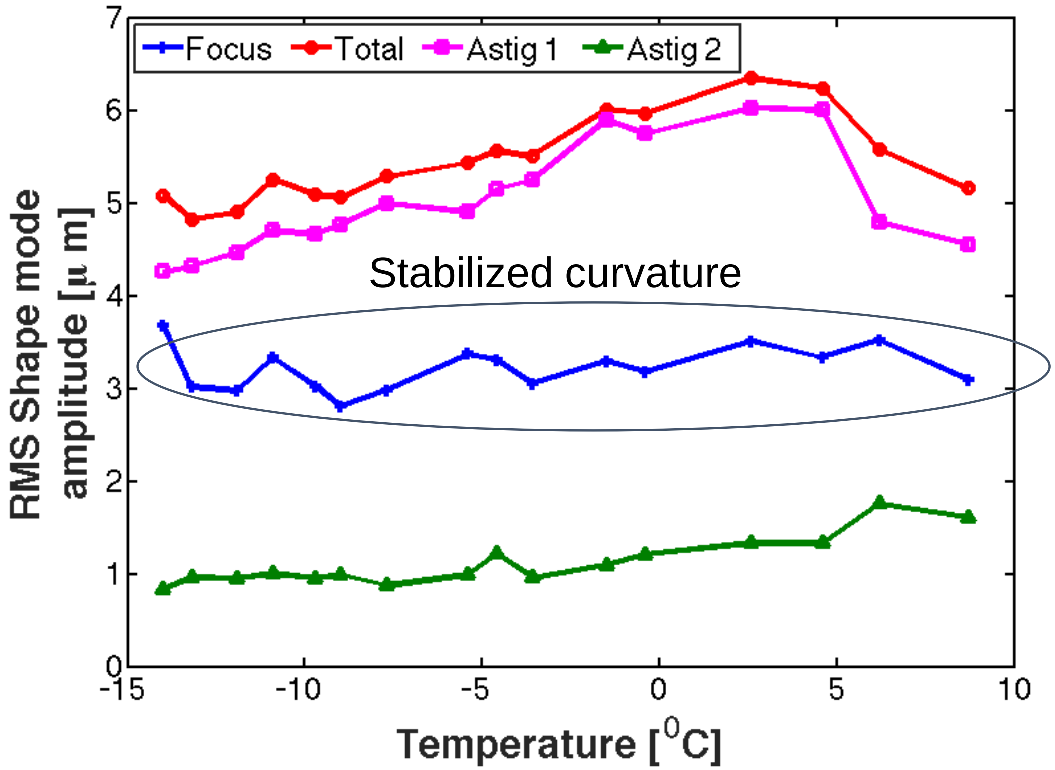
Reflective layer – Al/Cr nanolaminate

- 3 sublayers of Al (550 nm)
- 3 sublayers of Cr (55 nm)

# GS-13 Thermal testing







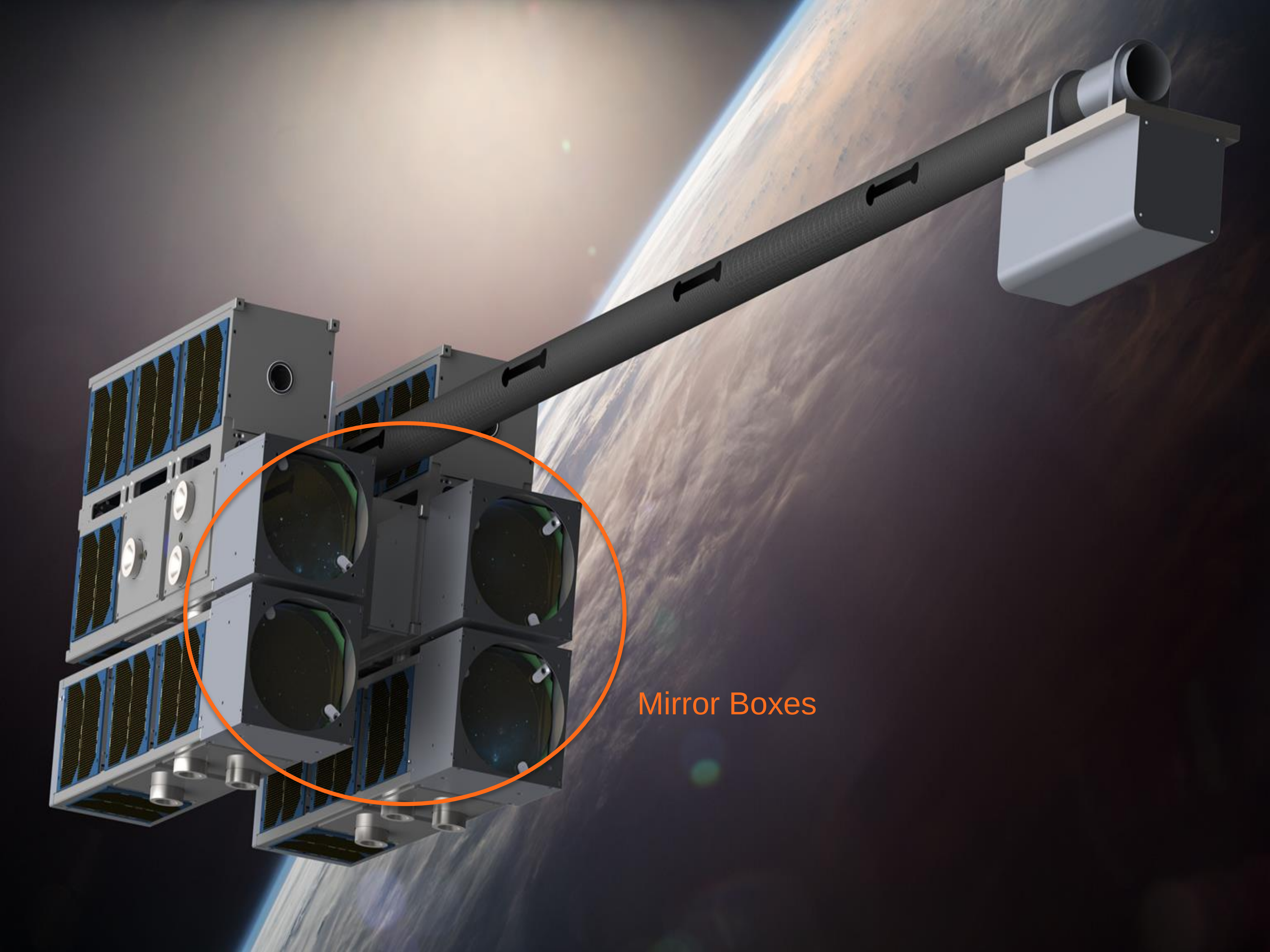

- Thermal balance layer tweaked to reduce focus mode variation from -15C to +20C (expected flight temperature range)
- Astigmatism variation due to mount/mirror CTE mismatch – low CTE mount to be fabricated
- Additional testing ongoing

# Work to go

- Produce flight-like deformable mirrors with GSFC rev. 2 substrates
  - Additional thermal stability, shape control verification

# Mirror Box

Lee Wilson

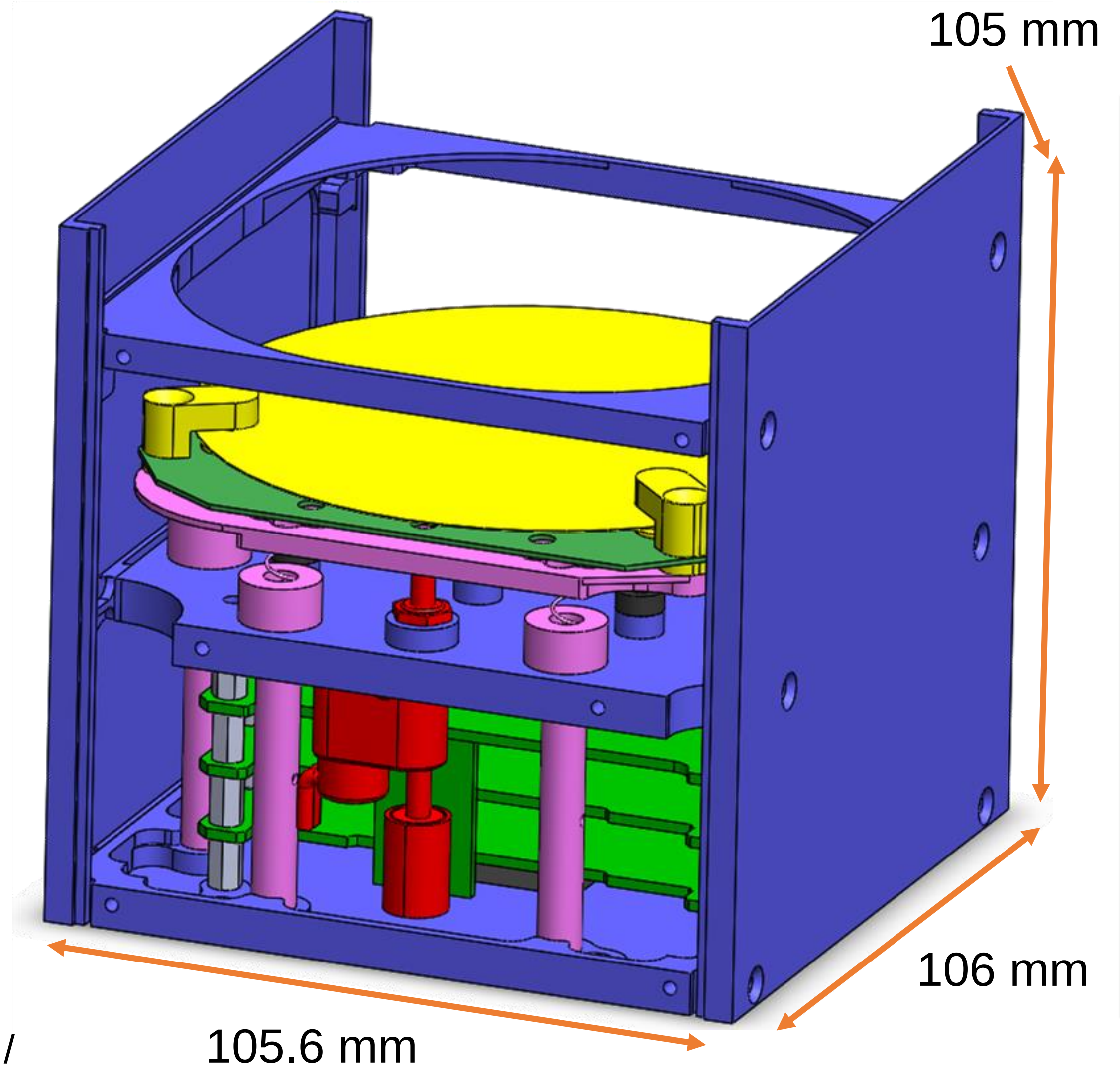

Mirror Boxes

# Accomplishments

- Mirror Box moved from concept into detailed design
  - Launch restraint system, frame & baffle design
  - Improved mirror mounts to avoid unintended mirror deformation
  - Optical encoders & limit switches included for picomotor control
- Optical test with improved mounts

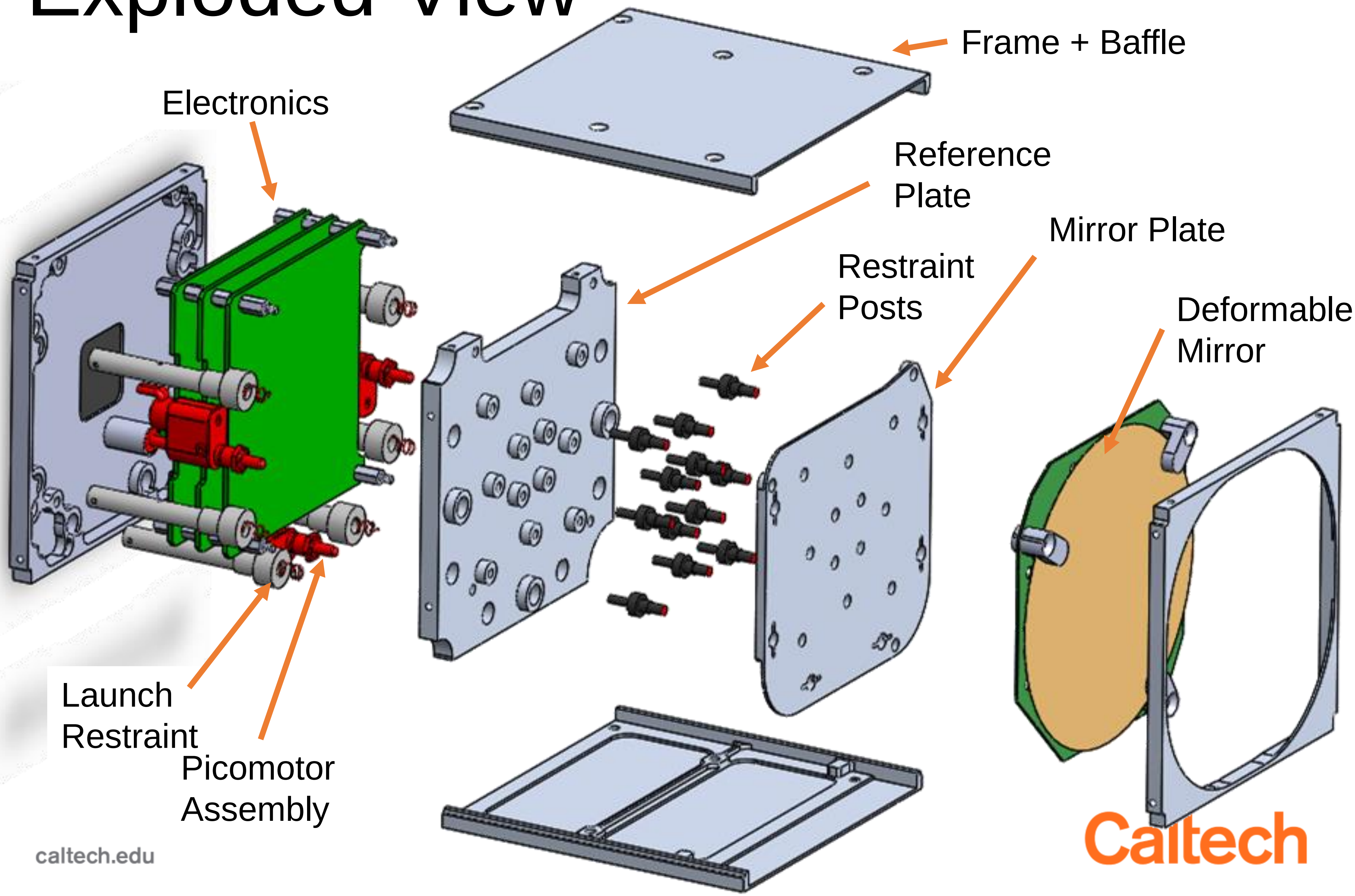
# Mirror Box Overview

- **Mirrors & Mounts**
  - Rigid & deformable mirrors & mounts
- **Picomotors**
  - Linear actuators
  - Piston/tip/tilt the mirror
- **Launch Restraint System**
  - Springs
- **Electronics**
- **Frame**
  - Includes baffle to block stray light
  - Milled from Al Plate
  - Base interfaces with CoreSat / Mirrorcraft



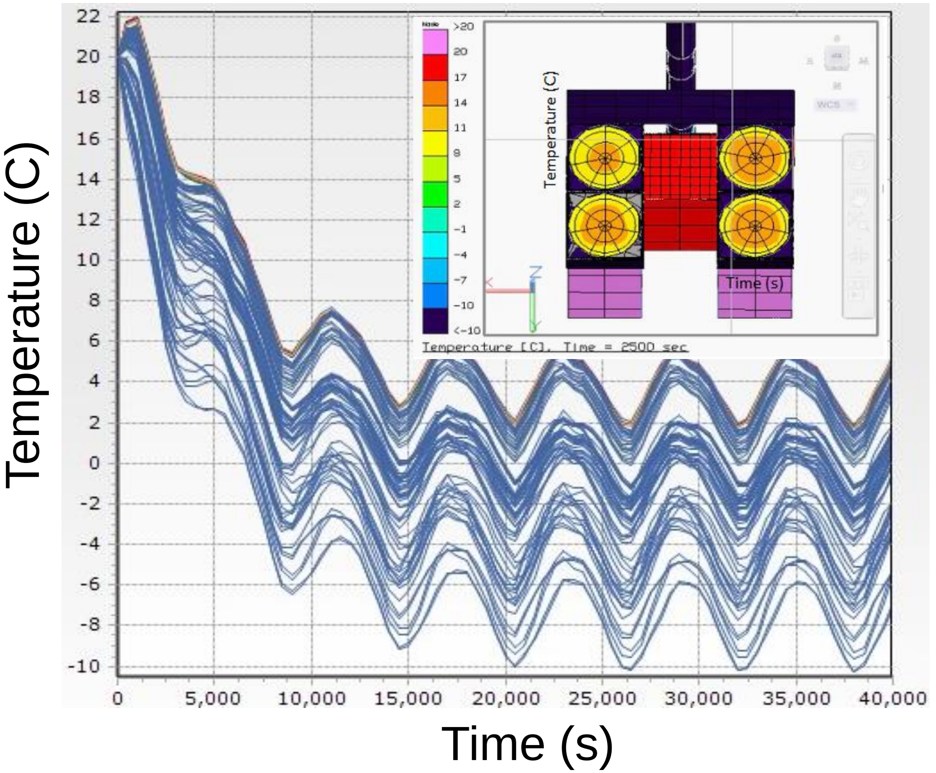

Deformable Mirror Box

# Exploded View



# Key Requirements

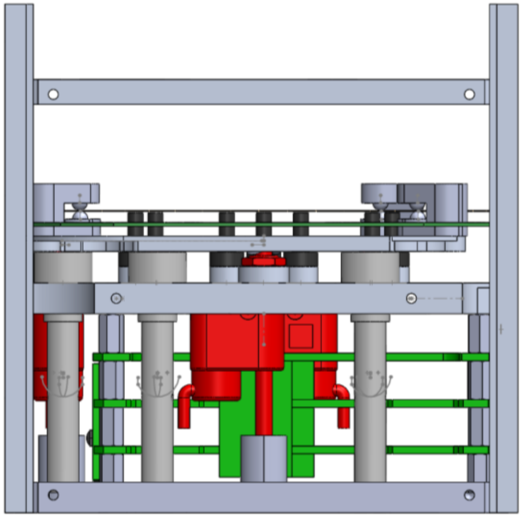
- Provide capacity for mirror to kinematically tip / tilt to 6.85°
- Mirror mounts do not excessively deform mirrors
- Mirror survives launch loads ≤ 6g
- Operating temperatures
  - **-25ºC to +15ºC**
- Survival temperature
  - **-60ºC to 50ºC**
- USB electrical interface with Surrey subsystems



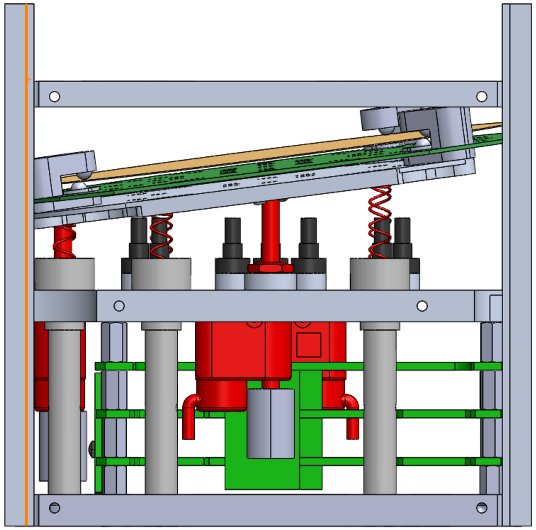

<u>Operating thermal profile for the mirror segments</u>

# Rigid Body Motion

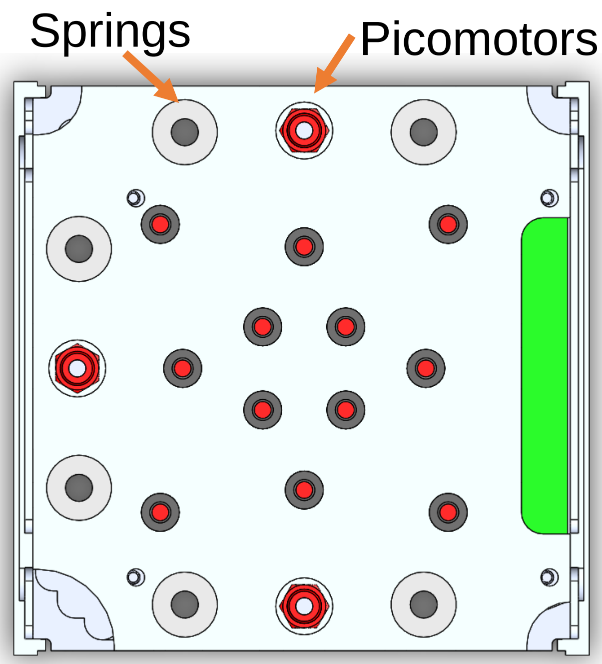
- Picomotors interface with kinematic mount
  - Shaft in contact with steel inserts
  - Cone, V-slot and Flat
- Same system for deformable & reference mirror boxes



Initial Configuration



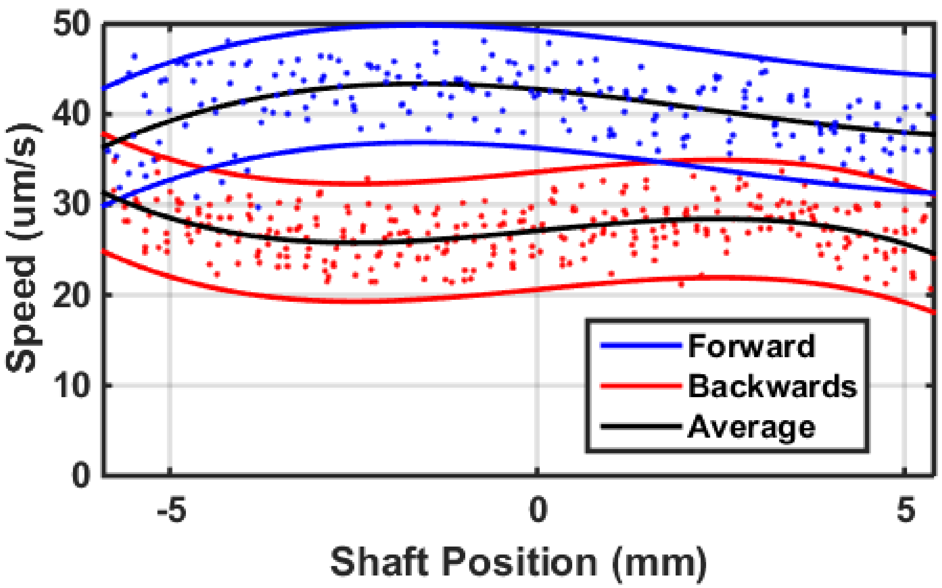
Tilting Mirror




Top View
Picomotor Layout

# Picomotor Control

- Picomotors
  - Newport Solutions 8354
  - Non-linear axial steps
  - $\mu_{mean}$ = 25-40 um/s
- Optical encoders
  - Avago AEDR-8400
  - Measure rotation of picomotors
  - 850 nm axial position resolution ~30 picomotor steps
  - Encoders find average increment for calibration
- Limit switches at top / bottom of picomotor travel
  - D2F2-FL-N



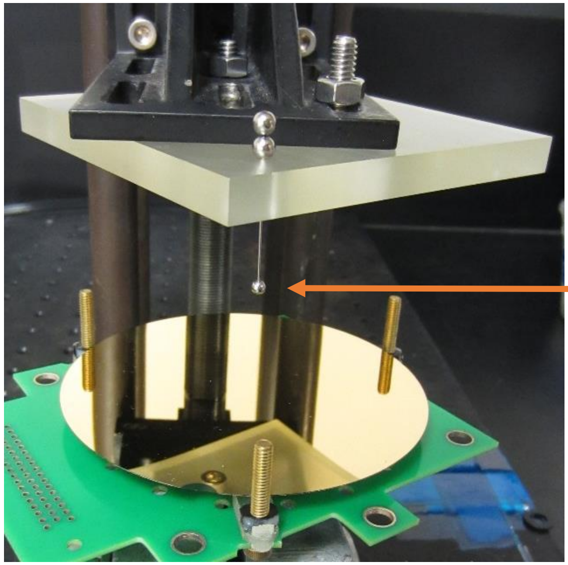
Picomotor Speeds

Limit Switch

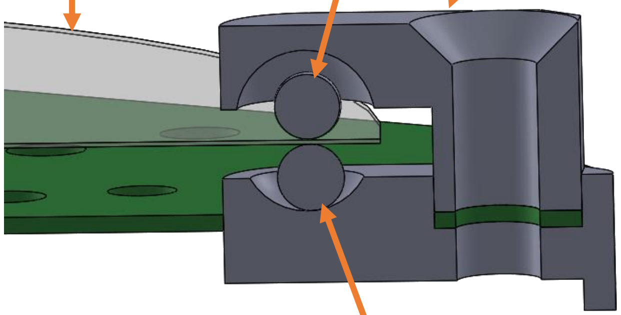

Picomotor
(Linear Actuator)

# Mirror Mounting

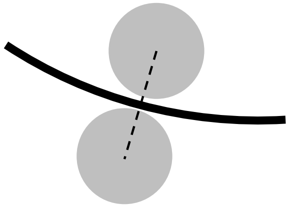
- Kinematic mounting to PCB
  - Spheres pinch mirror in 3 places
  - Spherical magnets aligns with surface normal
  - Cage retains magnet
- Jig used to systematically place magnets




Mounting Jig




Mount Design



Magnet/bearing align with surface normal

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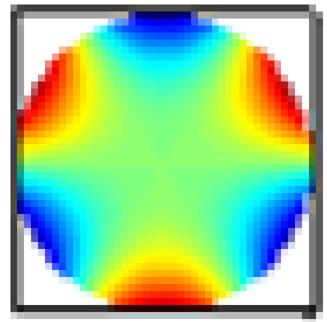
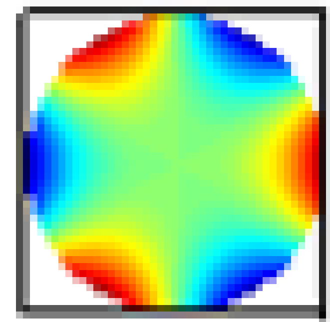
# Mirror Mount Deformation Results

- Zernike modes are an orthogonal basis for mirror deformation
  - Z9 and Z10 are trefoil modes
  - Test mounts at 120º separation
  - Ideal case - mirror rotated 60º mode signs should invert
  - Mounts impart ~60 nm RMS

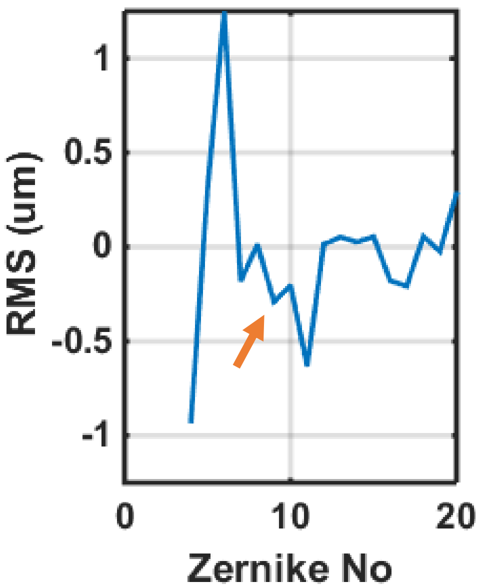


Z9

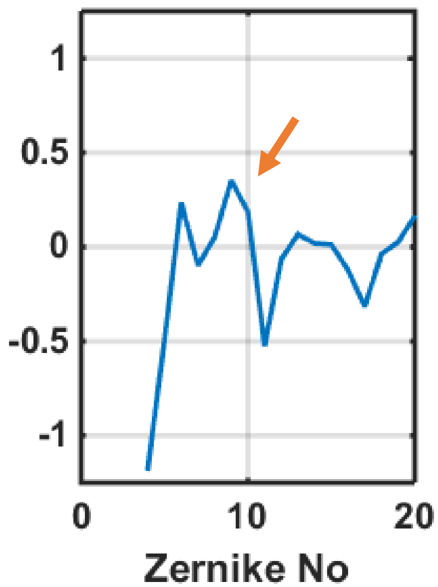


Z10

Key Zernike Modes




Mirror at 0°



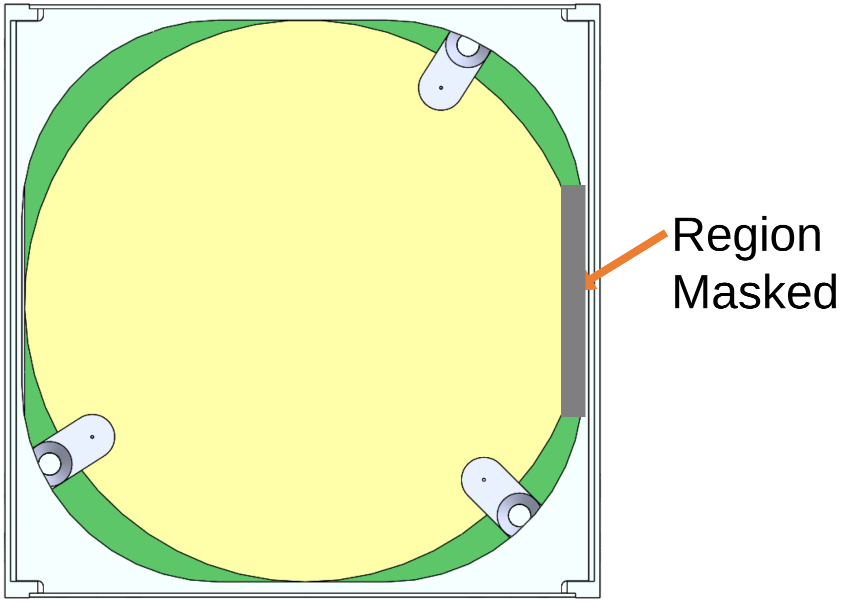

Mirror at 60°

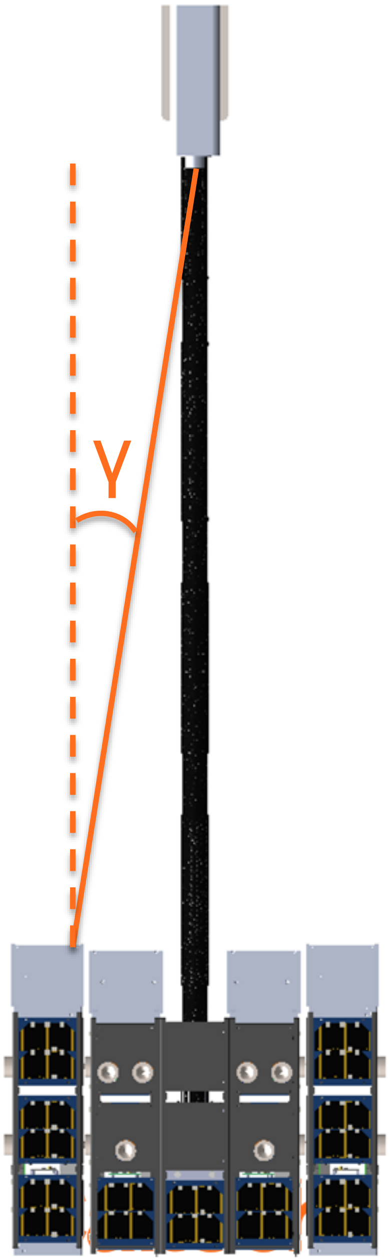
| Zernike | 0° RMS (um) | 60° RMS (um) | Name |
|---|---|---|---|
| 9 | -0.29 | 0.35 | Vertical Trefoil |
| 10 | -0.2 | 0.19 | Oblique Trefoil |

Trefoil Results
(Reverse Shack Hartmann Test)

# Mirror Shadowing

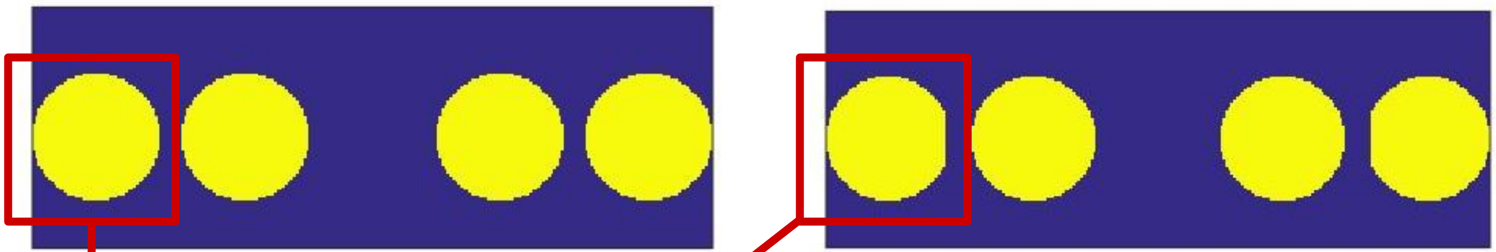
- Mirror box sides & baffle shadow mirror during operation
  - Wide Configuration ~ $\gamma = 8.1^{\circ}$
  - Mirror Diameter = 100 mm
  - Hole Diameter = 100 mm
- Region masked = 3.7 mm of one edge

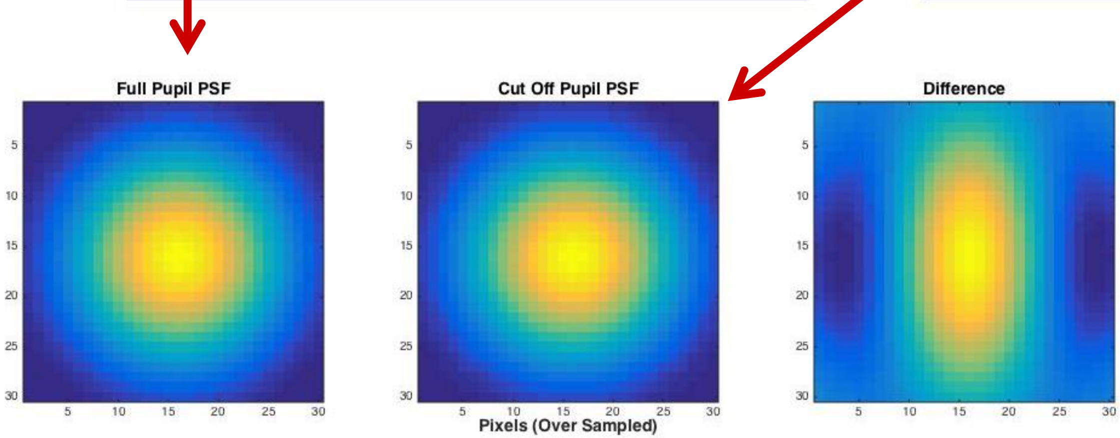


# Effect of shadowing on PSF

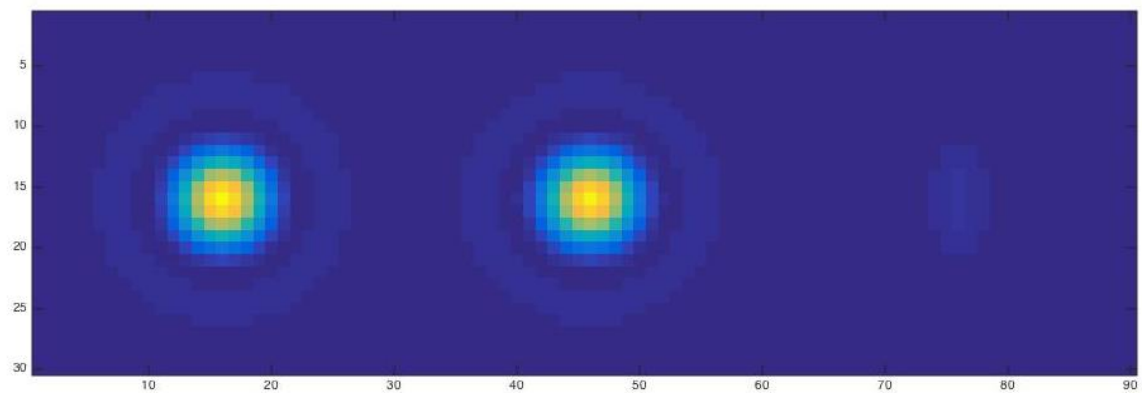
Un-shadowed pupil (wide configuration) Pupil given current mirror box design





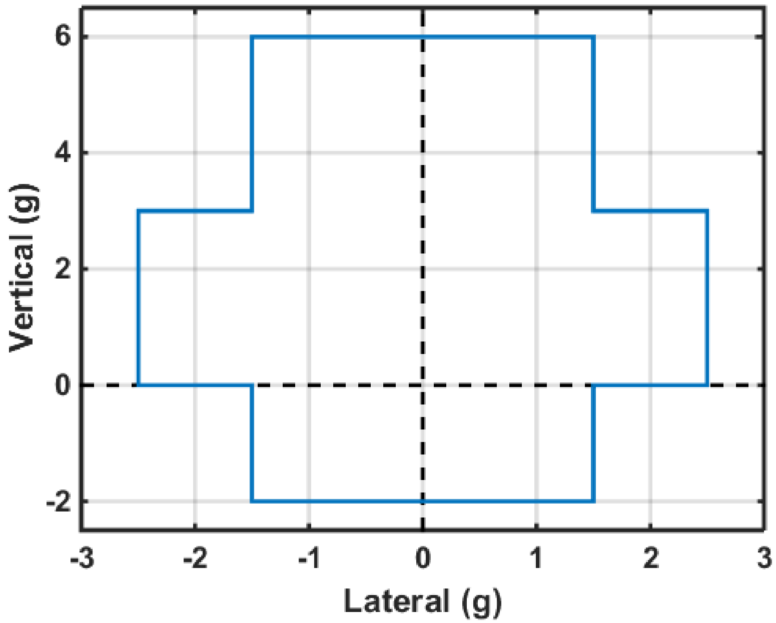

- Over sampled PSF core for single segment
- Difference scaled to show structure
- Peak intensity is decreased by 3% (assuming 100% clear aperture)

- PSF of single segment shown with proper pixel samplings
- Difference on same scale



# Launch Restraint

- Latching with 6 springs
  - Mirror + Mirror plate = 393 grams max
- Max 13 N / picomotor
  - Picomotors not engaged during launch
  - Spring force $\propto$ Picomotor extension




Delta IV Launch Environment

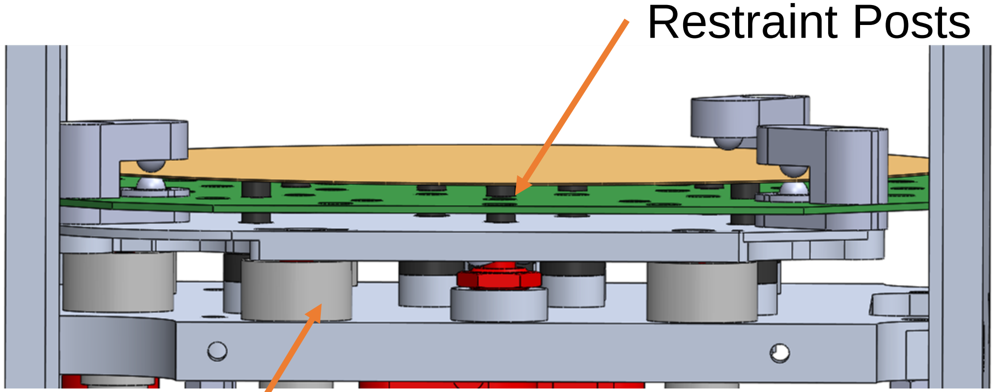
| | Latched Force | Fully Extended Force | Safety Factor on Latching | Safety Factor on Picomotors |
|---|---|---|---|---|
| Springs x6 9044K19 | 24.3 N | 37 N | 1.05 | 1.05 |



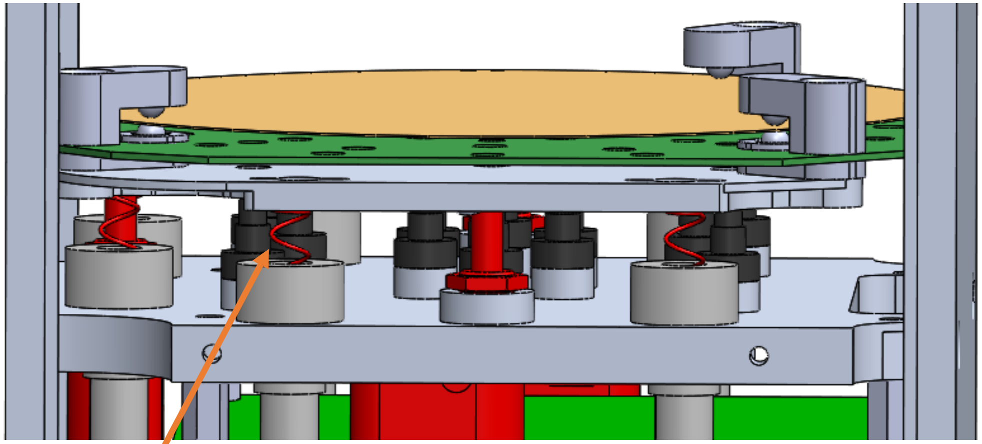
Delta IV Launch Environment

# Restraining Mirror

- Restraint posts prevent motion perpendicular to springs
- Silicone tips press on mirror back – reduce vibrations
- Lab implementation:
  - Holes drilled through mirror PCB allow restraint posts through
  - Mirror seated against silicone pads atop shoulder bolts

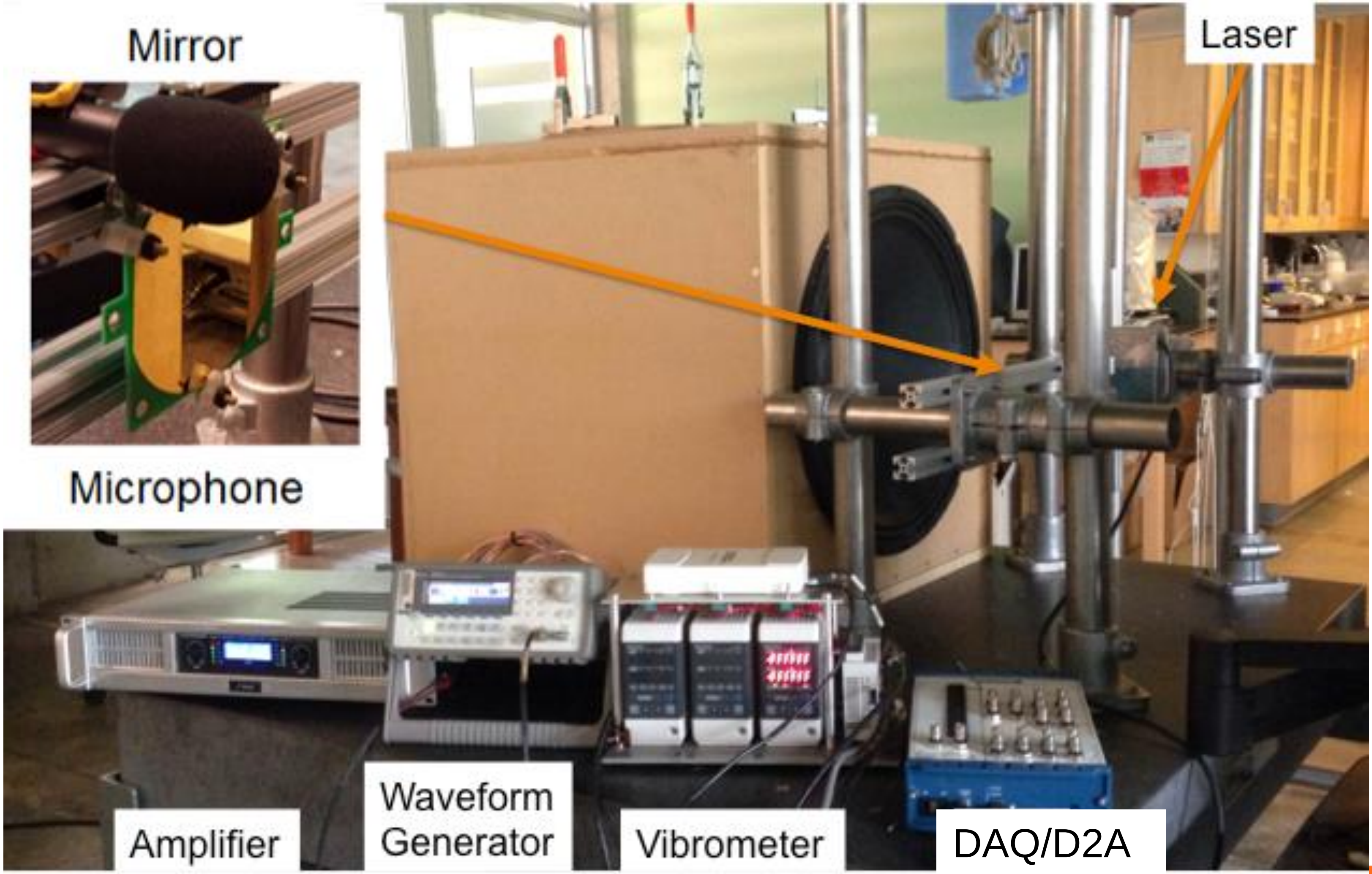



Launch Configuration




During Operation

# Acoustic Test Apparatus



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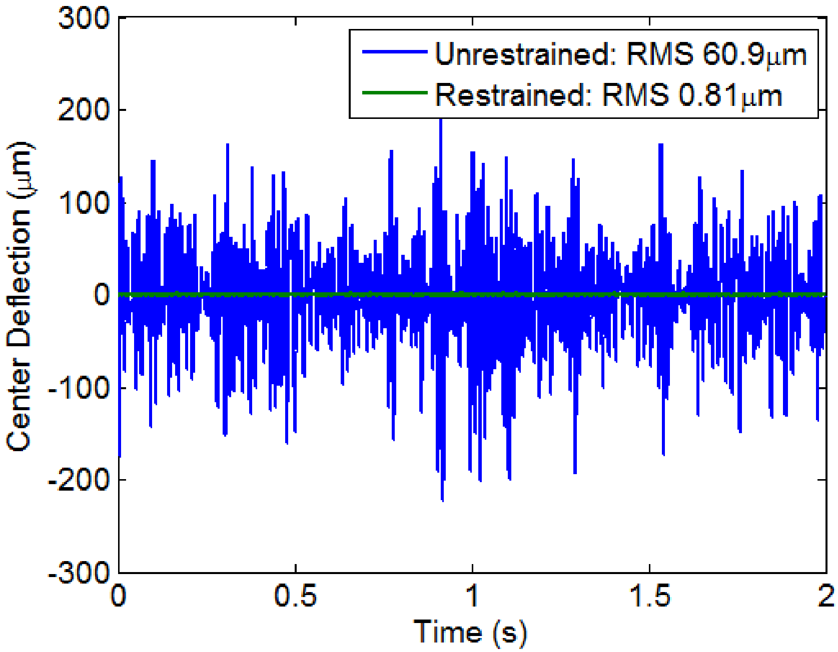
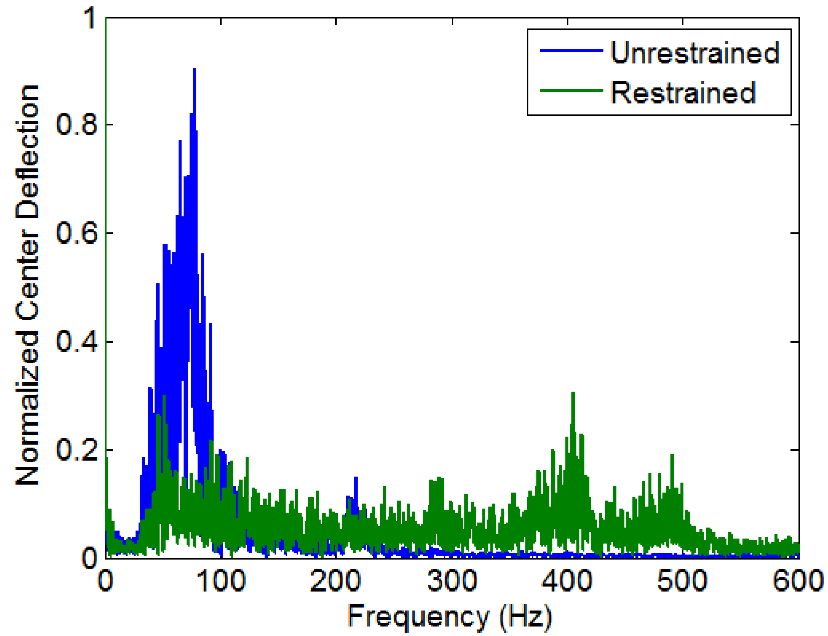
# Vibration Suppression




- Approximated Delta IV Heavy acoustic loads
- Mirror response measured at 115dB (low signal distortion)
  - ~ 75x reduction in RMS response
  - More broad-band response due to constrained configuration
  - Values to be measured at higher SPLs (TBD)



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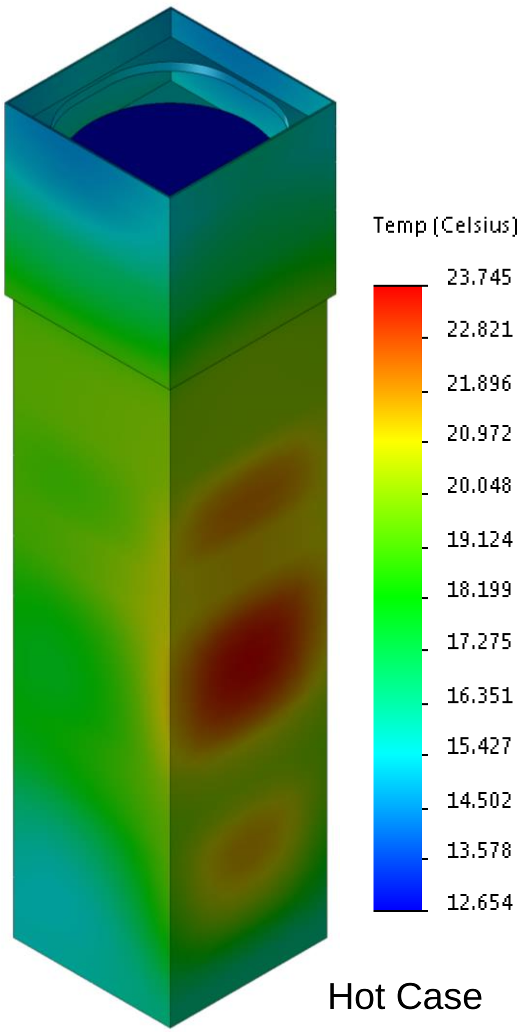
# Mirror Box Thermal Design & Modeling

- Passive thermal control
  - Mirror box exterior painted white (absorptance = 0.35, emissivity = 0.85)
- DM is the most temperature-sensitive component (20º C > $T_{DM}$ > -25º C during operations)
  - Conductively isolated from the rest of the box
  - Radiative coupling to PCB below is primary heat transfer mech.
  - Inefficient at rejecting heat to cold sky because of low-emissivity reflective coating
- Steady state FEM thermal simulation
  - Conservative estimates of hot and cold case temperatures
- Simulation accounts for
  - Solar (1400 W/m$^2$), Earth-reflected (albedo = 0.3), Earth-emitted (240 W/m$^2$) radiation
  - Limited view of the cold sky (140º cone blocked by Earth)
  - Waste heat from electronics (1.53 W) and MirrorSat (4 W)

| | Min (°C) | Max (°C) | Mirror (°C) |
|---|---|---|---|
| Hot Case (Survival & Operational) | 12.7 | 23.7 | 12.7 |
| Cold Case (Operational) | -25.7 | -15.1 | -22.1 |
| Cold Case (Survival) | -34.5 | -29.6 | -34.5 |




Hot Case

# Mass Budget

- ~ 0.66 kg / Deformable Mirror Box
- ~ 0.90 kg / Reference Mirror Box

| Subsystem | Current Mass (g) | Contingency (g) (30%) | Total (g) |
|---|---|---|---|
| Mirror – Deformable (Reference) | 28 (340) | 8 (-) | 36 (340) |
| Picomotors | 57 | - | 57 |
| Launch Restraint System | 71 | 21 | 92 |
| Electronics | 144 | 43 | 187 |
| Frame | 224 | 67 | 291 |
| **Total Mass** | **524 (791)** | **140 (118)** | **664 (909)** |



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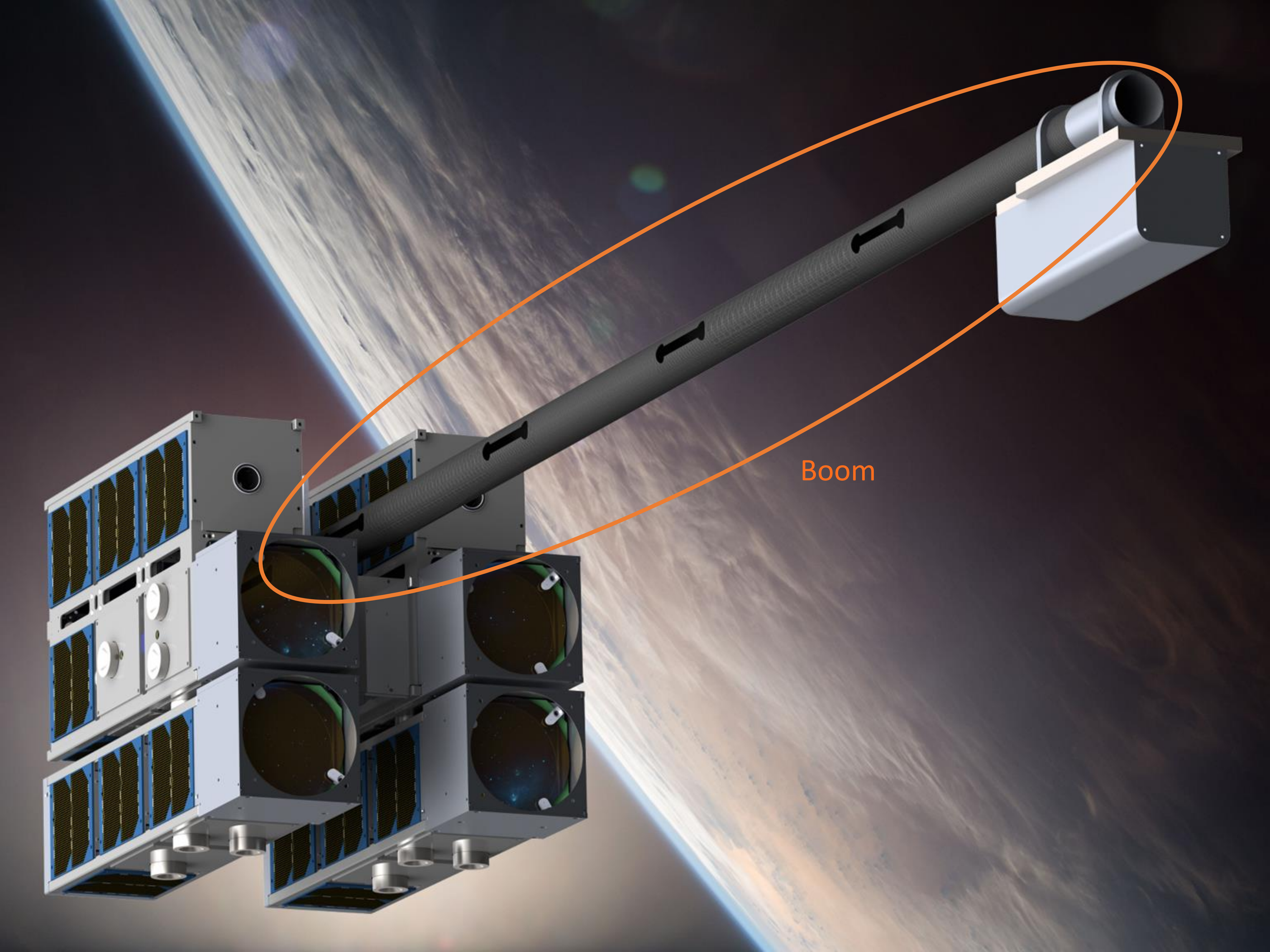
# Future Work

- Additional thermal simulations for reference mirror mounting
- Manufacture protoflight hardware
- Vibration test on protoflight hardware
  – Investigate if “mirror walking” during launch is a problem
  – Wire bond survivability
- Optics test on protoflight hardware

# Boom

Christophe Leclerc, Serena Ferraro,
Federico Bosi


Boom

# Boom overwiev

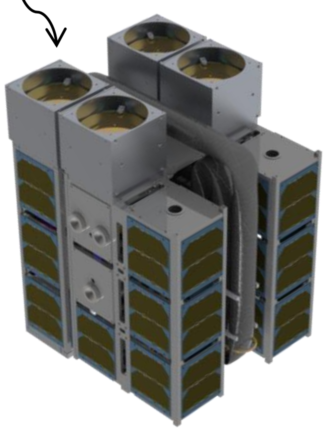
**Functional**

- Enable 1.16m telescope focal length
- Lightweight and compact launch configuration
- Can self deploy

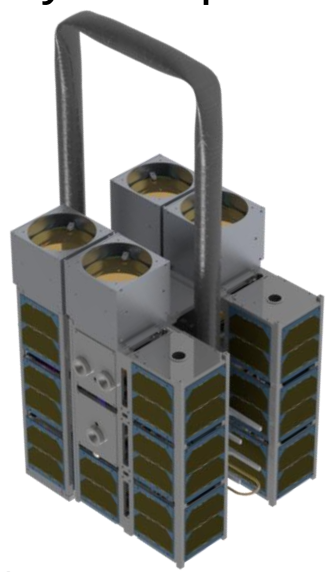
**Architecture**

- Hollow cylindrical boom wrapped around S/C via 4 folding-tape-spring hinges attached to S/C and Camera through interfaces
- Two stage unconstrained deployment process

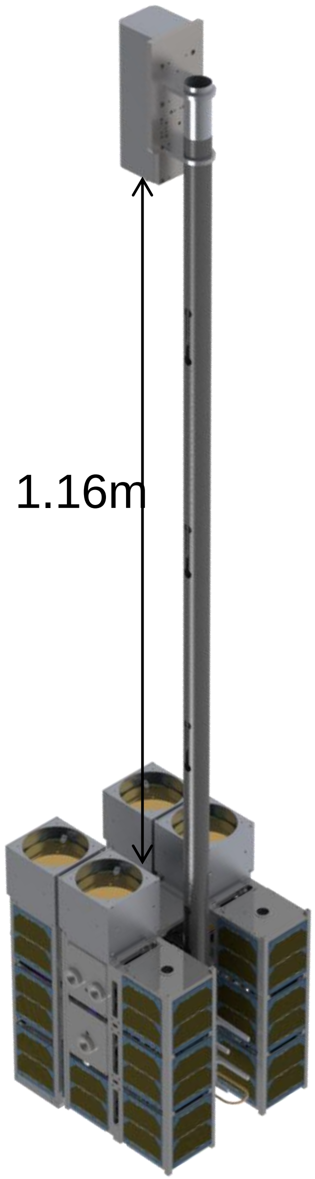
Camera



Stage 1 Deployment



Stage 2 Deployment



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# Accomplishment

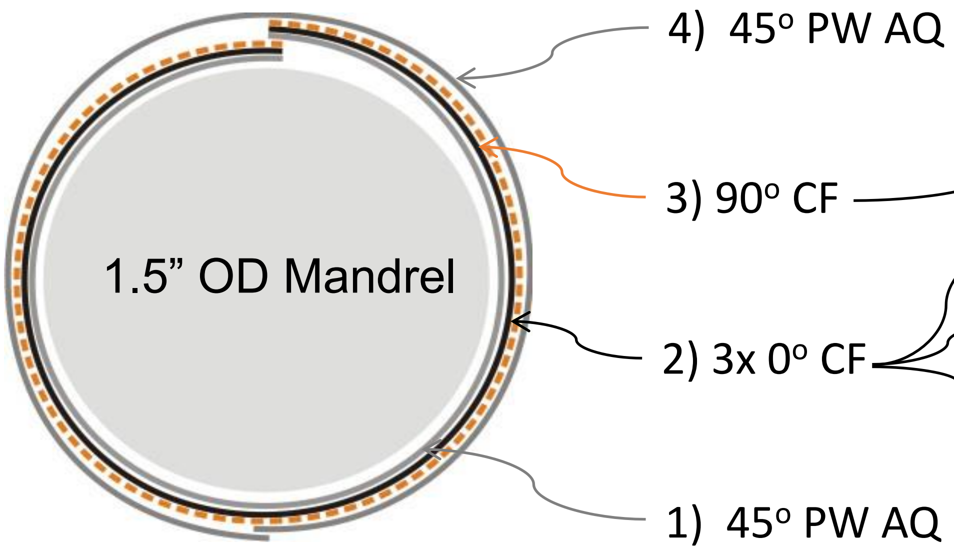
- **New composite material**: use of cyanate ester resin matrix
- **In-house two full length booms manufacturing** (previously realized by AFRL in Albuquerque)
- **Material characterization**: outgassing test and viscoelastic analysis
- **Hinges characterization**
- **Manufacturing and testing of Boom-CoreSat Interface**: kinematic mount and separation device
- **Stage 1 deployment experiments**

# Boom Lay-up

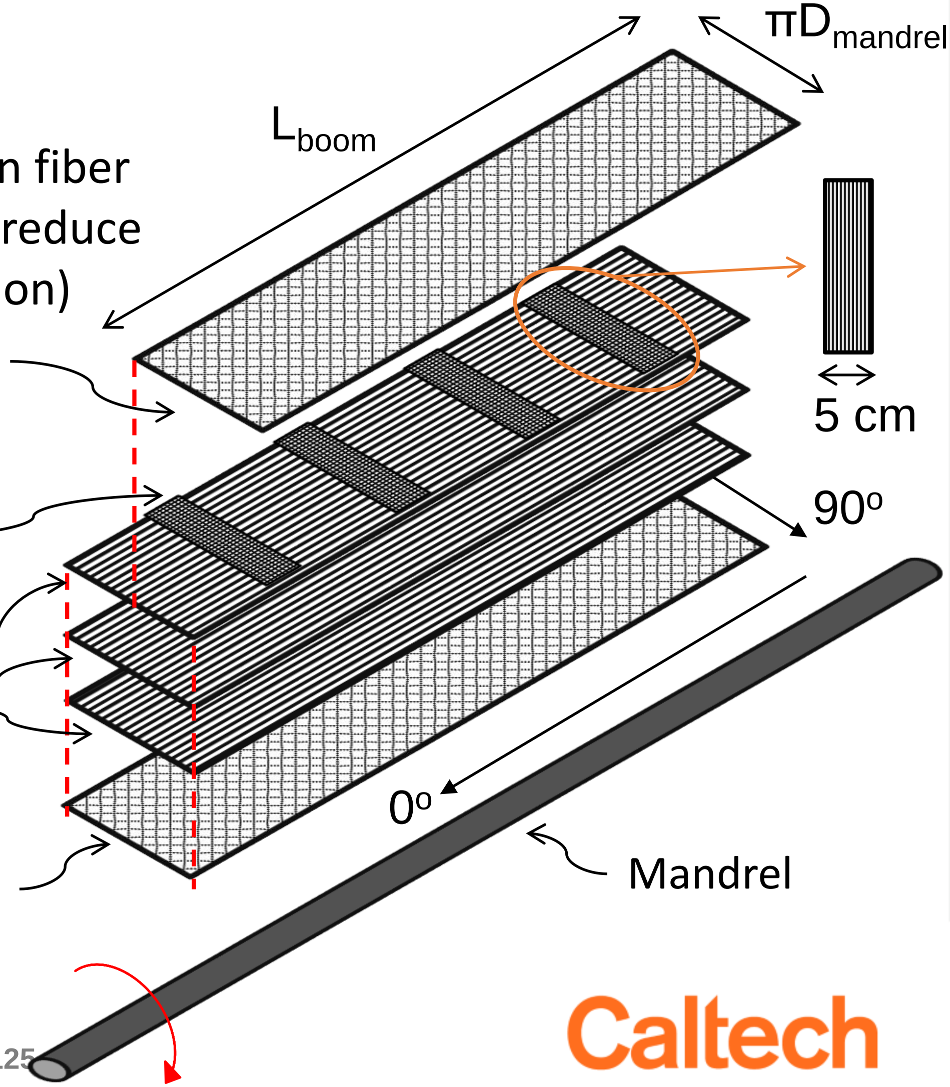
**Objective: improve seaming** area and **prevent opening** of the boom (happened with AFRL booms).

The composite consisted of

- Plain-weave (PW) Astroquartz
- ThinPreg 180CE unidirectional carbon fiber with a cyanate ester resin matrix (to reduce outgassing and low moisture absorpion)




Boom Cross Section



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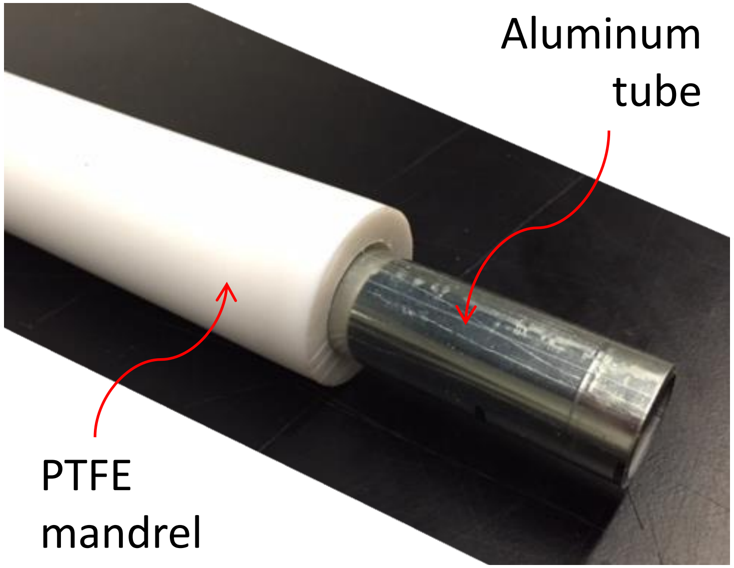
# Mandrel Material Choice

**Objective:** choose a mandrel through which the boom is easy to remove, has a good surface quality and maintain its straightness after the curing cycle.

The mandrel is composed of:

- External hollow **PTFE** mandrel. Because of its high CTE, the boom is easy to remove from the mandrel and will not have wrinkles.
- Internal **Aluminum** tube to keep the PTFE mandrel straight.

The mandrel's length is 1.85 m, therefore it is possible to manufacture a full length boom (1.45 m) without any junction zone.



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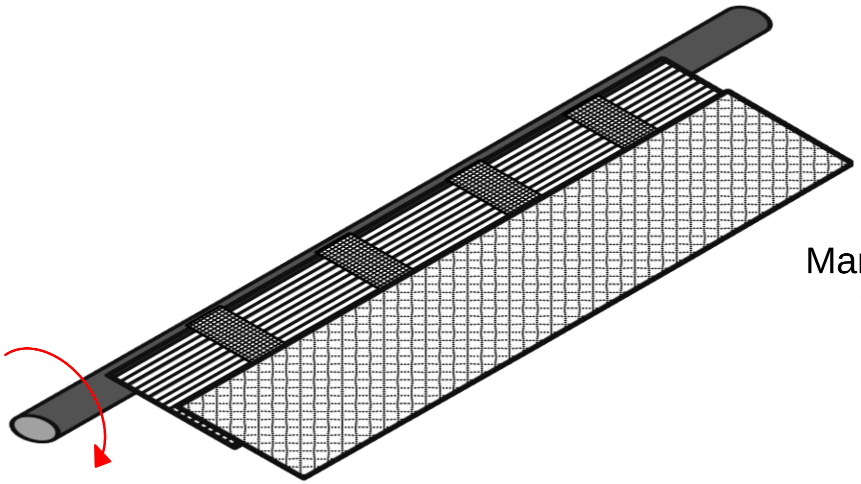
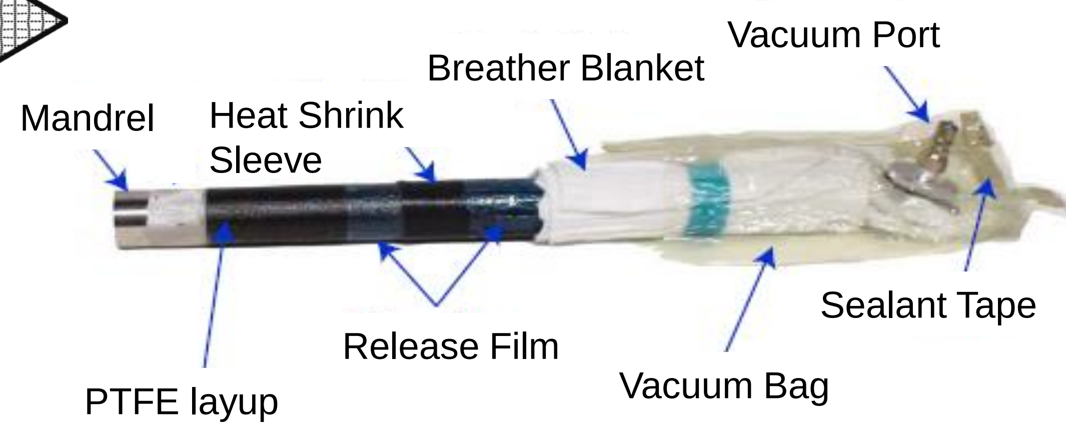
# Fabrication Process

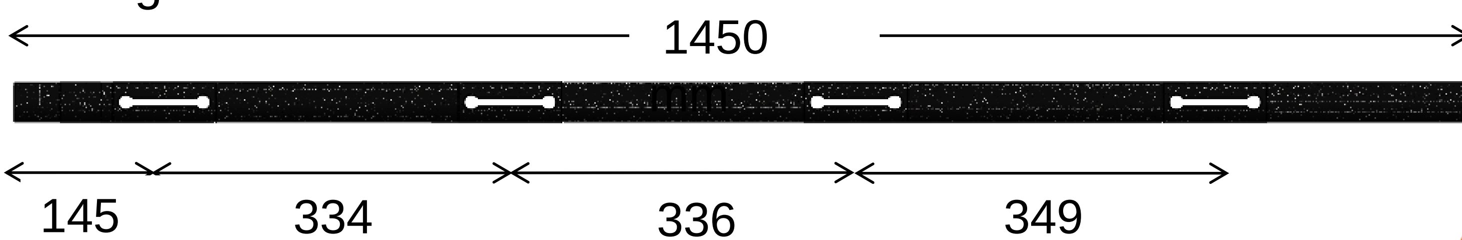
1) Roll onto cylindrical mandrel



2) Vacuum bag, autoclave cure & remove from mandrel




3) Cut hinges in appropriate locations, optimized for stored configuration



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# Final Boom

Two full length boom have been realized:

- Total mass of each boom is **65 g**;
- Diameter is 38.8 mm;
- Total length is 1.45 m;
- Thickness is 200 μm;
- Straightness is 5 mm/1.45 m (~0.34% ).



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# Comparison New & Old Booms

**New booms** (Caltech fabrication) do not present any opening during multiple folding and unfolding, thanks to the new lay-up and manufacturing process.

**Old booms** (AFRL in Albuquerque ) show opening of the seam during folding.

# Outgassing

**Objective:** Validate the low outgassing properties and low moisture absorption of the composite material with the new cyanate ester resin.

- Tests were performed in accordance with ASTM E595-07;
- From NASA standard, a material is “Low Outgassing” if
  - TML < 1% (Total Mass Loss);
  - CVCM < 0.10% (Collected Volatile Condensable Material).

| Test | TML % | WVR % | CVCM % |
|---|---|---|---|
| 6 samples | 0.17 | 0.11 | 0.00 |

- WVR is Water Vapor Regained.

From these results, the material **successfully passed** the outgassing tests.



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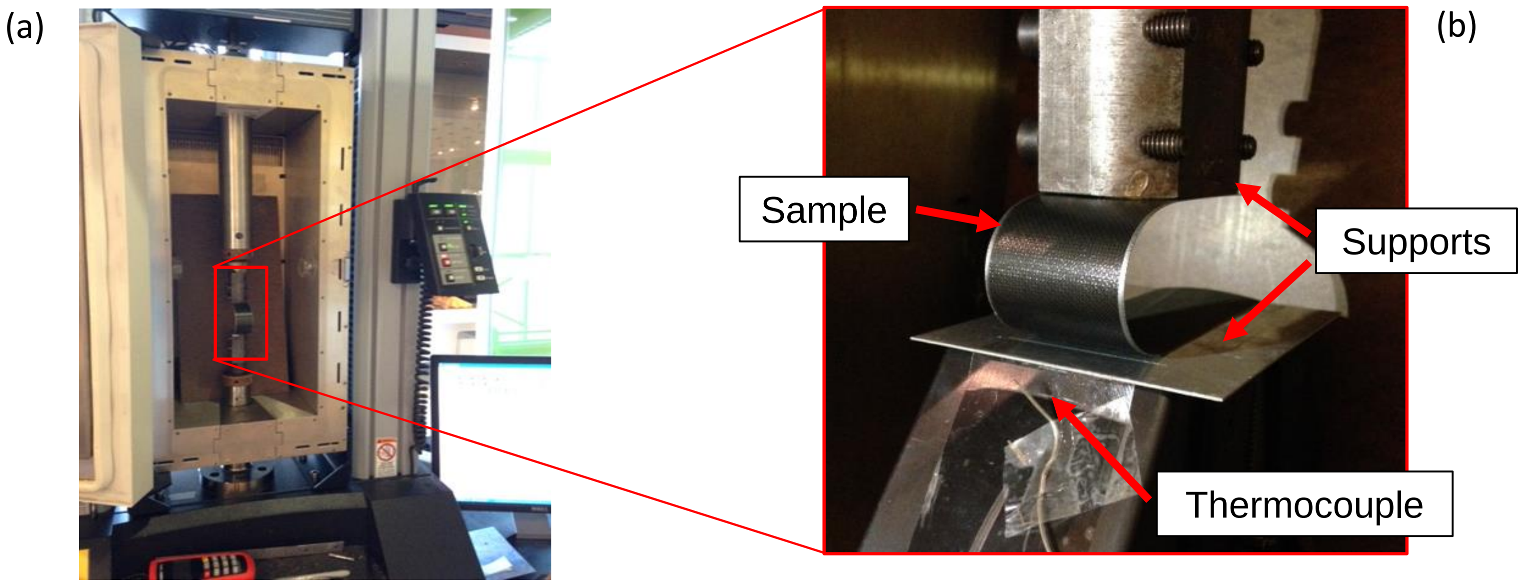
# Viscoelastic Test

**Objective:** Ensure boom retains sufficient potential energy for deployment after long-term storage.

**Test Method**:

- Sample buckled and positioned inside a preheated thermal chamber;
- Supports kept at fixed distance to simulate stored radius of curvature;
- The change in reaction force exerted by the sample is measured with a load cell.



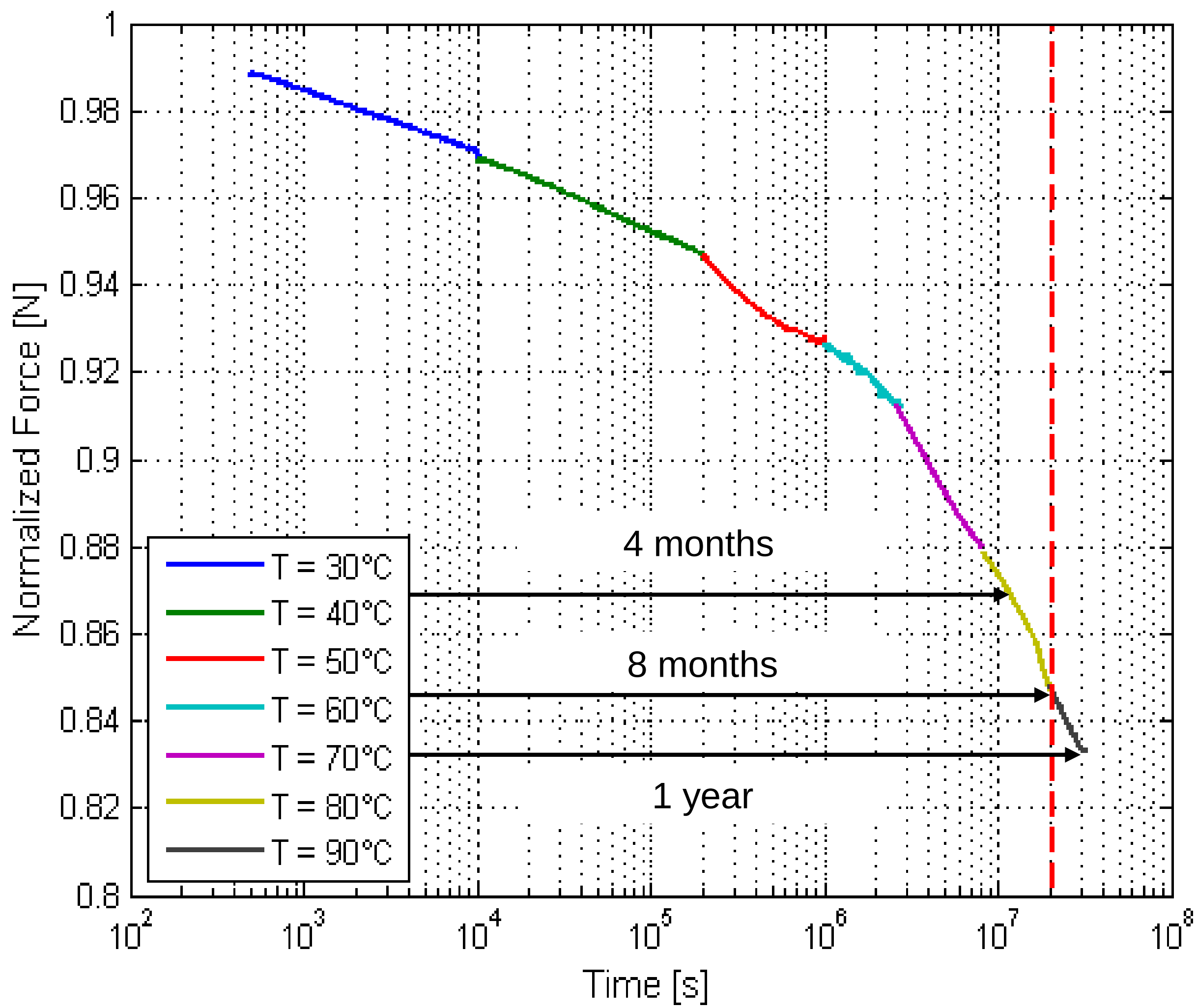

(a) Experimental set-up: Instron Mechanical testing machine with its thermal chamber; (b) detail of the sample .

# Viscoelastic Properties: Master Curve

Though the master curve we know the viscoelastic behavior of the material over time: to simulate 4 months of storage time the sample need to be <u>aged 84 minutes at 80 °C</u>.

**Results expected:**

- **~12%** decrease in reaction force over 4 months;
- **~14%** decrease in reaction force over 8 months;
- **~16%** decrease in reaction force over 1 year.



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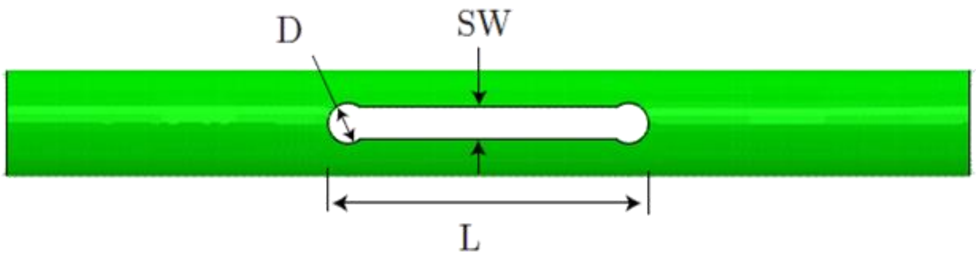
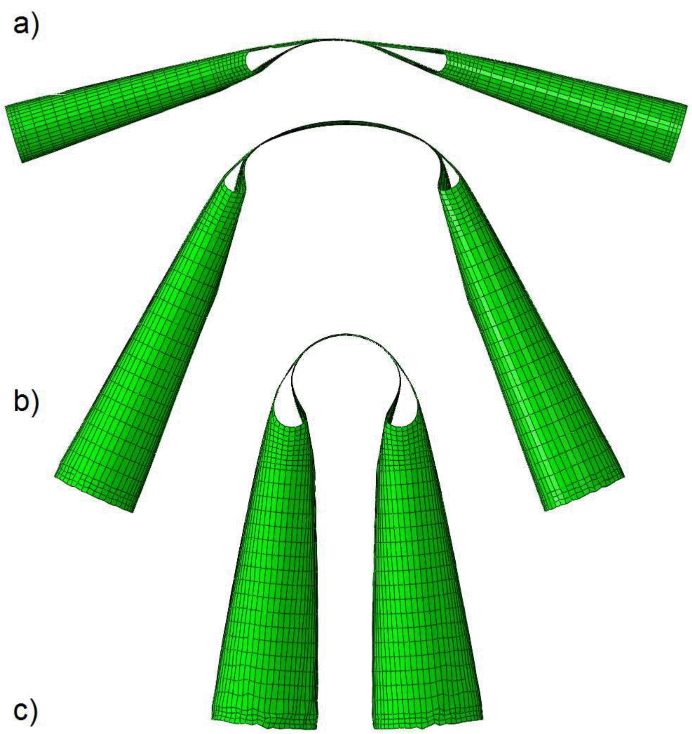
# Hinge Design

- Dimensions
  - 200 µm composite's total thickness;
  - 38.8 mm boom's diameter.
- The cutting pattern has been design through a structural optimization:
  - "Dog-bone" hinge cutting pattern;
  - D = 15mm, L= 90mm, SW = 8mm;




**Based off of Mallikarachchi, H.M.Y.C. and Pellegrino, S. (2008-2012)**



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# Hinge Characterization

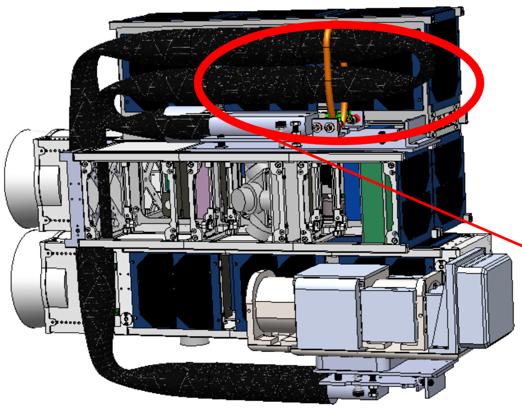
**Objective**: Measure the moment exerted by the hinge with respect to the hinge configuration, defined by its angle. Compare unaged and aged hinge behavior.

**Results**: ~12% decrease in steady moment if behavior at the peak is neglected.

**Conclusions**: - Quasi-static deployment test confirms master curve prediction;

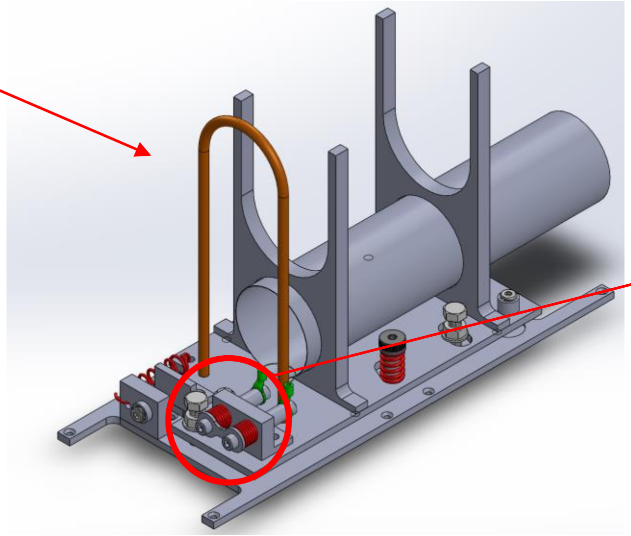
- Reduced moment did not prevent successful hinge deployment, longer storage time will not compromise boom deployment.

# Boom-CoreSat Interfaces

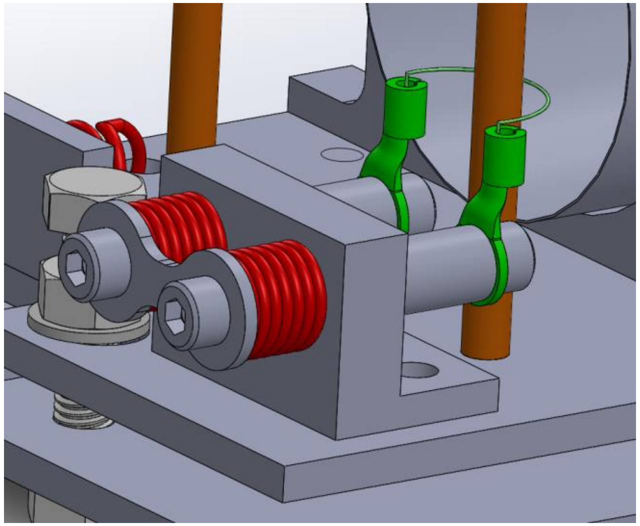


AAReST stored configuration

**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.



**Objective**: Validate last year's designs through manufacturing and testing and suggest improvements.



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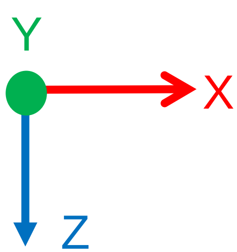
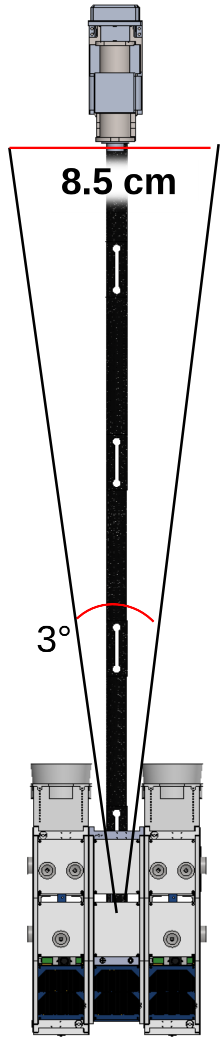
# Boom-CoreSat Interfaces: Testing

## Kinematic Mount

| Axis | Degrees of Rotation | Camera Lens Displacement |
|---|---|---|
| x | 4° | 11.3 cm |
| y | 3° | 8.5 cm |
| z | 6° | 1.0 cm |

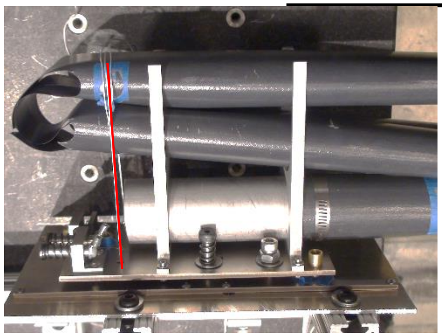
- More than enough adjustability in all 3 axes of rotation.

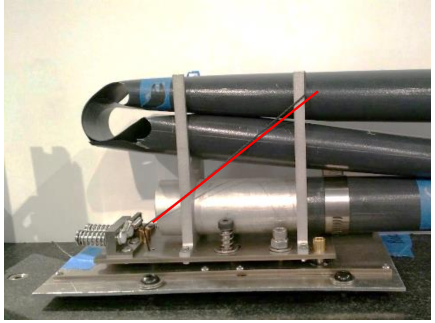


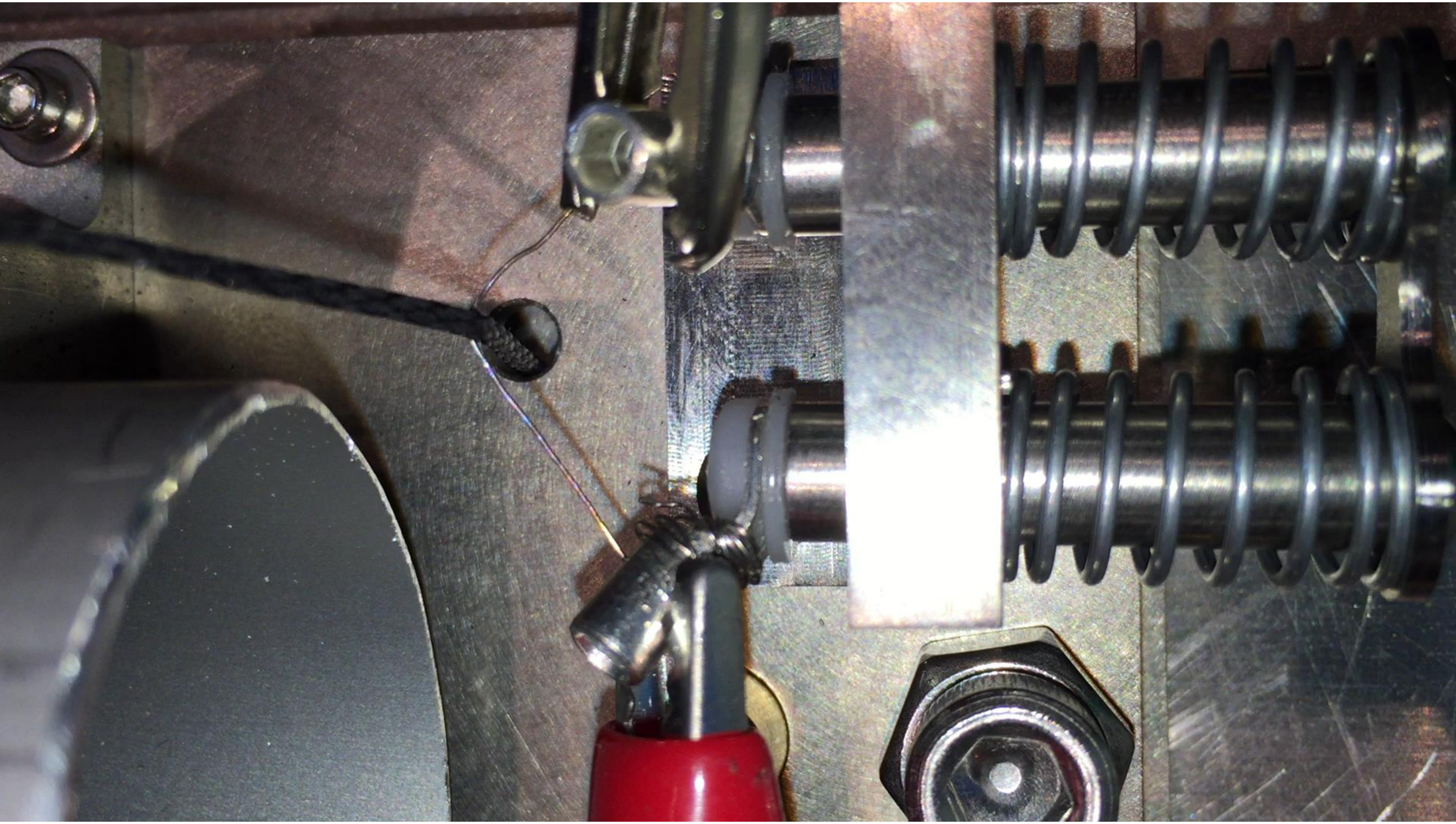

## Separation device

- Ran multiple trials at various currents;
- Several Vectran configurations and tensions (need angled cable);
- **9 sec** cut time for **1.6 A**;
- **Reliable**: no failure in 26 tests.





# Separation Device Testing





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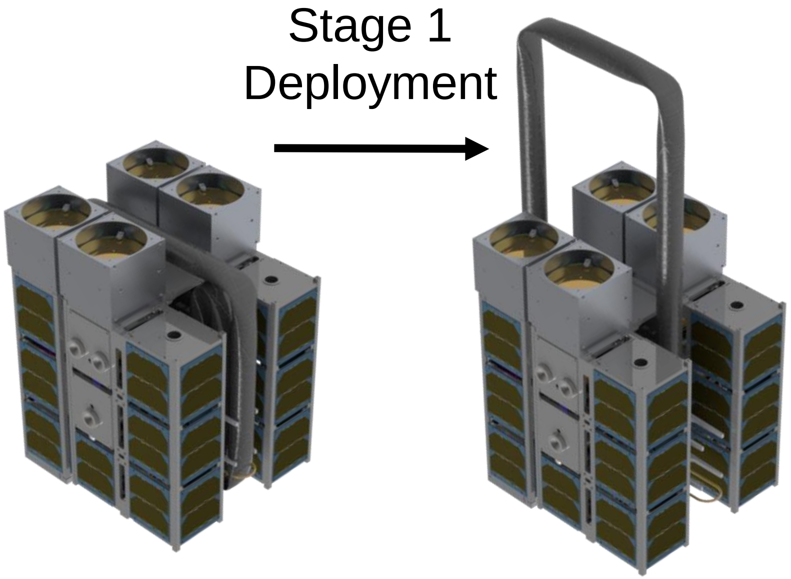
# Stage 1 Deployment Test

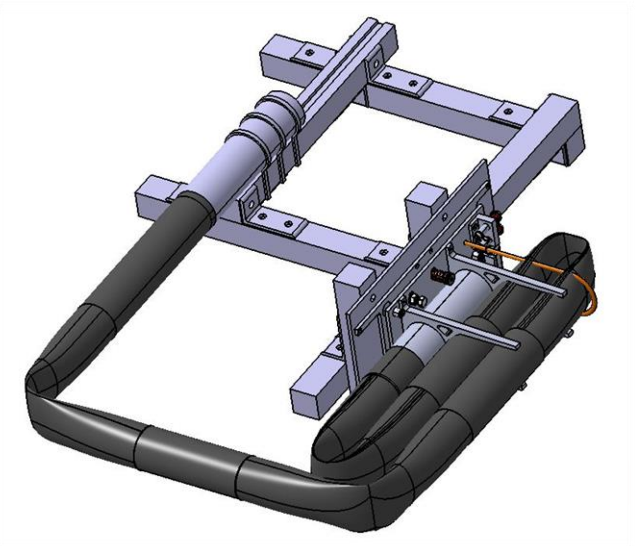
**Motivation:**

Ensure reliable and repeatable stage 1 deployment during which the boom follows the prescribed trajectory

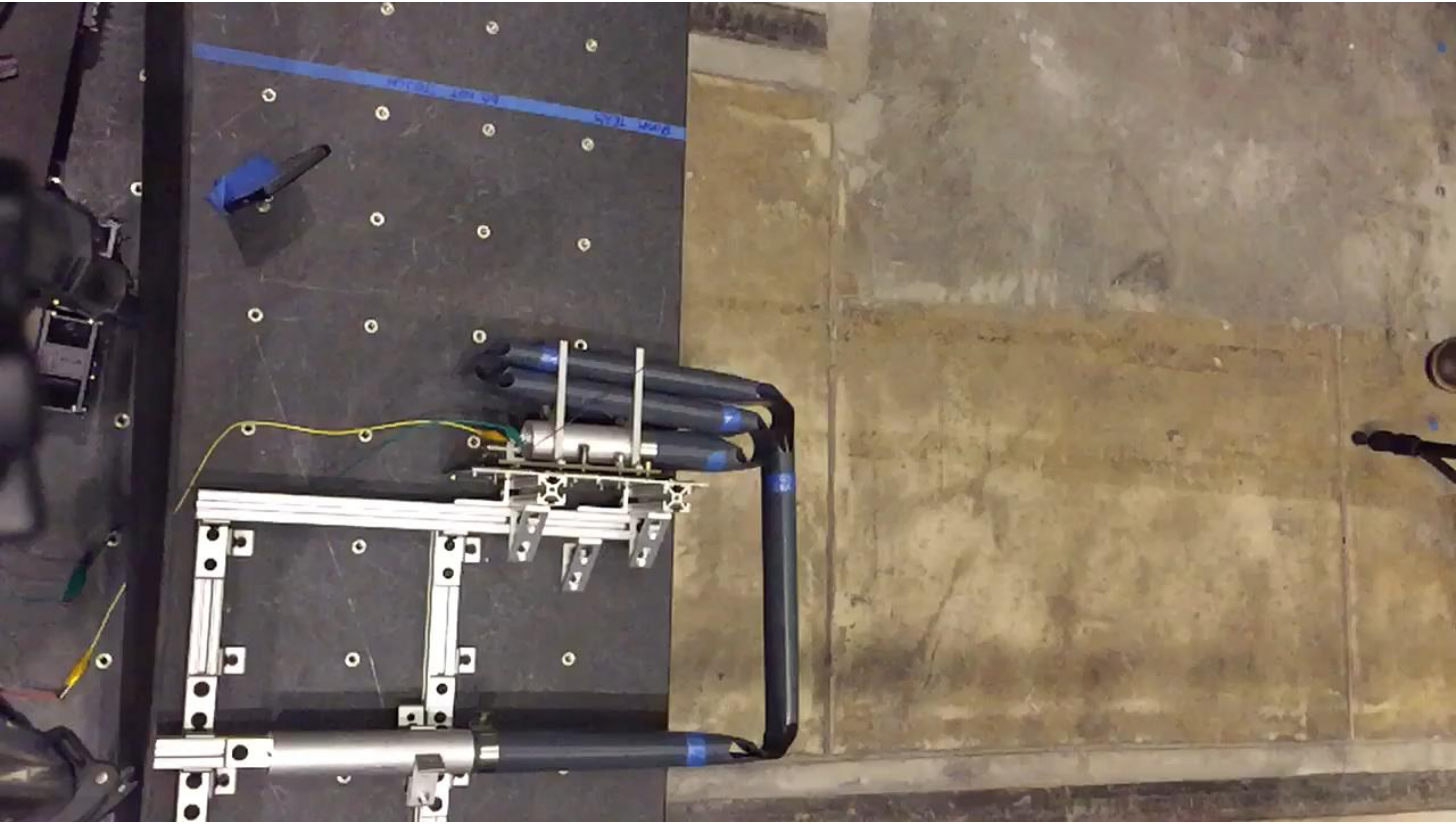
**Objectives:**

- Design and build a highly modular setup
- Validate stage 1 deployment kinematics
- Validate kinematic mount
- Test separation device
- Find final position of stage 1 deployment



# Stage 1 Deployment Test: Video 1





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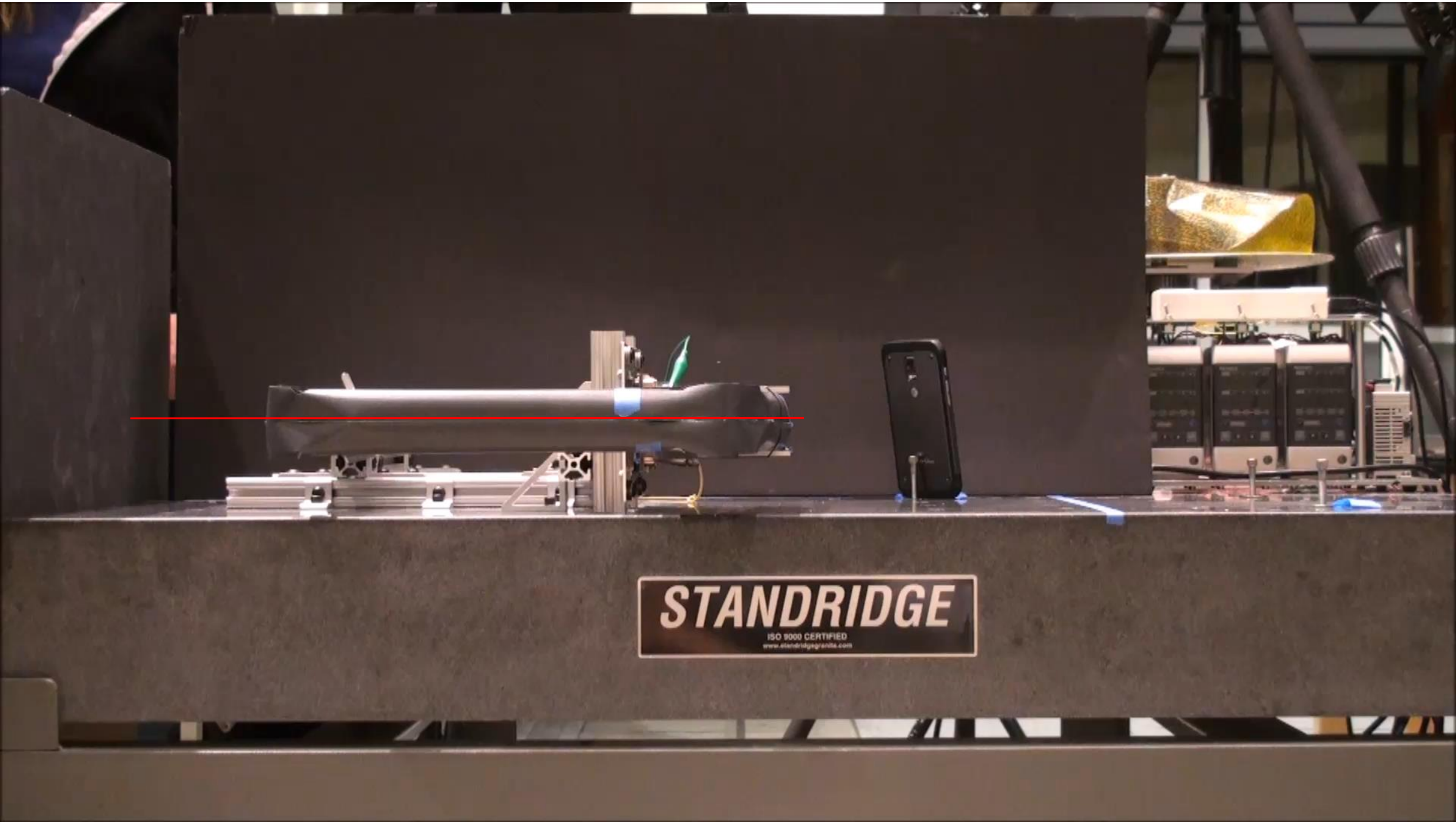
# Stage 1 Deployment Test: Video 2



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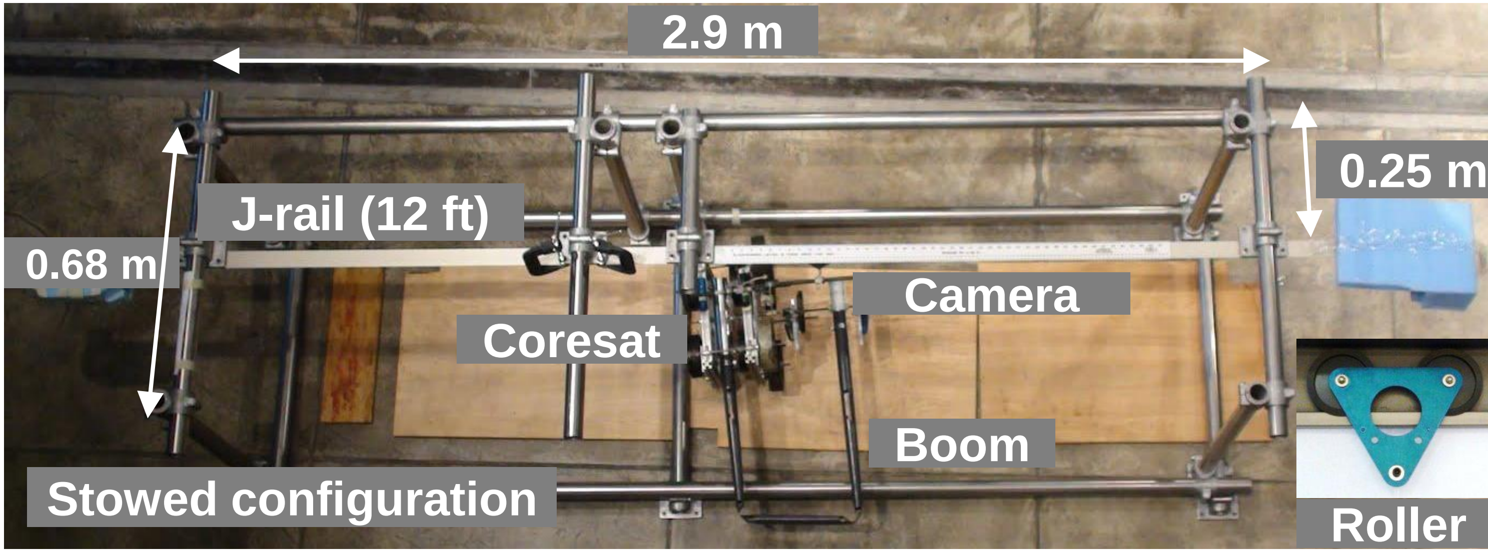
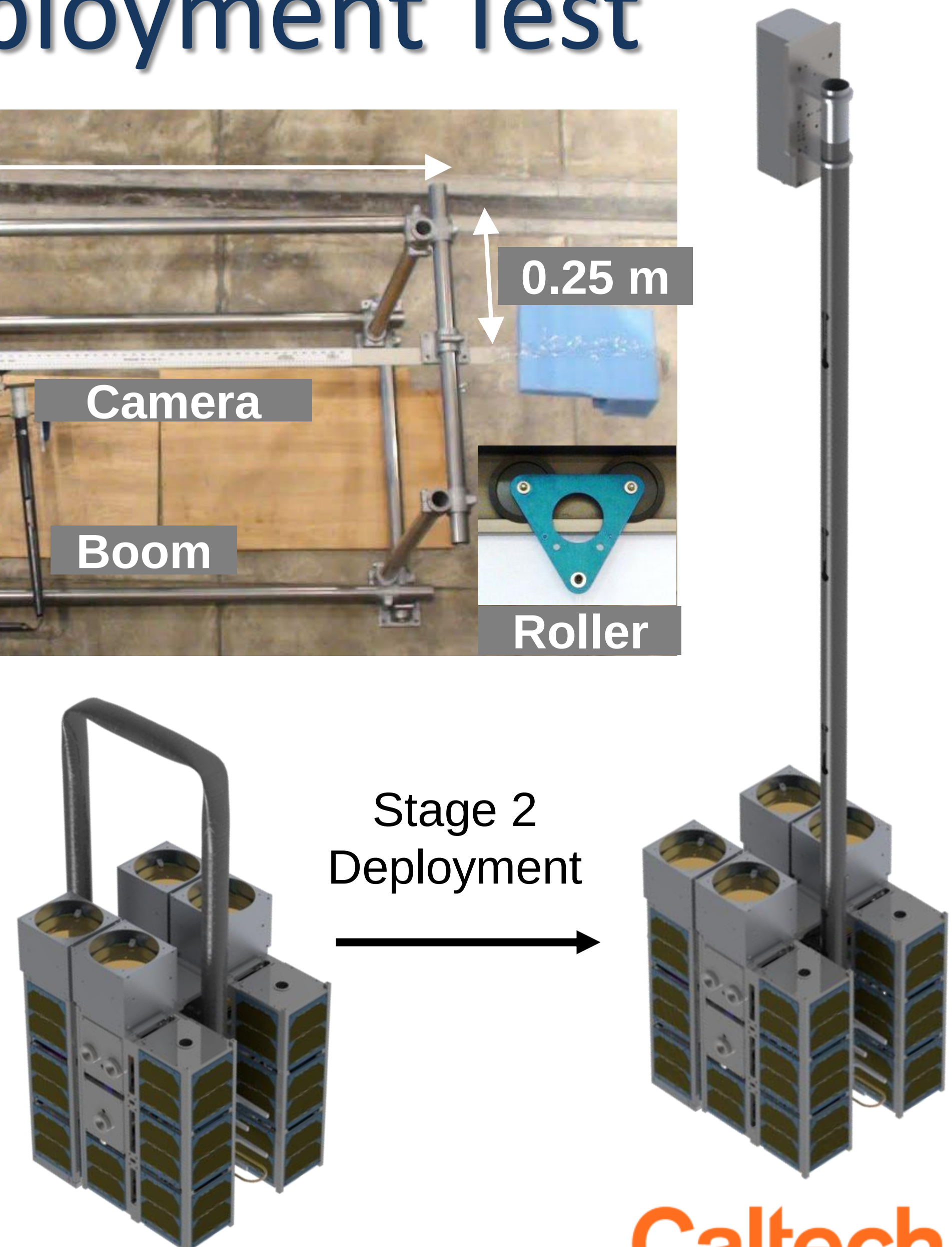
# Stage 2 Deployment Test




- Gravity offload setup used to test stage 2 deployment
- Representative masses (4kg & 30kg) suspended from J-rail – can rotate freely;



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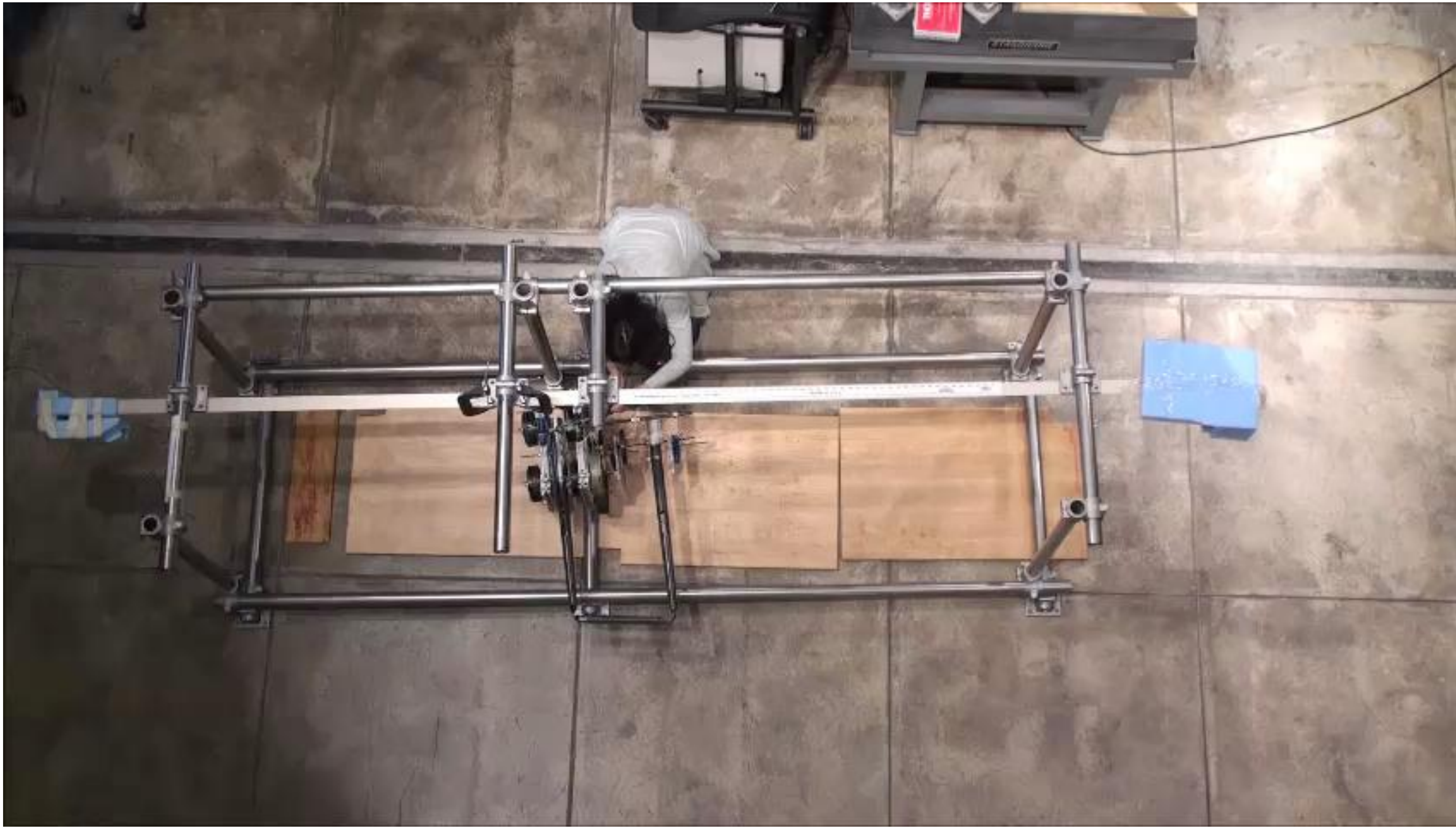
# Stage 2 Deployment Test





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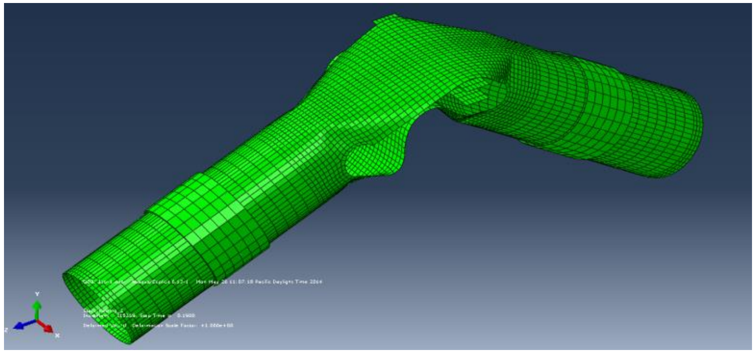
# Future Works

**Long-Term Storage**

- Compare results with FEM simulations
- Further experiments on aged hinges and full boom



**Boom-CoreSat Interfaces**

- Analyze kinematic mount design from thermal and structural standpoint and make necessary modifications
- Complete the design of the Boom-camera interface

**Stage Experiments**

- Perform stage 1 and 2 experiments with the final version of the boom



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# Camera Package

Manan Arya, Kathryn Jackson,
Maria Sakovsky

# Accomplishments

- Finalized mechanical design of optical components
- Created final design for camera interfaces
- Fabricated prototype of optical components
- Prototype optical testing procedures created and testing started

# Outline

- Camera overview
- Mechanical design and fabrication
- Camera performance
- Optical testing
- Future work

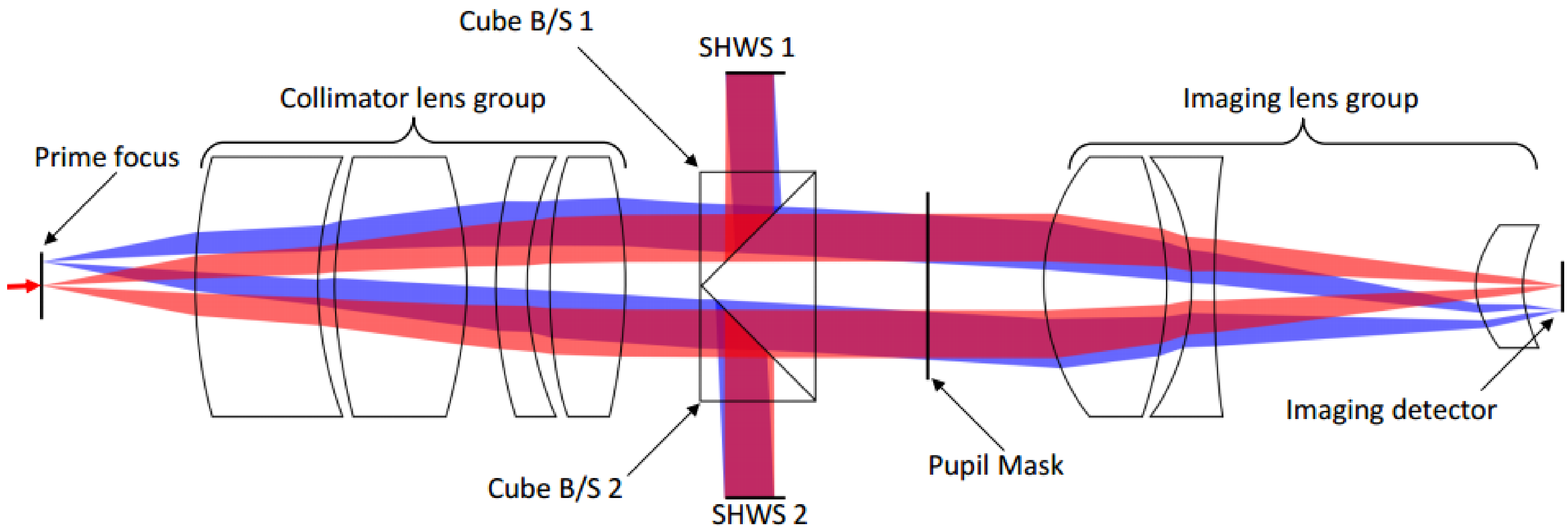
# Camera Requirements

**Functional:**
- Image star using a sparse aperture primary mirror
- Work with reconfigurable primary mirror
- Provide feedback on mirror shape
- Take engineering images of CoreSat during MirrorCraft reconfiguration

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

**Performance:**
- 80% encircled energy radius < 90% diffraction limit
- 0.34° full field-of-view
- Bandwidth: 465 – 615 nm
- SNR > 100

# Optics Overview




- Lens design optimized in Zemax for spot radius at imaging plane and WF error at pupil conjugate
- Mask and SHWS located at pupil conjugate
- Each SHWS looks at half of the pupil
- Mask prevents stray light to the detector in both narrow and wide configurations



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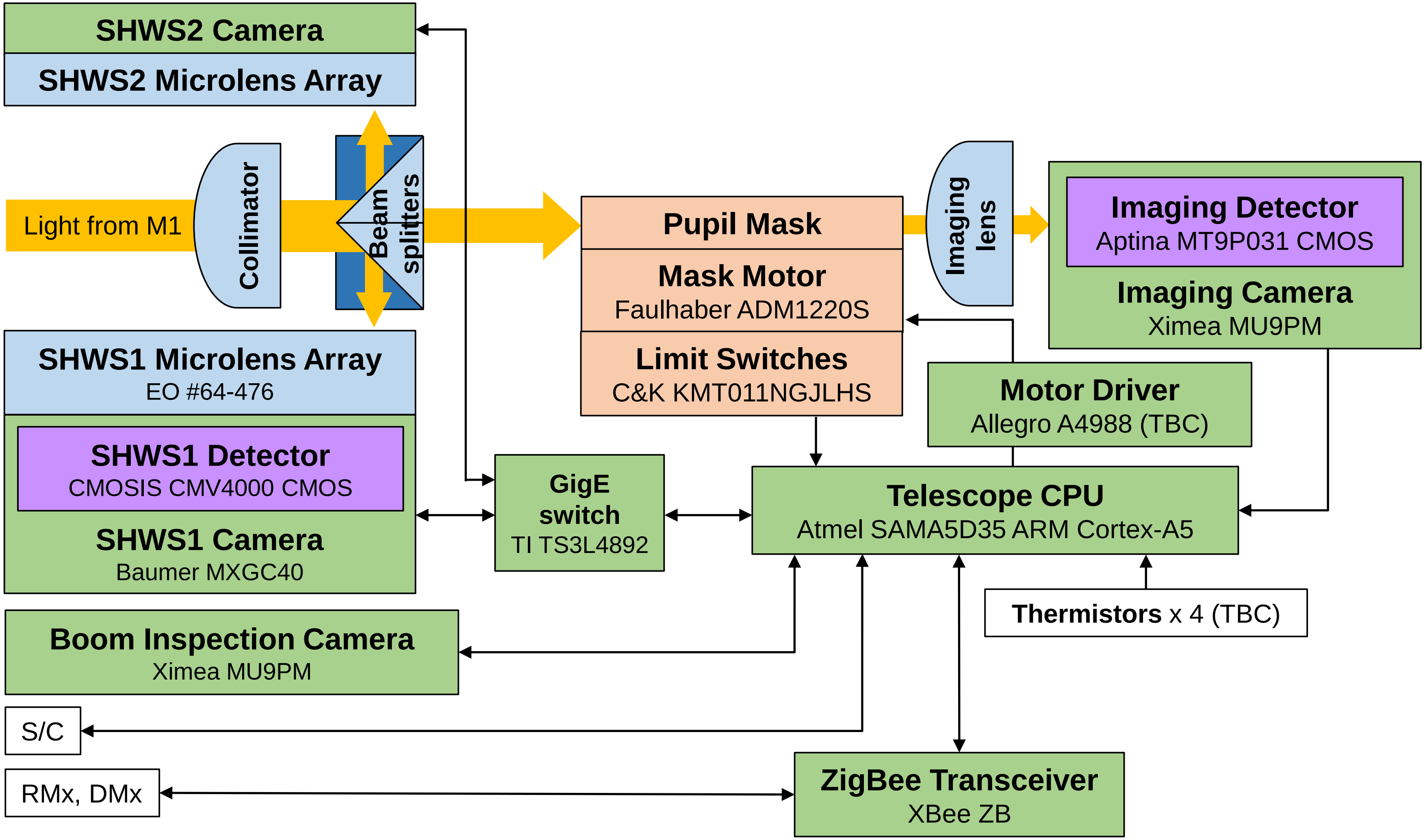
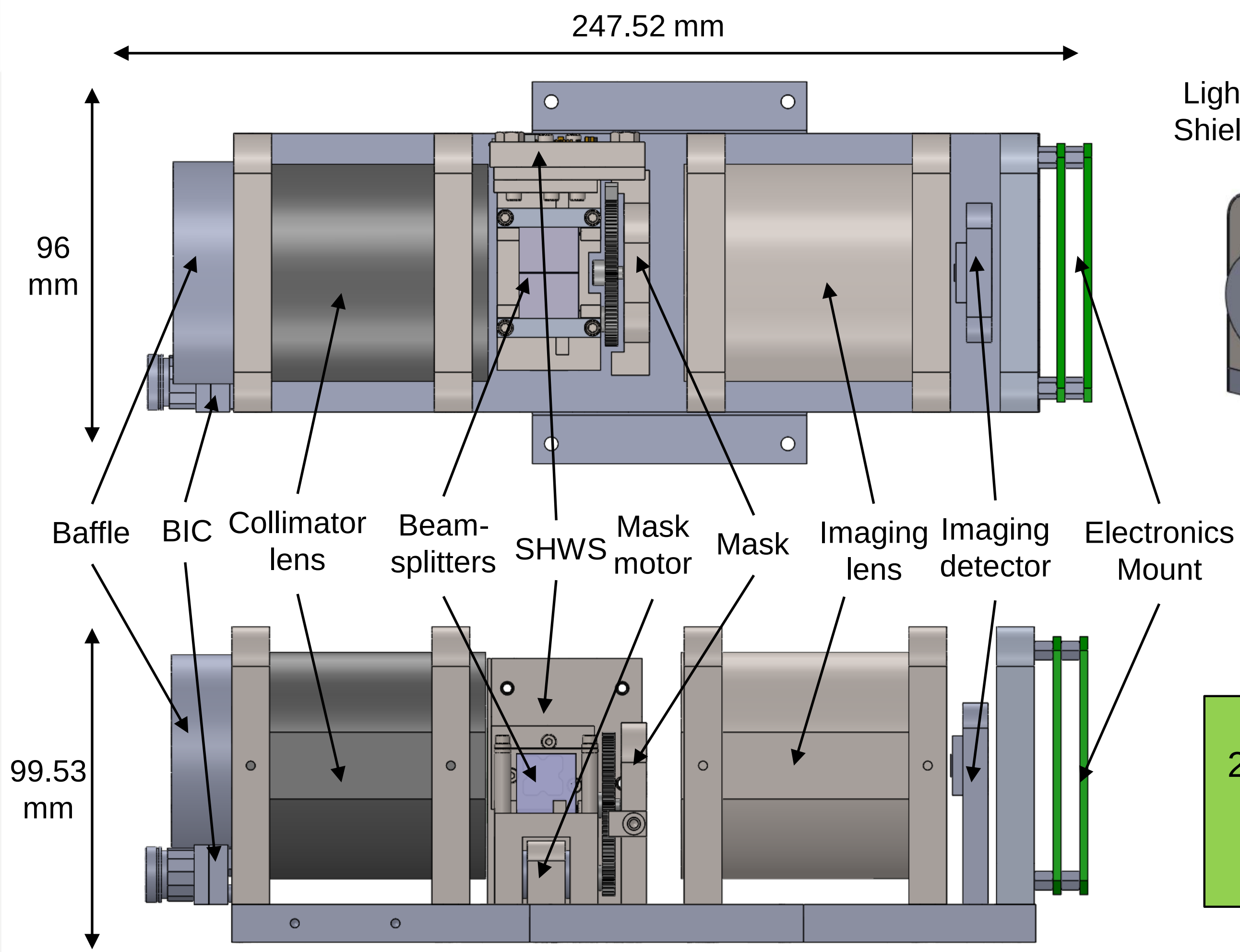
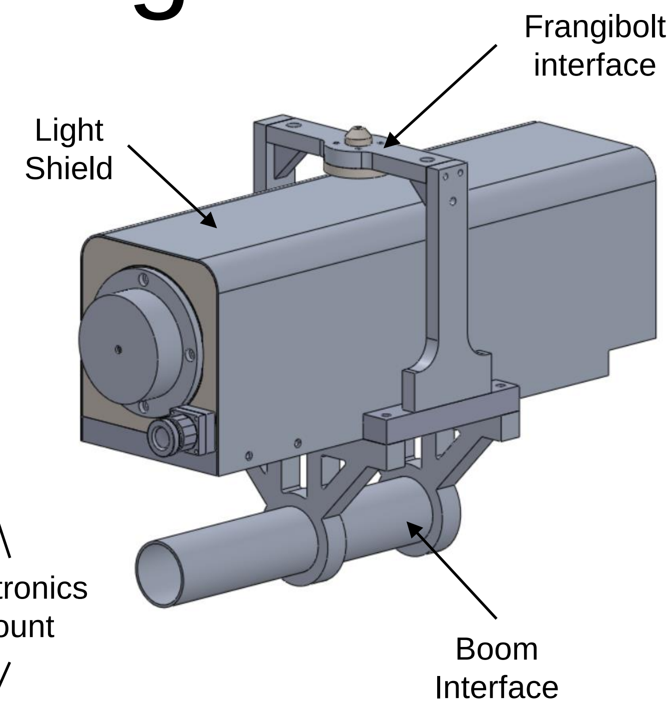
# Interfaces


SHWS2 Camera
SHWS2 Microlens Array
Light from M1
Collimator
Beam splitters
Pupil Mask
Mask Motor
Faulhaber ADM1220S
Limit Switches
C&K KMT011NGJLHS
Imaging lens
Imaging Detector
Aptina MT9P031 CMOS
Imaging Camera
Ximea MU9PM
SHWS1 Microlens Array
EO #64-476
SHWS1 Detector
CMOSIS CMV4000 CMOS
SHWS1 Camera
Baumer MXGC40
Motor Driver
Allegro A4988 (TBC)
GigE switch
TI TS3L4892
Telescope CPU
Atmel SAMA5D35 ARM Cortex-A5
Thermistors x 4 (TBC)
Boom Inspection Camera
Ximea MU9PM
S/C
RMx, DMx
ZigBee Transceiver
XBee ZB

# Mechanical Design




**Volume**
25 x 9.6 x 10 cm < 34 x 10 x 10 cm

(includes frangibolt interface but not the boom mount)



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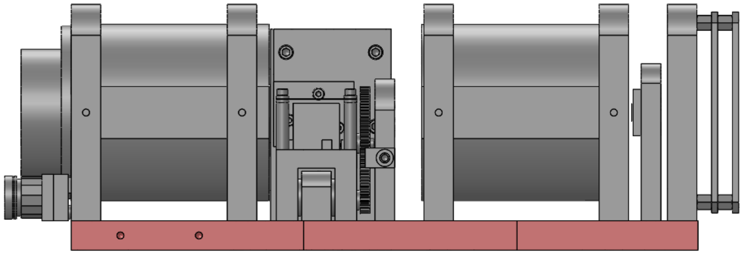
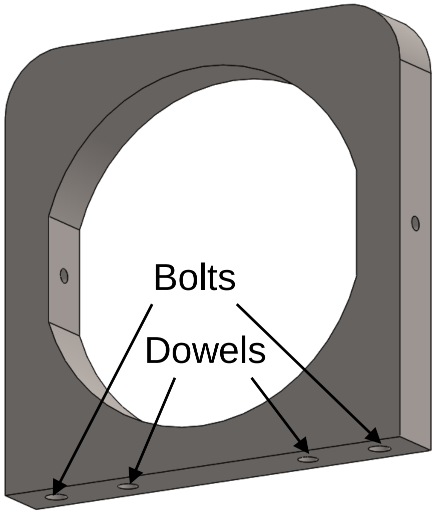
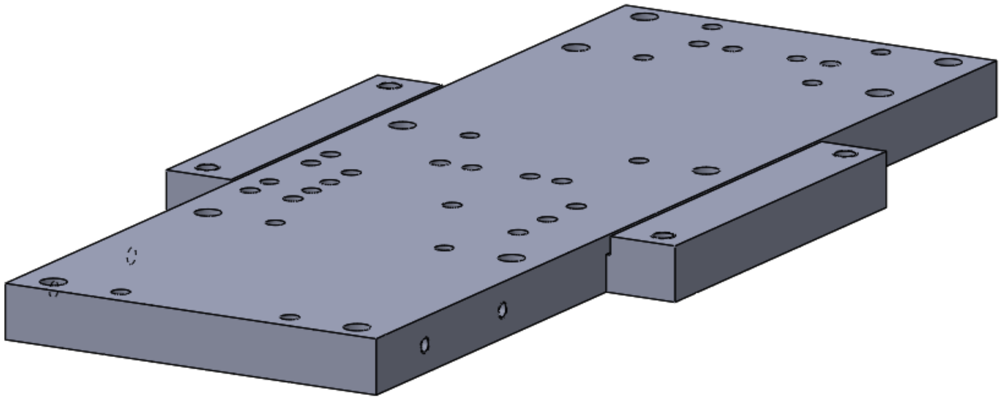
# Metrology Plate



**Purpose:** alignment of optical components to tolerance

- All mounts aligned in position and rotation using two dowel pins, secured with two bolts
- Shim components to fix misalignment if necessary





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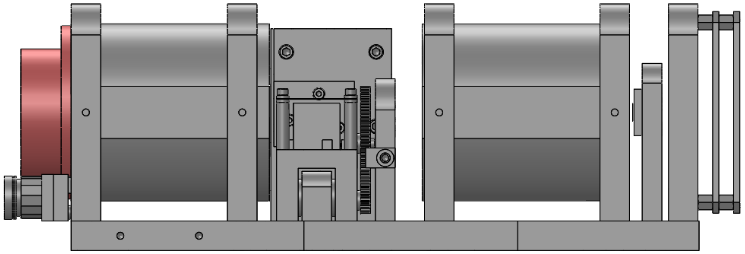
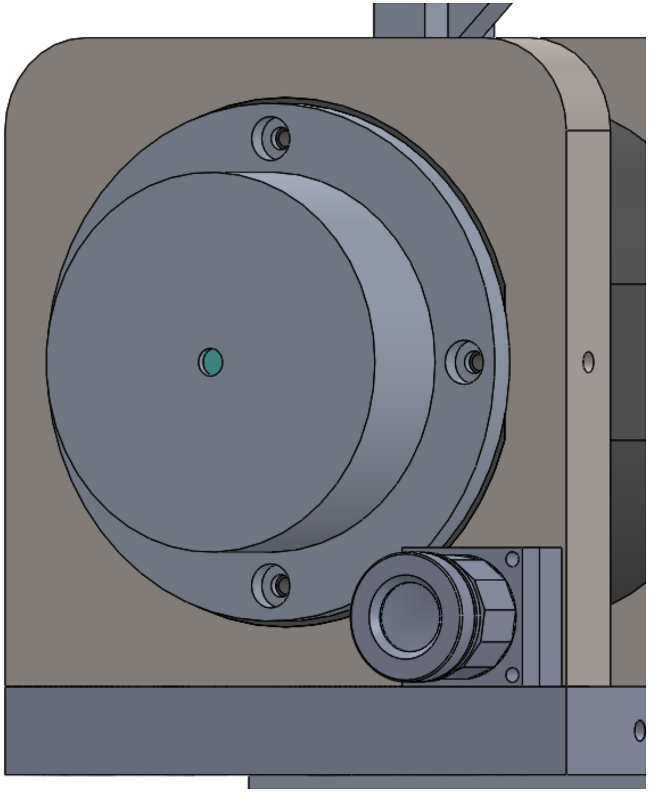
# Baffle

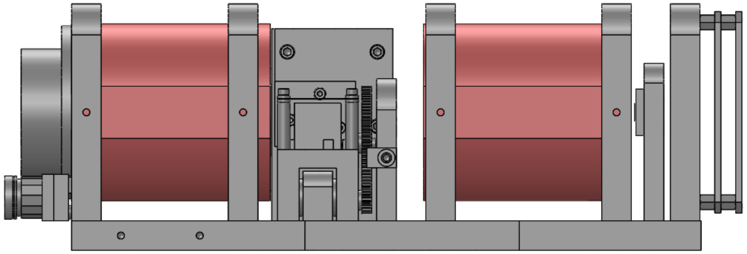


**Purpose:** reduce stray light from outside the mirrors

- Opening placed at focal point allowing 0.3 deg point of view
- Secured to the front of the collimator barrel

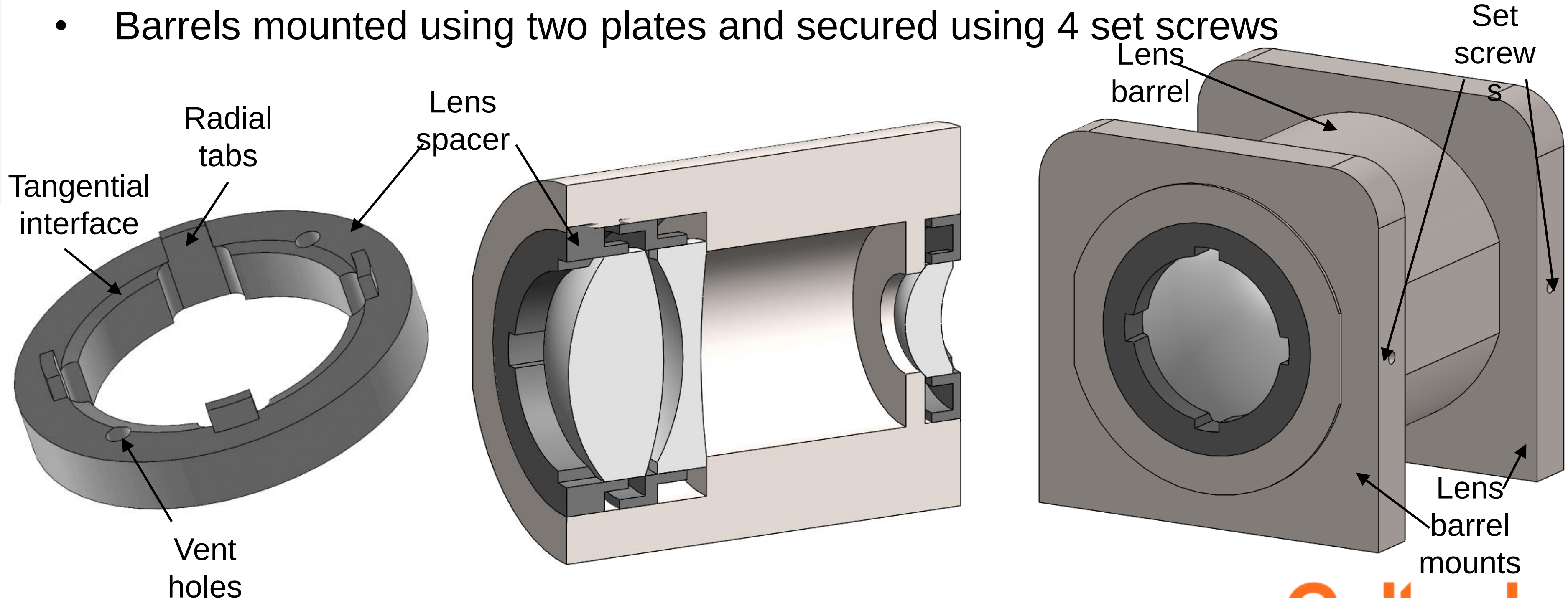


# Lens Groups



**Purpose:** space and center lenses along optical axis

- Lens prescription optimized in Zemax software
- Individual lenses mounted to spacers that are threaded into the lens barrels
  - Tangential interface, radial tabs for centering lens
  - Spacers keep correct distance between lenses
- Barrels mounted using two plates and secured using 4 set screws



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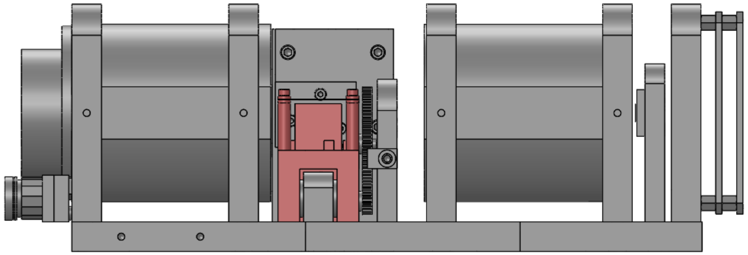
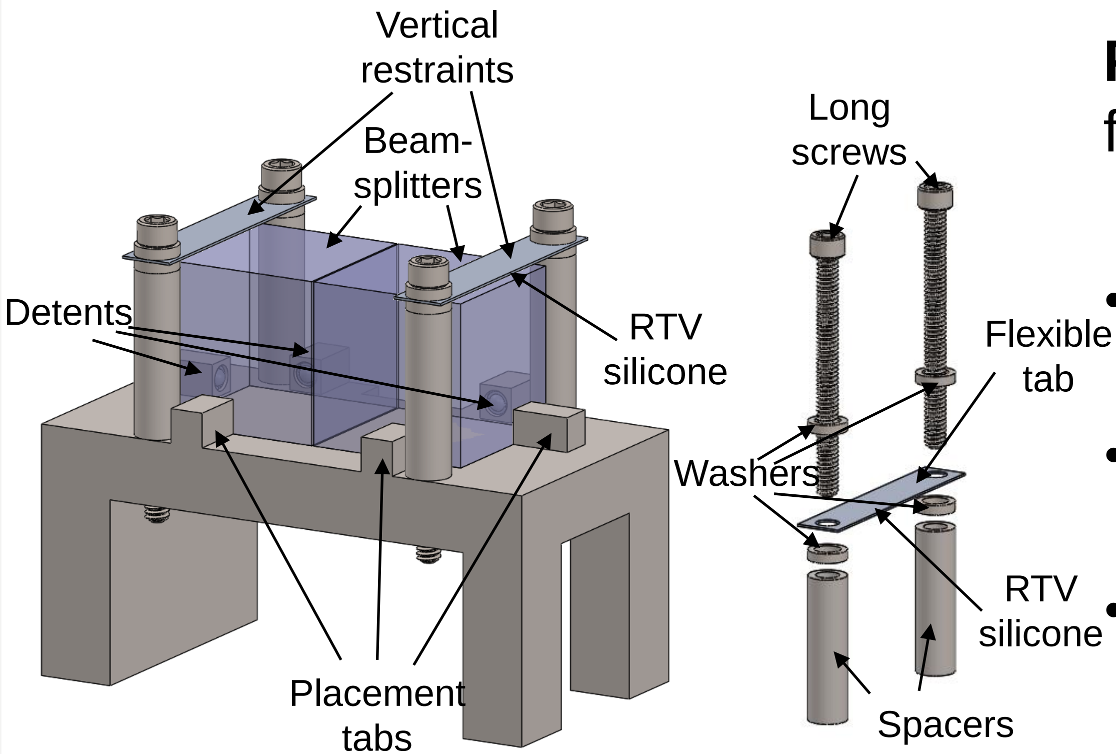
# Beam Splitters

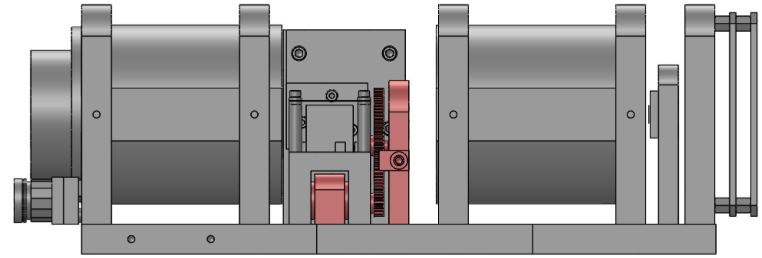





**Purpose:** split light for wave-front detection and imaging

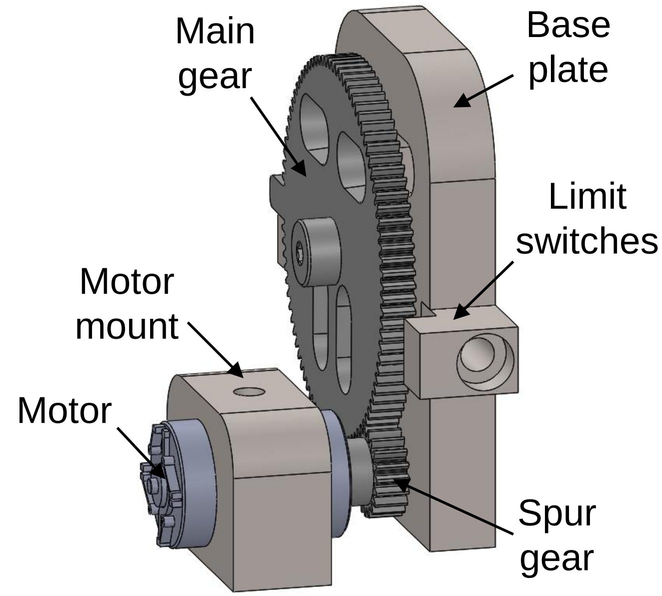
- EO # 68-537 B/S: 15 mm cube, 70R/30T
- Meets 0.3 deg field of view requirement
- Detents and low outgassing RTV silicone for thermal expansion

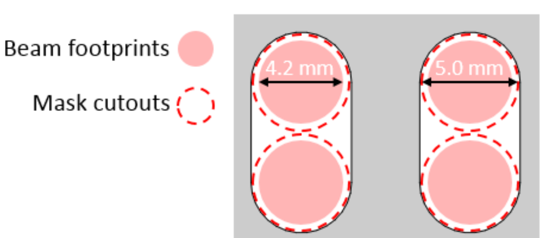
# Mask Mechanism

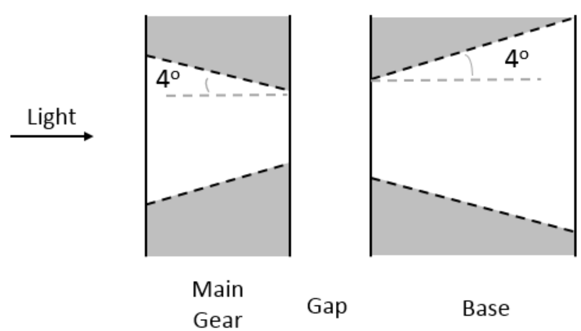


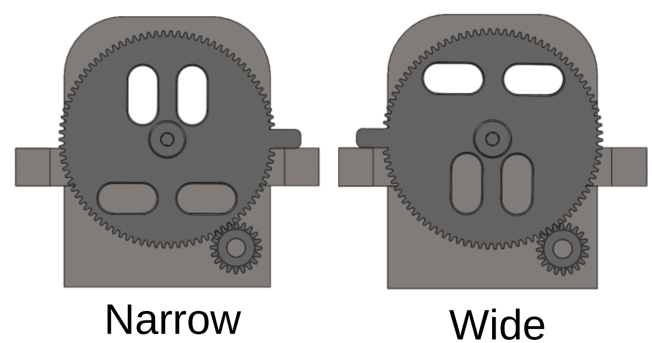
**Purpose:** mask light not originating from mirrors

- Actuated by stepper motor (Faulhaber ADM1220S)
- Cutouts larger than beam footprint account for misalignment in system
- Holes tapered along optical axis to meet 0.3 deg field of view requirement



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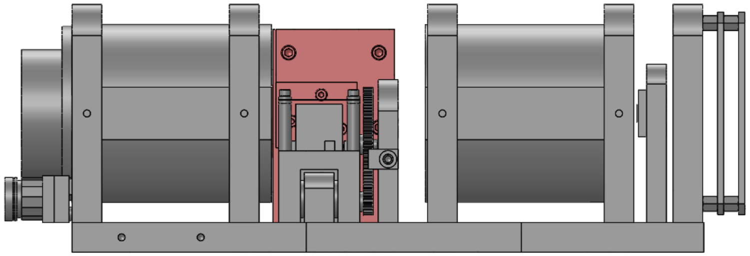
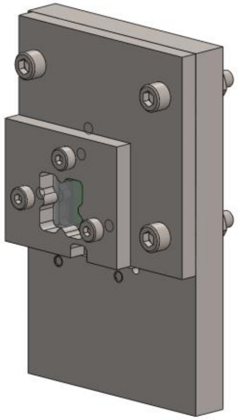
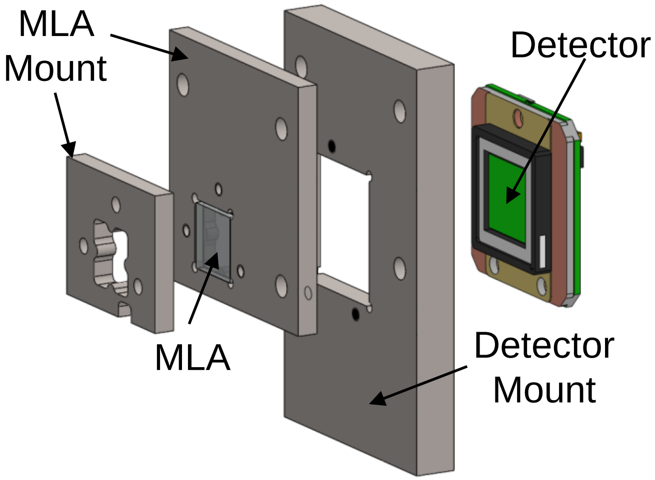
# SHWS

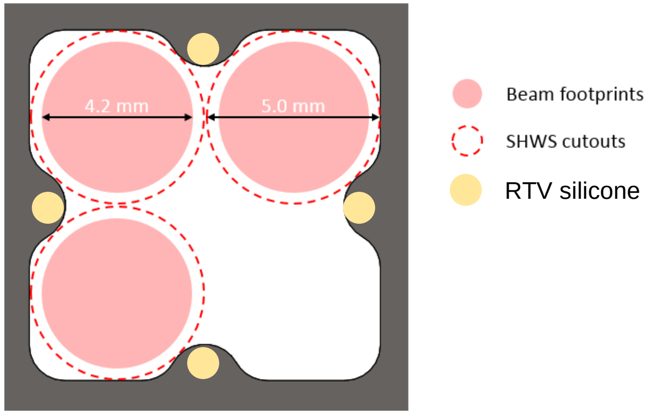


**Purpose:** provide feedback on mirror shape and wavefront error

- Microlens array (EO#64-476) and detector (CMOSIS CMV4000 CMOS)
  - MLA: 5.1 mm focal length, 300 um pitch; ~177 slope samples per mirror segments
  - Detector: 11.26 x 11.26 mm area to cover MLA
- Shims between two mount segments aligns detector/MLA in piston, tip/ tilt
- Beads of RTV silicone for thermal expansion





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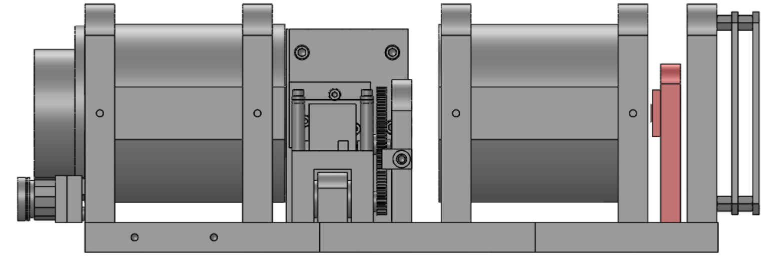
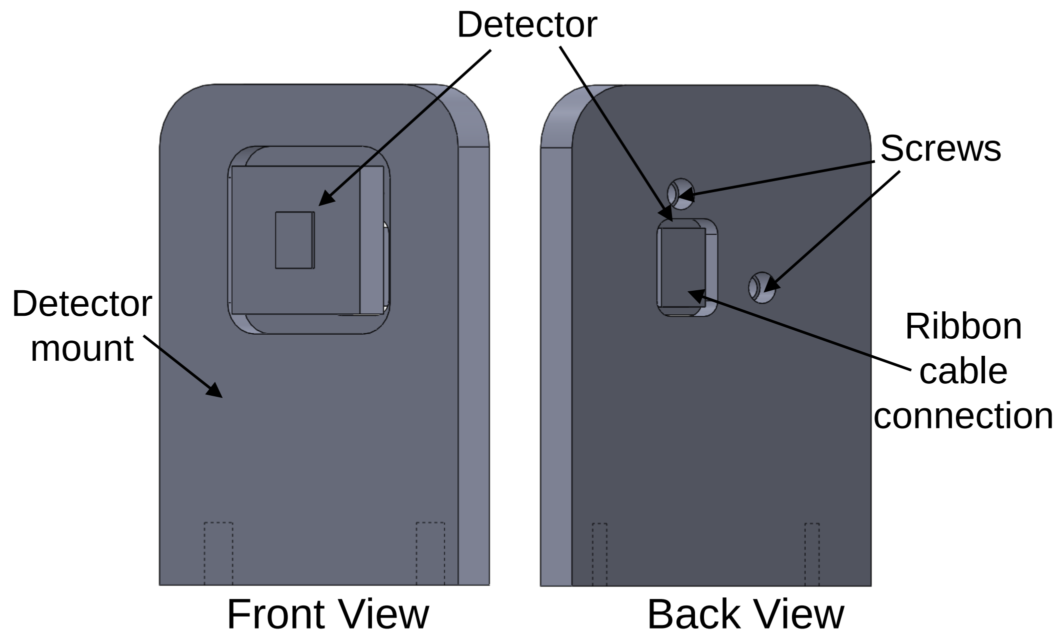
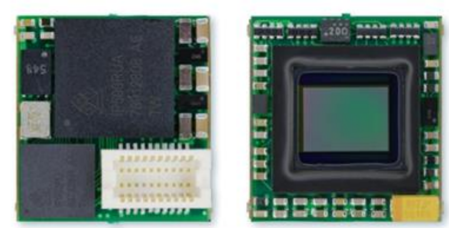
# Imaging Detector



**Purpose:** science imaging

- Aptina MT9P031 CMOS detector in the Baumer MU9PC camera
- 2.2 µm pixels oversample the Ø14.2 µm spot from a single primary mirror segment





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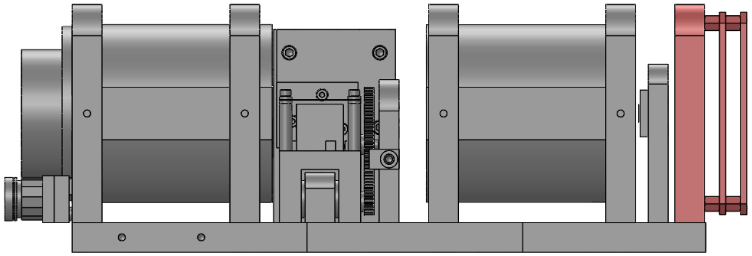
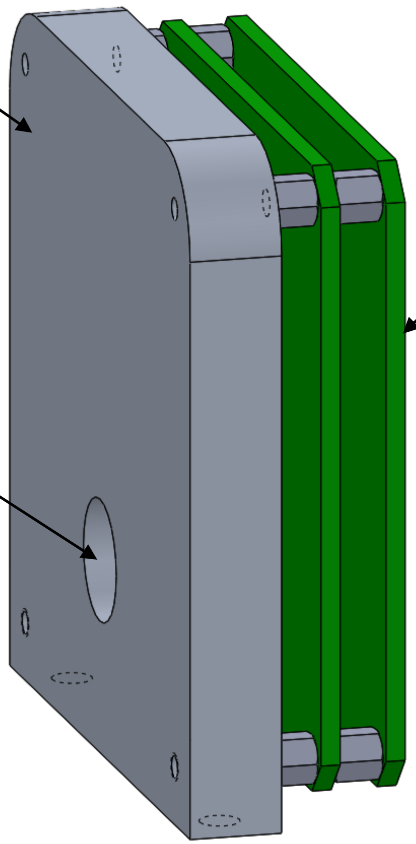
# Electronics






- Room to mount SHWS electronics, telescope CPU, BIC connection, motor electronics, Zigbee antenna
  - Wiring done through component mounts
- Can add more boards if necessary, still meets volume constraints
- Can fit 7 x 7 cm boards
- Electronics dissipate heat at the back and have minimal effect on optics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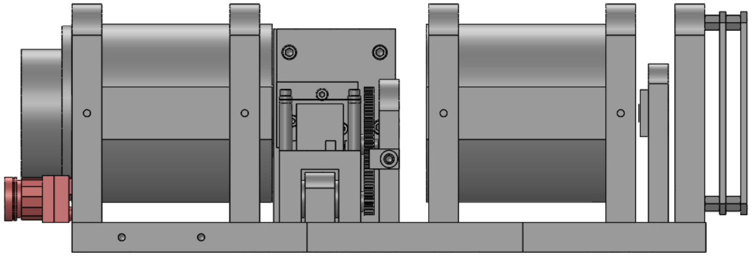
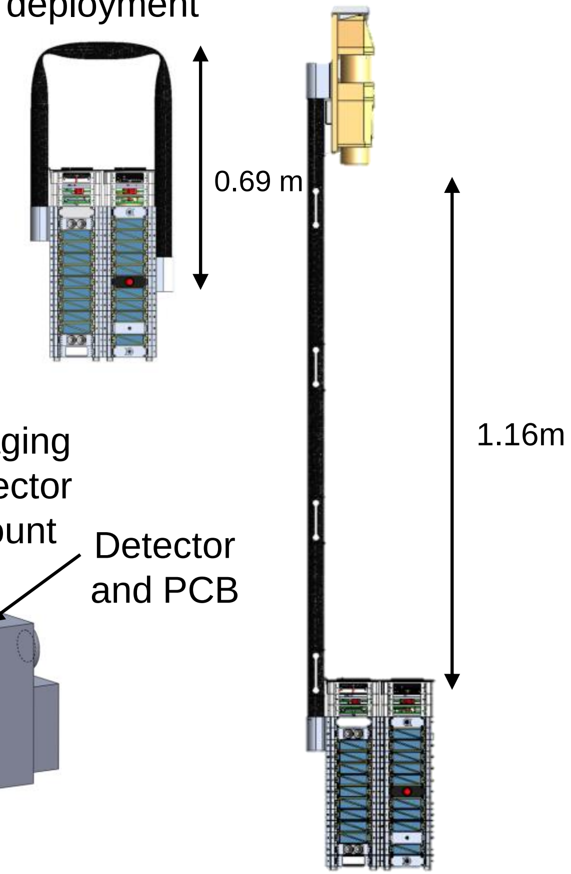
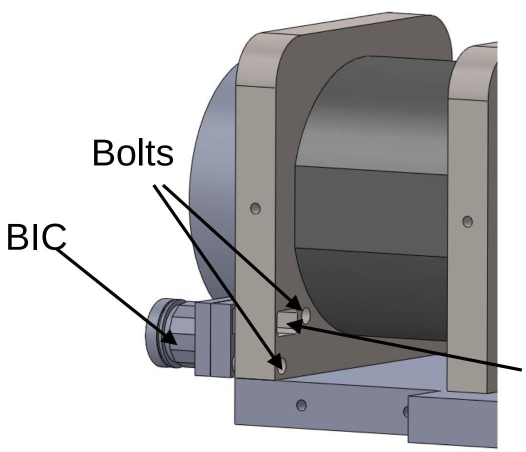
# Boom Inspection Camera

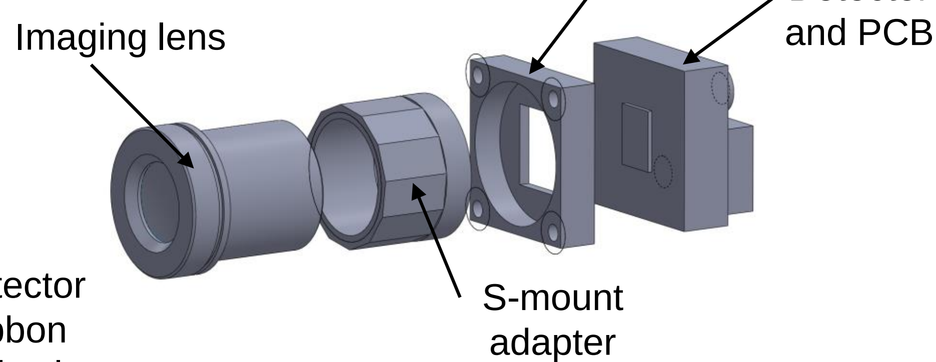


**Purpose:** inspect boom during deployment, image reconfiguration

- Sunex DSL218 Fisheye lens and Aptina MT9P031 CMOS detector
  - 1.22 mm, f/2.0, 180 deg field of view
- Chosen for good depth of field (~12 cm to ∞) and low-light performance



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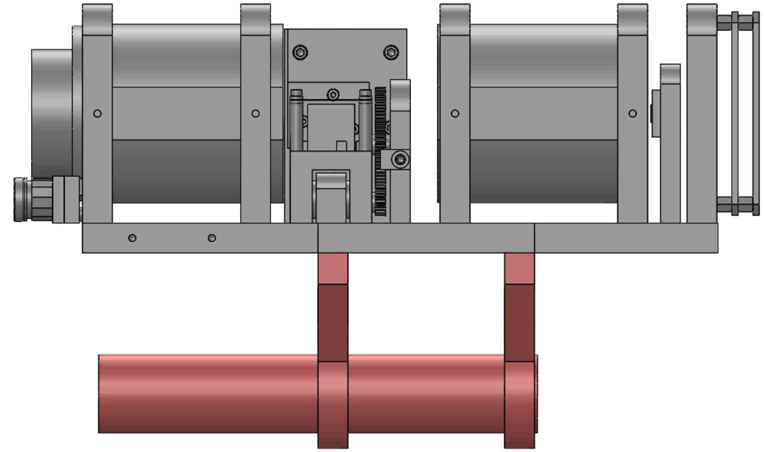
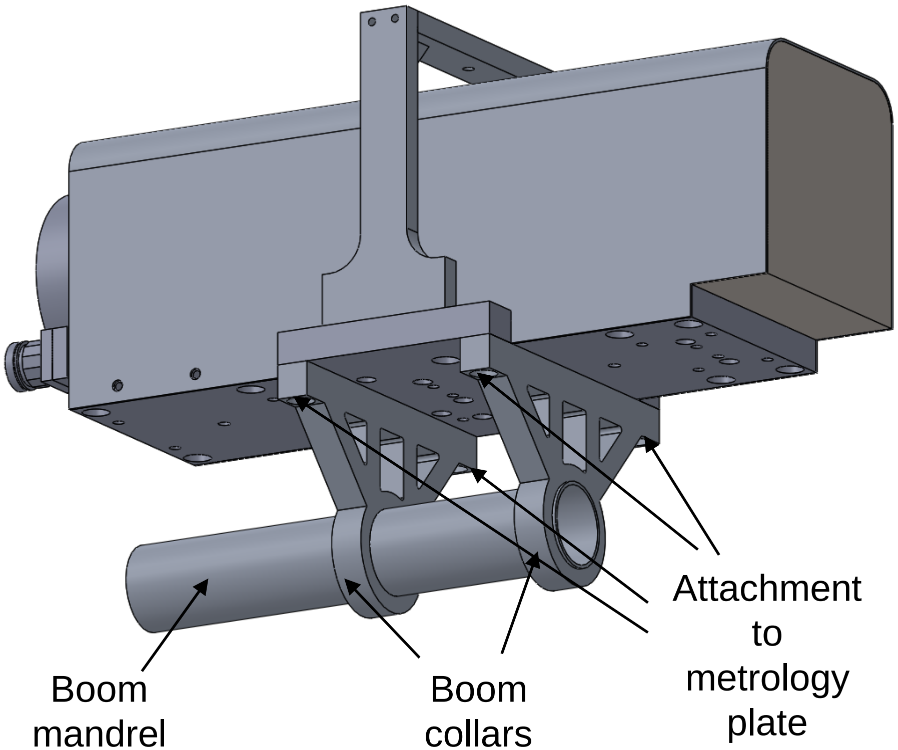
# Boom Mount






**Purpose:** secure boom to camera and maintain correct spacing between the S/C and camera

- mandrel inside boom and two collars over the boom attached with adhesive
- Placed at the centre of mass of the camera



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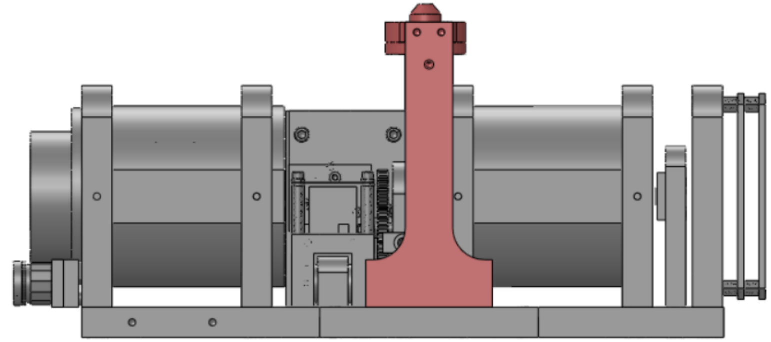
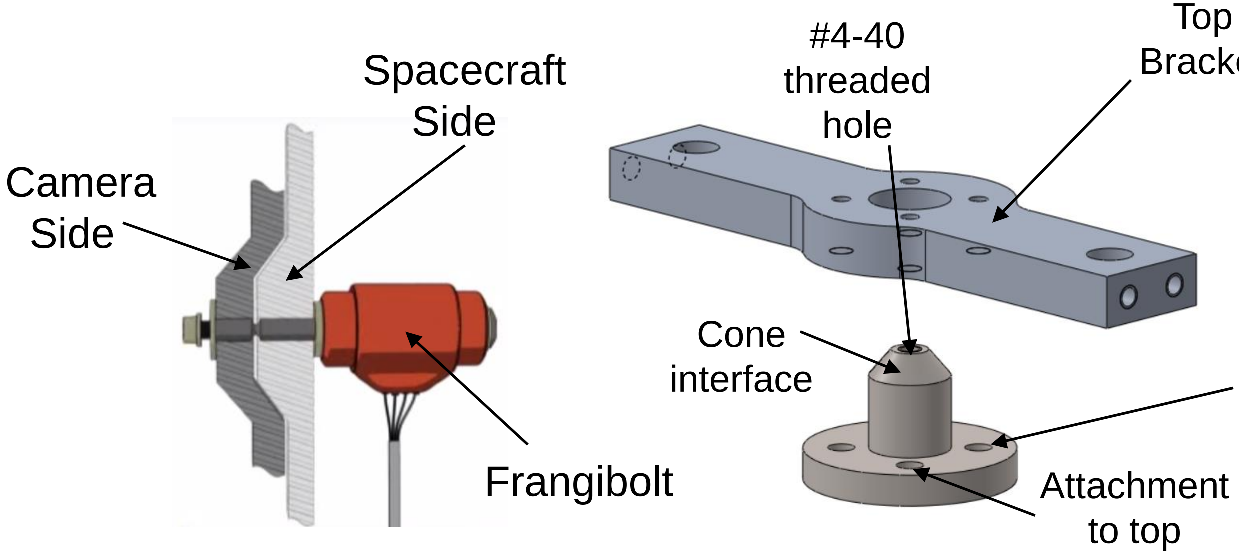
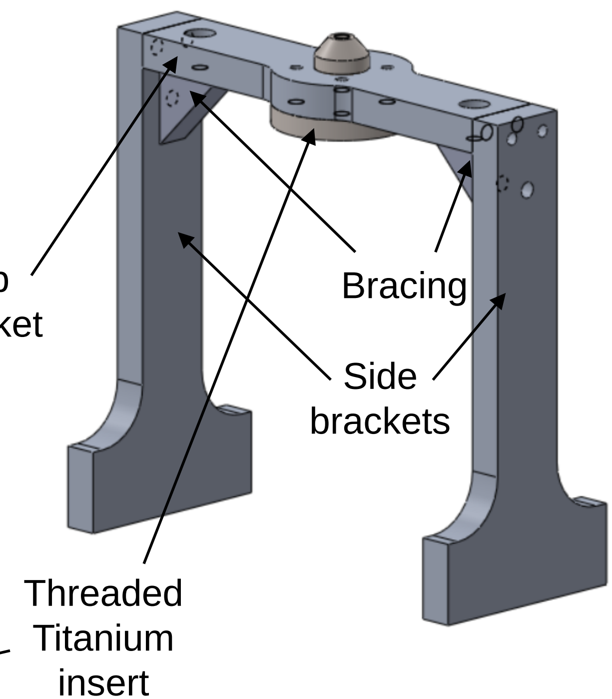
# Frangibolt



- Shape memory alloy cylinder elongates and fractures a notched bolt
- FD04 standard Frangibolt: 2224 N tensile strength, 15W at 9V DC, #4 bolt
- Cup-cone interface between Frangibolt mount and spacecraft to react lateral loads
- #4 bolt threads into titanium part
- Mount located at centre of mass



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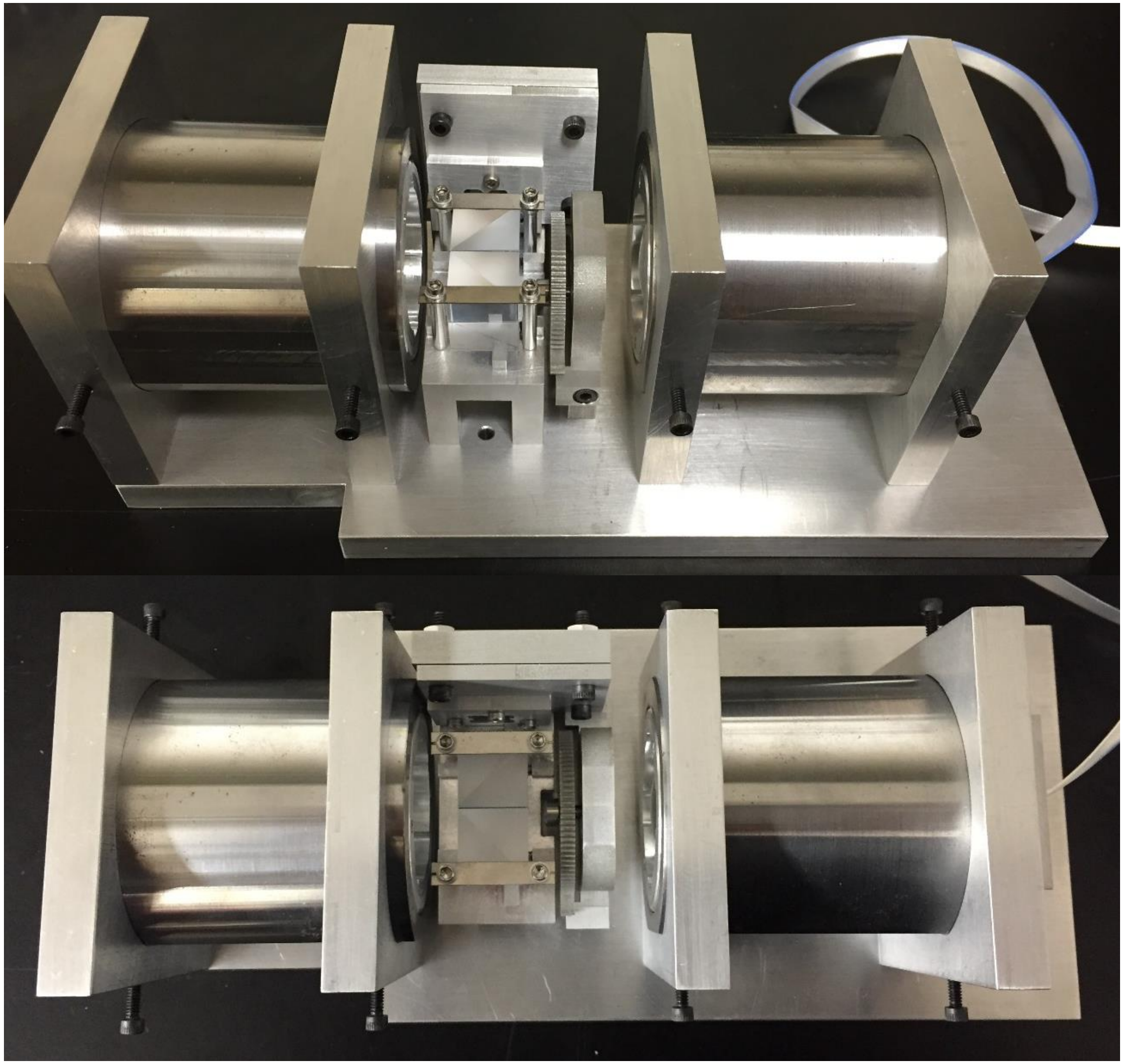
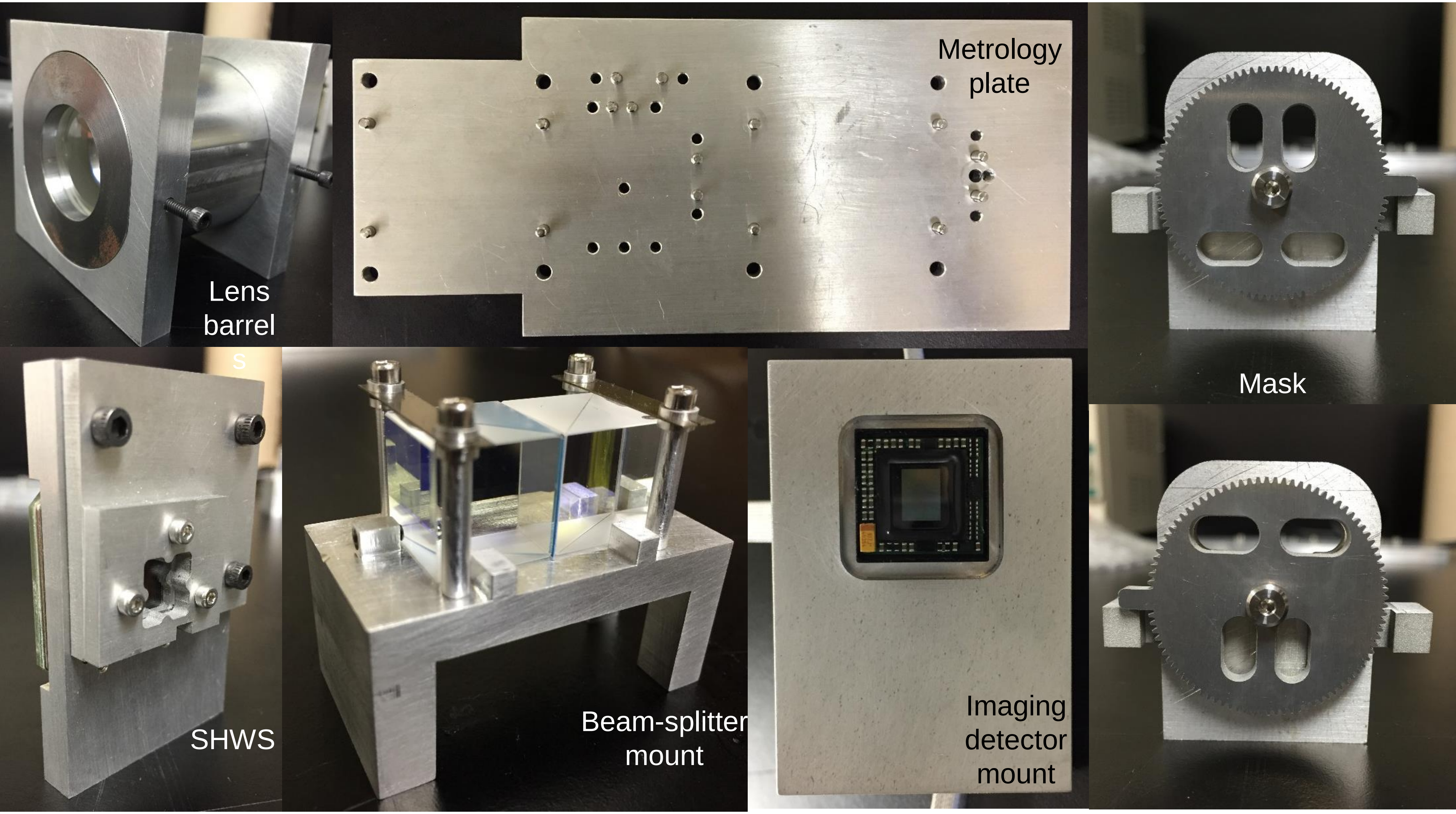
# Camera Prototype



- Prototype fabricated from aluminum, final product will be mostly titanium
- Fabricated components:
  - Metrology plate
  - Lens barrels
  - Beamsplitter mount
  - Mask
  - SHWS x 1
  - Imaging detector mount
- Test ease of fabrication, optical alignment, mechanical functionality, assembly procedures, optical performance

# Prototype Components



# Mass Budget

| Component | Mass (g) | Margin (10%) |
|---|---|---|
| Metrology Plate | 833.9 | 917.3 |
| Collimator | 542.2 | 596.4 |
| Focal Group | 513.6 | 564.9 |
| Lens Mounts (4x) | 388.4 | 427.3 |
| Electronics Package | 263.7 | 290.0 |
| Fasteners & Wiring | 100.0 | 110.0 |
| SHWS Board (1x) | 56.8 | 62.5 |
| SHWS Mount (2x) | 154.1 | 169.5 |
| Light Shielding | 90.1 | 99.1 |
| Beam Splitter Assembly | 67.8 | 74.6 |
| Boom Inspection Camera | 17.4 | 19.1 |
| Image Detector w/ Mount | 45.4 | 49.9 |
| Mask Mechanism | 45.5 | 50.0 |
| Baffle | 26.1 | 28.7 |
| Motor Assembly | 12.3 | 13.5 |
| Frangibolt Bracket (Al) | 82.8 | 91.1 |
| Boom Bracket (Al) | 135.7 | 149.2 |
| **Total** | **3375.6** | **3713.1** |

**Mass**
3.71 kg < 4 kg

(includes frangibolt interface and the boom mount)



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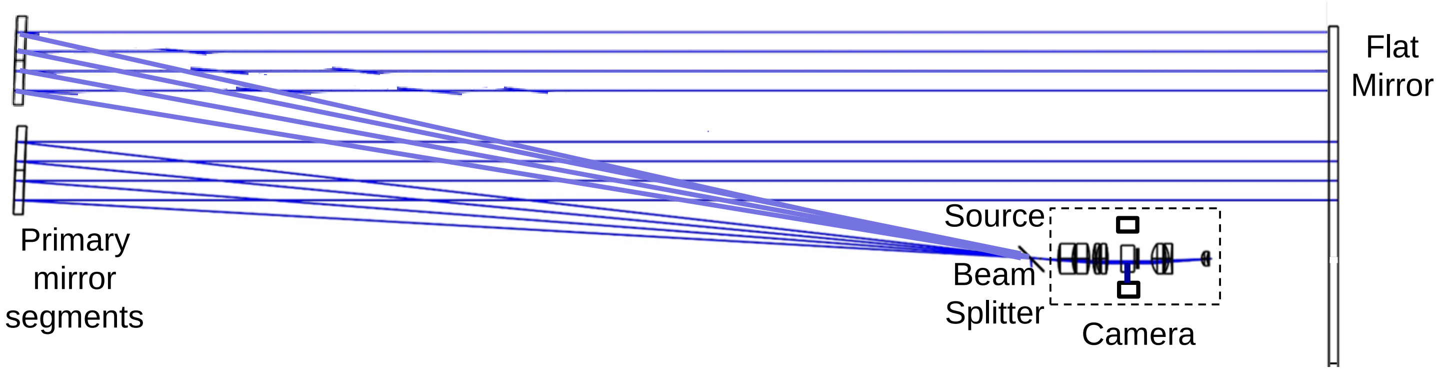
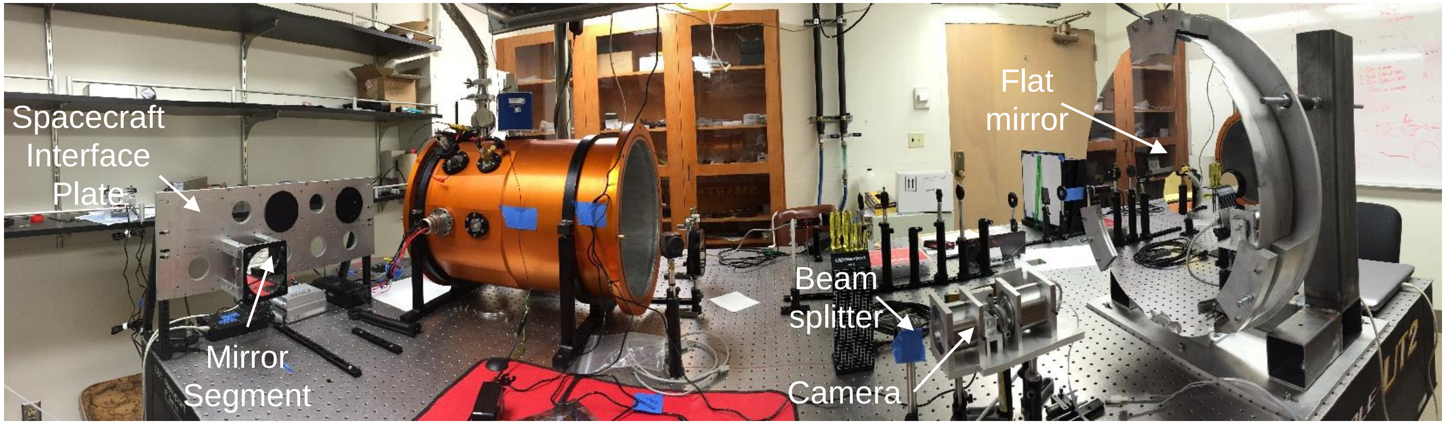
# Power Budget

| Part | Peak (W) | Standby (W) | WF Sensing Mode (W) | Imaging Mode (W) | Reconfiguration Mode (W) | Safe Mode (W) |
|---|---|---|---|---|---|---|
| Telescope CPU | 0.60 | 0.45 | 0.60 | 0.60 | 0.60 | 0.45 |
| Imaging Detector | 0.74 | 0.30 | OFF | 0.74 | OFF | OFF |
| SHWS | 3.12 | 2.88 | 3.12 | OFF | OFF | OFF |
| BIC | 0.74 | 0.30 | OFF | OFF | 0.74 | OFF |
| ZigBee | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| Mask | 0.60 | 0 | OFF | OFF | 0.60 | OFF |
| **Total** | | | **3.87** | **1.49** | **2.09** | **0.60** |
| **+ Margin (10%)** | | | **4.26** | **1.64** | **2.30** | **0.66** |

**Power**
4.26 W < 5 W

# Optical Testbed Overview

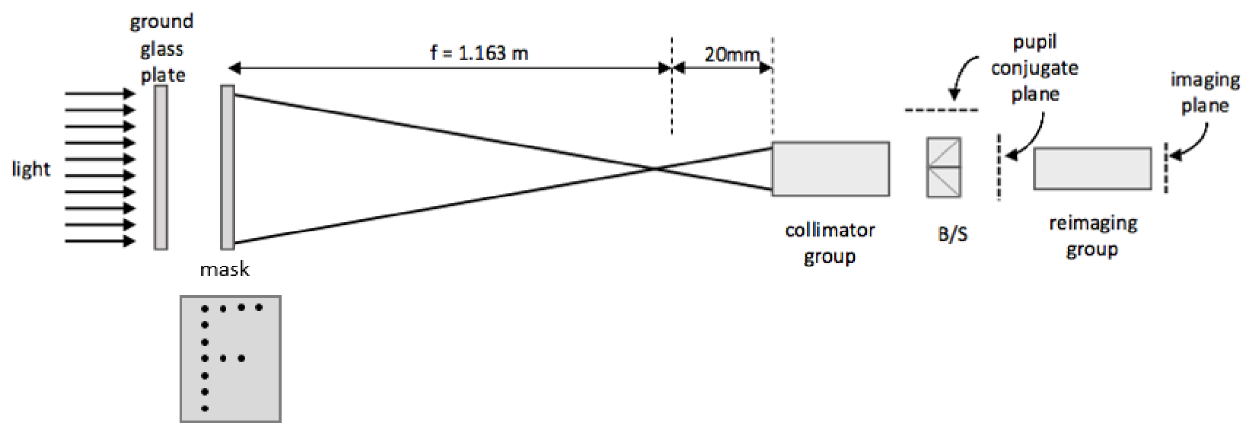


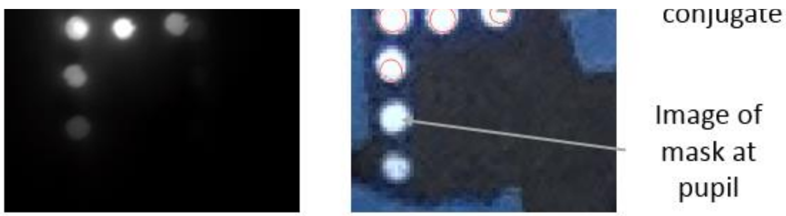



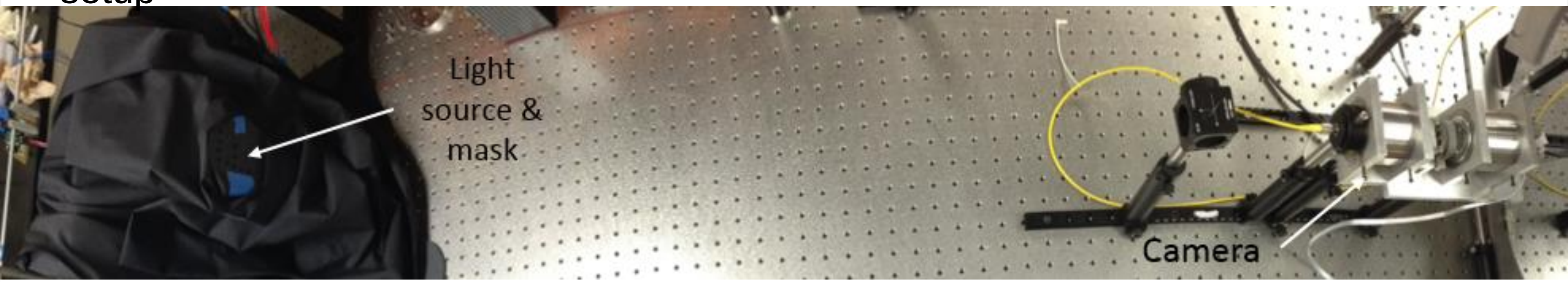

- Auto-collimation technique to simulate light from a distant star
- Primary mirror segments and flat mirror on kinematic mount
- Currently testing using spherical mirrors

# Collimator Testing

- Qualitative test demonstrating functionality of collimator barrel
- An image of a letter mask at the pupil plane is taken at the pupil conjugate and compared to predicted image
- Verifies the location of the pupil conjugate
- Slight defocus due to misalignments in test setup



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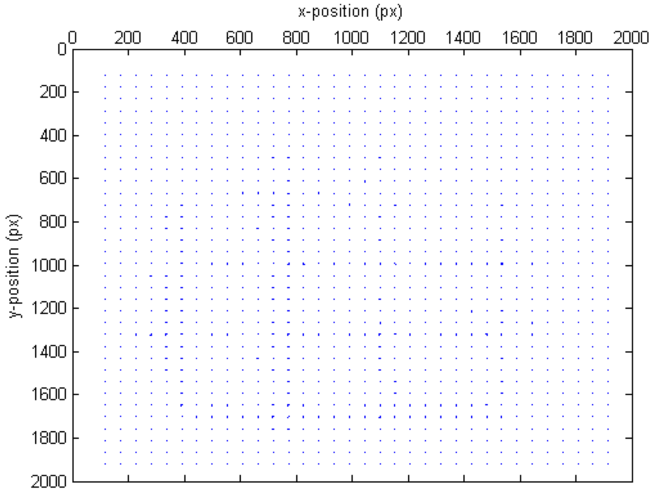
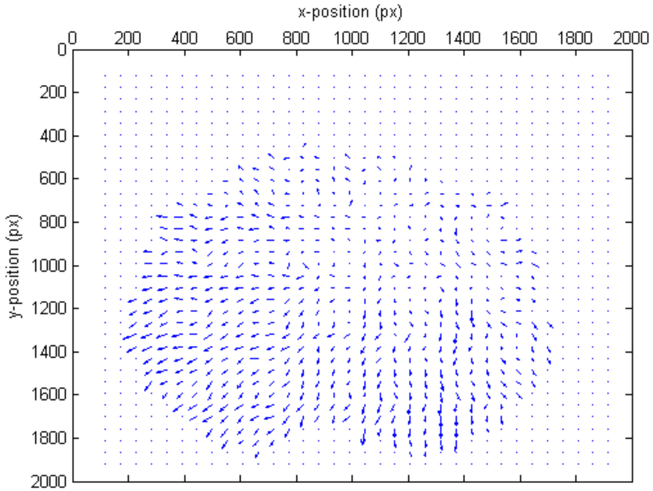
# SHWS Testing

- The distance between SHWS detector mount and MLA mount is shimmed at three locations to adjust piston, tip/tilt
  - 5.1 mm focal length
  - 0 deg relative tip/tilt between MLA and detector
- Alignment using plane wavefront
  - Spot deflections are measured and converted to wavefront slopes
- Deviation from plane wavefront used as calibration for SHWS algorithms




Unscaled




Scaled



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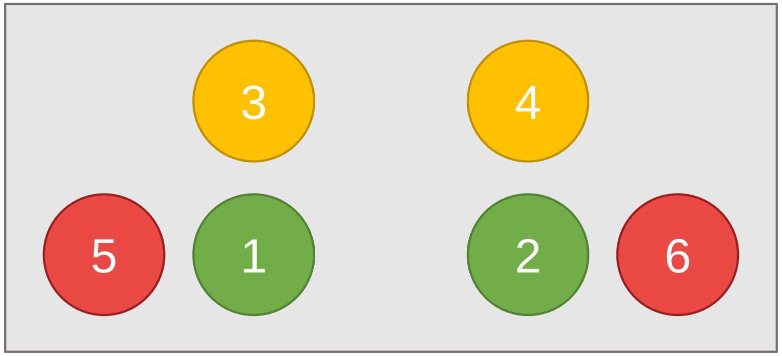
# Mask Testing

- Mask testing done by placing spherical mirror in each one of the mirror positions
  - Image on detector checked for both narrow and wide configurations and compared against expected results
  - Image also checked before and after mask to check that spot is unchanged
- No light transmitted from on-axis mirror, as expected

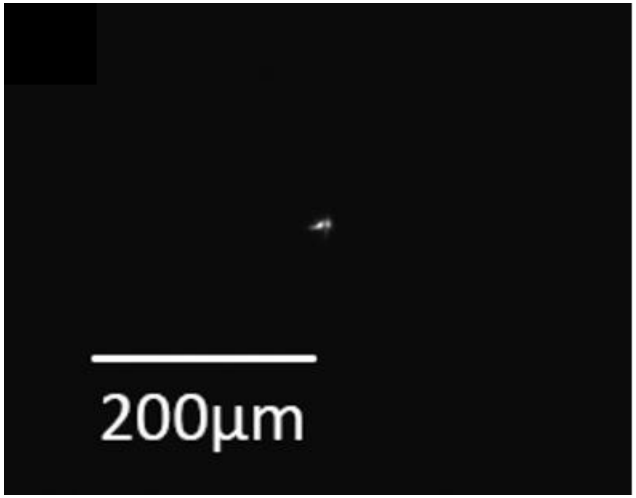


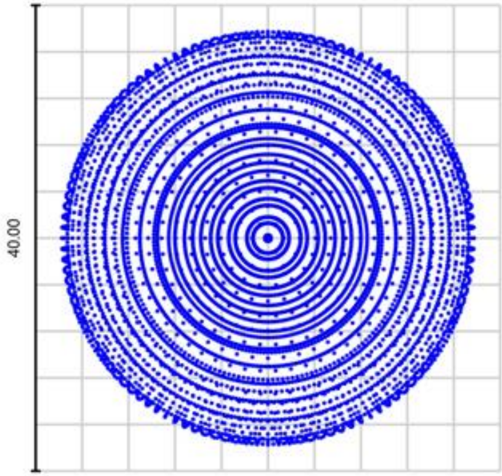

Fully illuminated
Partially illuminated
Not illuminated

| Mirror | Wide | Narrow |
|---|---|---|
| 1 | Pass | Pass |
| 2 | Pass | Pass |
| 3 | Pass | Pass |
| 4 | Pass | Pass |
| 5 | Not tested | Not tested |
| 6 | Not tested | Not tested |

# Point Source Test

- Laser source positioned at the focal point of the camera
- Spot measured at the imaging detector
- Predicted spot size from Zemax simulations = 39 um
- Measured spot size = 36 um





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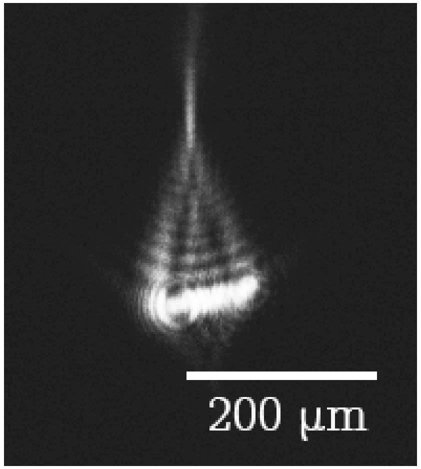
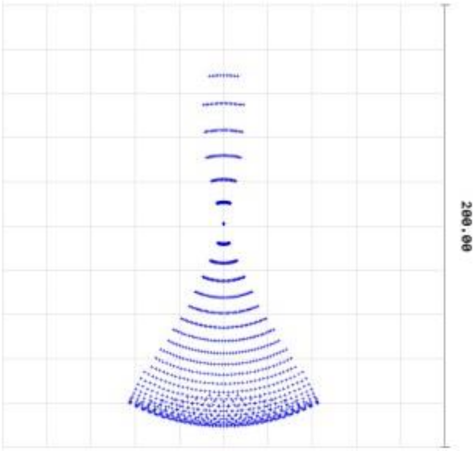
# Telescope Testbed End-to-End

- Verification of overall testbed alignment
- Test done with a single spherical mirror in one of the reference mirror positions
- Shape of spot as expected, but too large
  - Predicted size: 160 um
  - Measure size: ~250 um
- Error likely due to misalignments in the testbed



# Conclusion & Future Work

**Conclusions:**

- Camera and interface mechanical design complete
- Camera functional prototype fabricated
- Prototype testing in progress

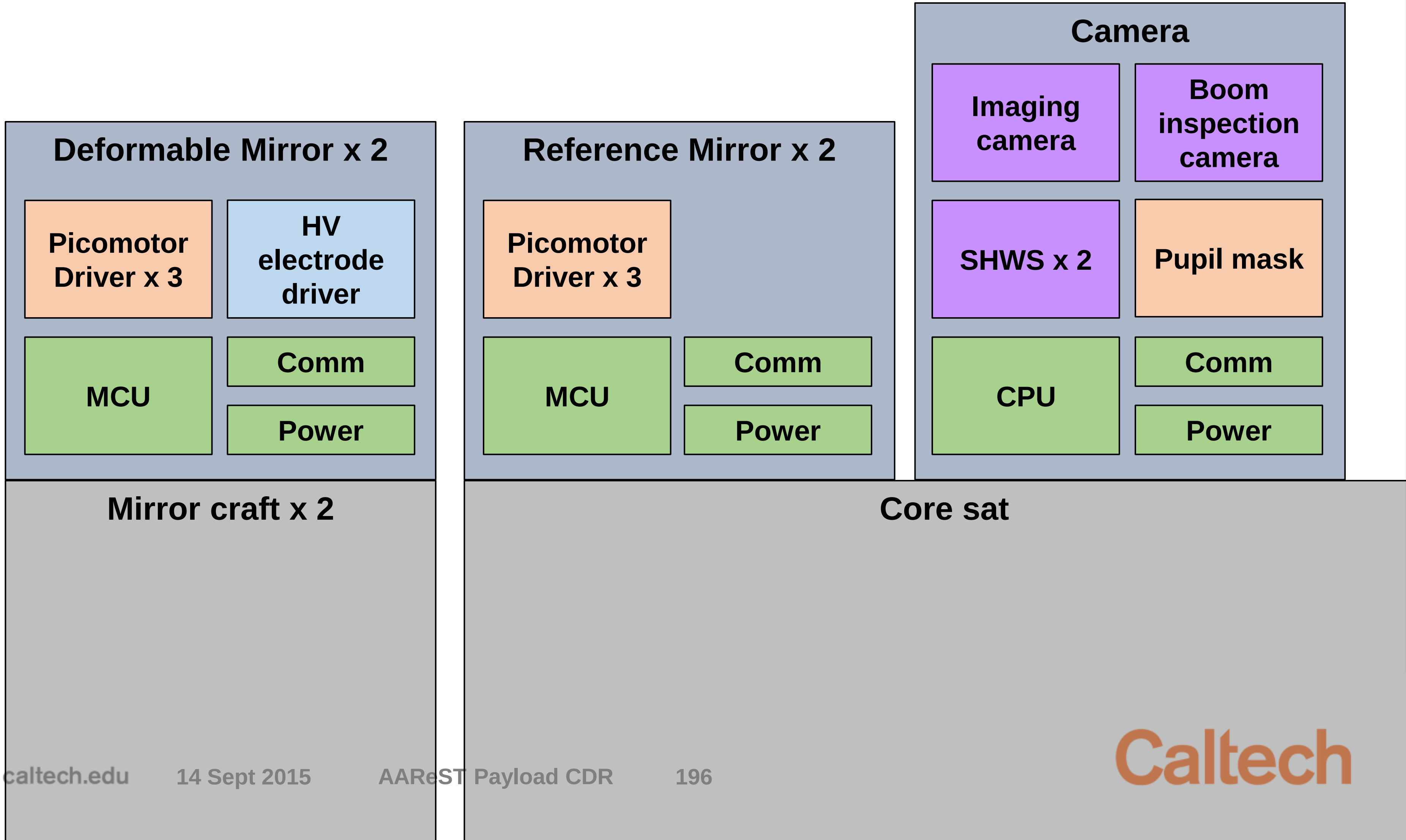
**Future work:**

- Testbed modifications
- Complete optical testing
- Thermal & vibration testing
- Integration with electronics

# Electronics

Nicolas Lee, Manan Arya,
Stephen Bongiorno, Finn Carlsvi,
Thibaud Talon

# Electronic system components



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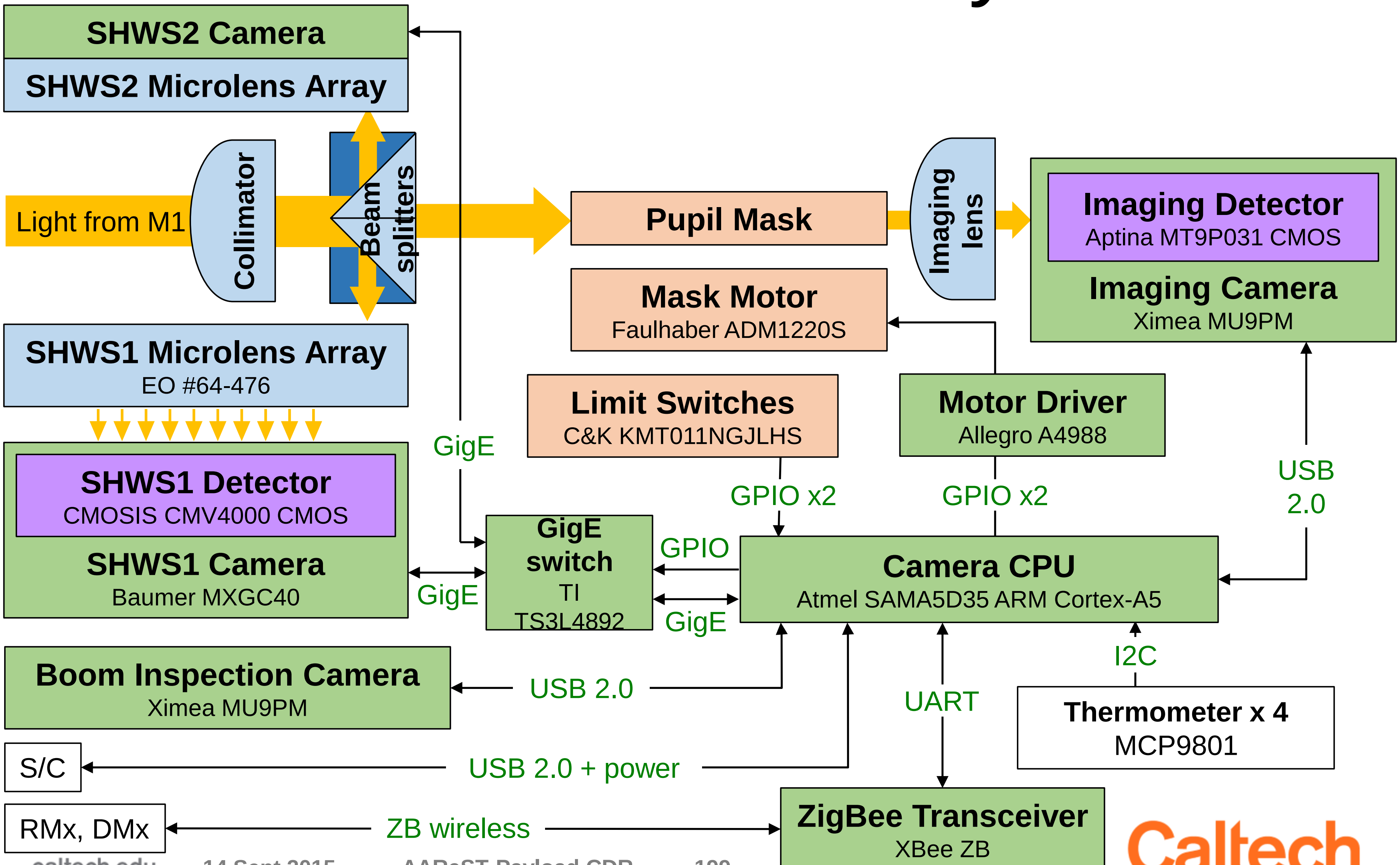
# This year's accomplishments

- Successful interface between camera CPU and image sensors
- New circuit design prototyped for electrode and picomotor drivers
- Demonstrated mirror deformation using new mirror electronics design (on RS-14)

# Requirements (Camera)

- USB interface to spacecraft
- ZigBee wireless interface to mirror payloads
- Electronics boards < 7 cm x 7.9 cm
- Power < 5 W

# Camera electronic system



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# Camera CPU

- Atmel ARM-based SAMA5D3 processor
- Up to 536 MHz CPU frequency
- Manages payload C&DH using Linux OS
- Command files uploaded from S/C through USB (discussed more later)
- Use unmodified CPU module board with integrated memory (SODIMM200 interface)
- 3.3 VDC input power
- 0.45-0.6 W power consumption

# Imaging camera / BIC

- Aptina MT9P031 CMOS sensor
- Ximea MU9PM camera module
- USB 2.0 interface
- 5 VDC input
- 0.3-0.9 W power consumption

# SHWS imager x 2

- CMOSIS CMV4000 CMOS sensor
- Baumer MXGC40 camera module
- GigE interface
- 12 VDC input
- 2.88-3.12 W power consumption: run one SHWS at a time

# GigE switch

- Texas Instruments TS3L4892 IC
- 16-Bit to 8-Bit SPDT Gigabit LAN Switch
- 1.1 GHz max bandwidth
- 3.3 VDC input
- *Not tested yet*

# Mask motor

- Faulhaber ADM1220S stepper motor
  - Two phase, 20 steps per revolution
- Allegro A4988 microstepping bipolar stepper motor driver
  - Full- to 1/16$^{th}$-step modes
- C&K KMT011NGJLHS limit switches
  - SMT top-actuated switch (0.15mm travel)
  - Interrupt-enabled digital input



Caltech

# Zigbee tranceiver

- XBee 2mW RF module
- 2.4 GHz ISM band
- 35 kbps data rate with packetization and error checking
- 3.3 VDC input
- 0.15 W power consumption



Caltech

# Camera power distribution

- Input power: 5 V from USB interface
- Regulated 3.3 V, 5 V, 12 V buses
- Camera CPU controls power to motor driver and image detectors

# Camera power budget

| Part | Peak (W) | Standby (W) | WF Sensing Mode (W) | Imaging Mode (W) | Reconfiguration Mode (W) | Safe Mode (W) |
|---|---|---|---|---|---|---|
| Telescope CPU | 0.60 | 0.45 | 0.60 | 0.60 | 0.60 | 0.45 |
| Imaging Detector | 0.74 | 0.30 | | 0.74 | | |
| SHWS | 3.12 | 2.88 | 3.12 | | | |
| BIC | 0.74 | 0.30 | | | 0.74 | |
| ZigBee | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| Mask | 0.60 | | | | 0.60 | |
| **Total** | | | **3.87** | **1.49** | **2.09** | **0.60** |
| **+ Margin (10%)** | | | **4.25** | **1.64** | **2.30** | **0.66** |



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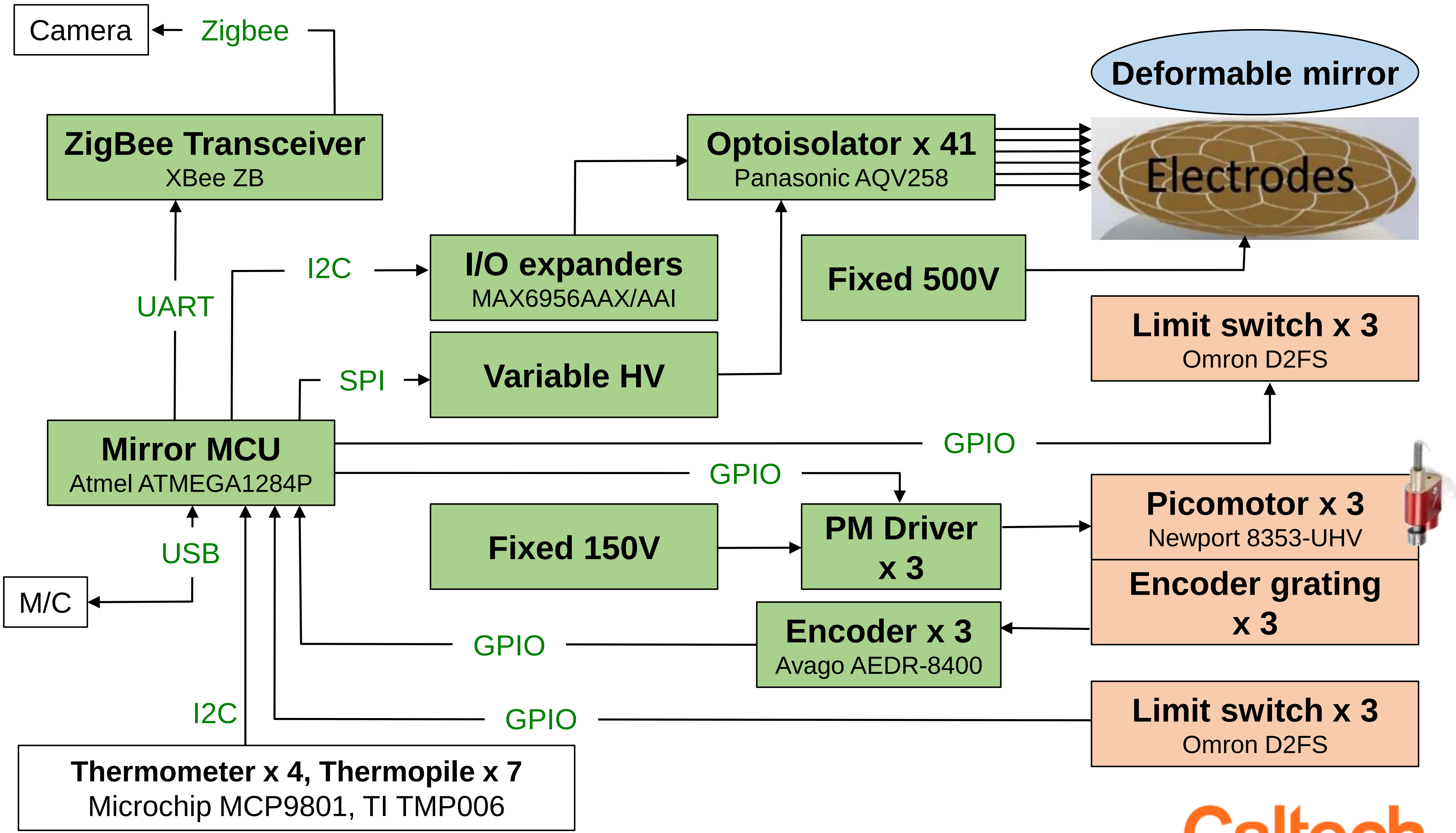
# Requirements (Mirror)

- USB interface to mirror craft
- ZigBee wireless interface to camera
- Volume : 84 x 82 mm board size, up to 3 boards
- Power constraints : < 2 W
- HV DC output for driving mirror actuators *(Wavefront correction)*
  - +/- 500 V range for driving 41 modes
  - 0.1 V resolution at the output
- HV analog output for driving picomotors *(Translation)*
  - 140V amplitude
  - Required slew rate: > 0.7 V/ns

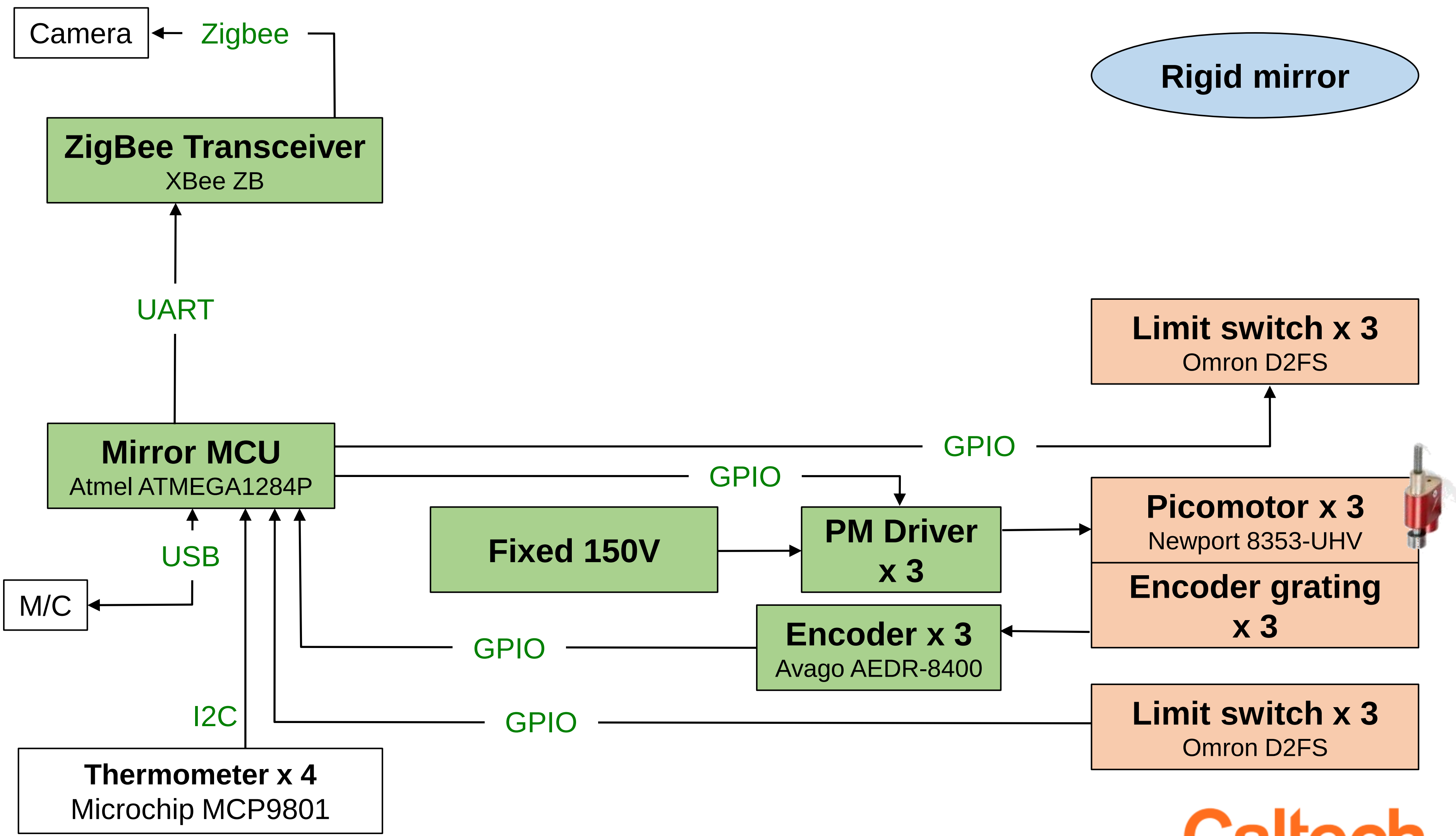
# Mirror electronics block diagram






Caltech

# Reference mirror variant



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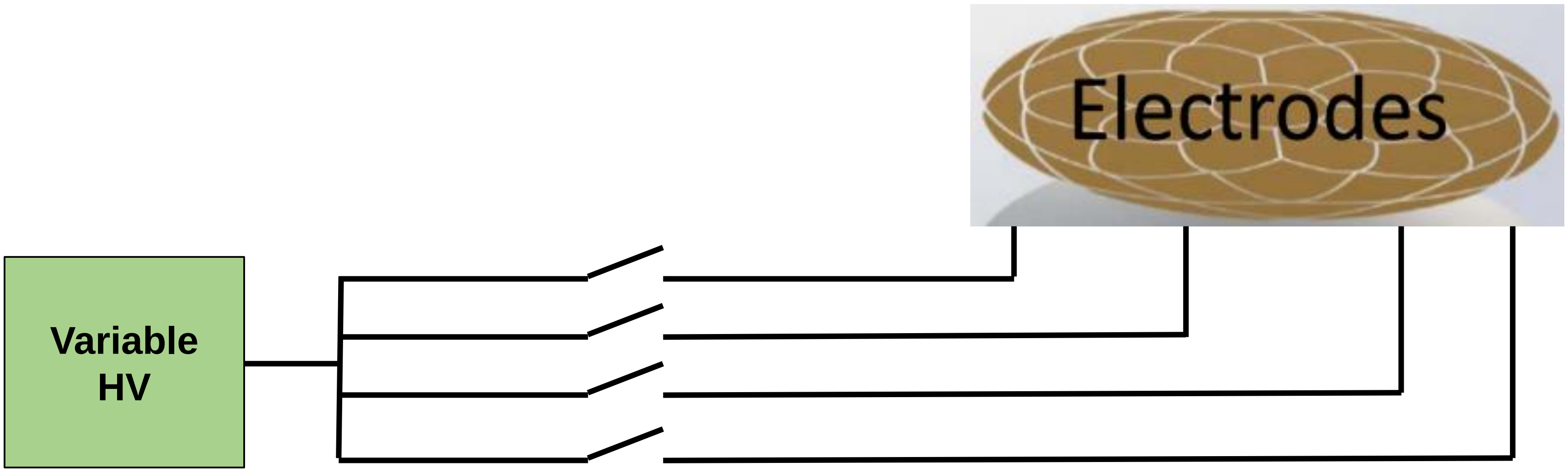
# Mirror shape control

- Sequentially refresh electrodes with appropriate voltage
- Individual opto-isolated MOSFET switch (Panasonic AQV258) connects each electrode to variable HV supply



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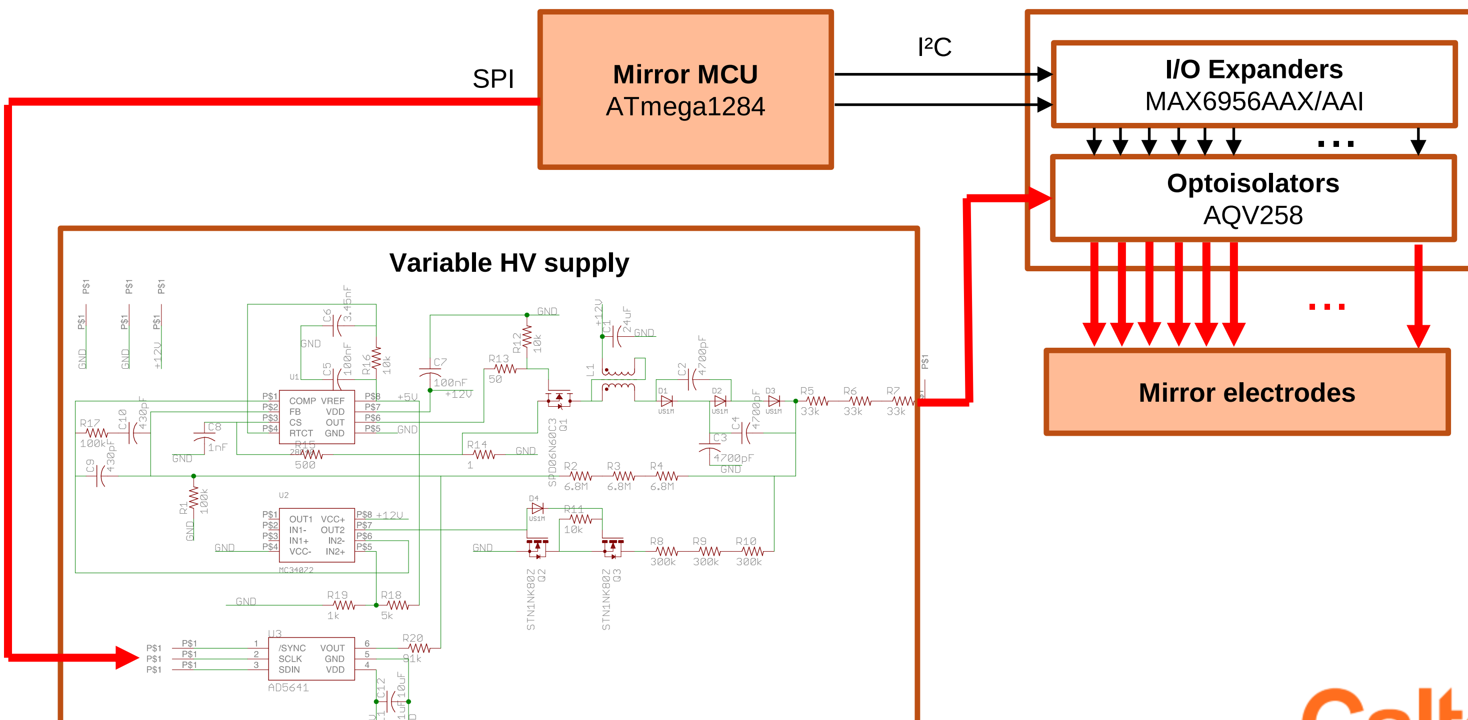
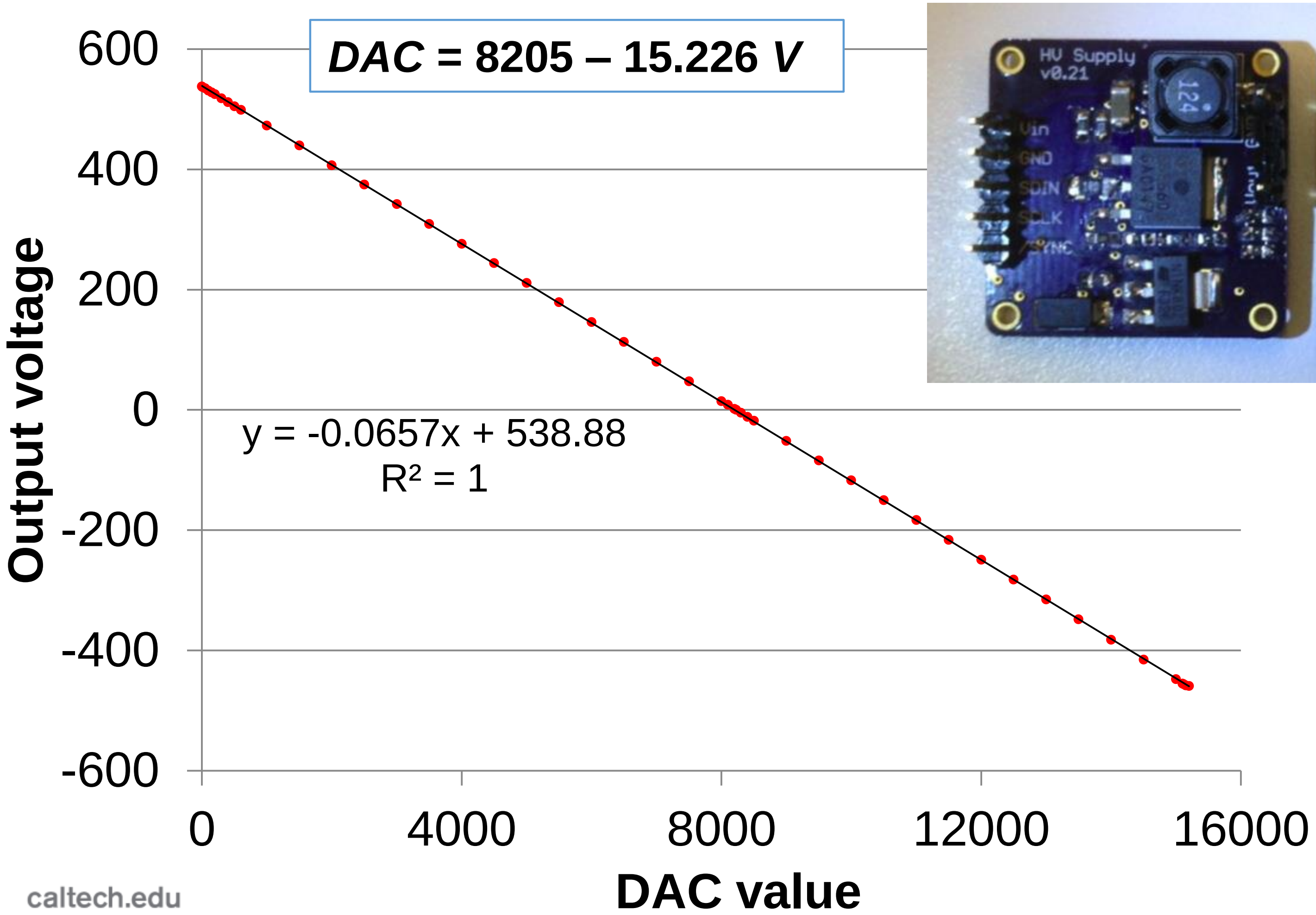
# Mirror electrode driver

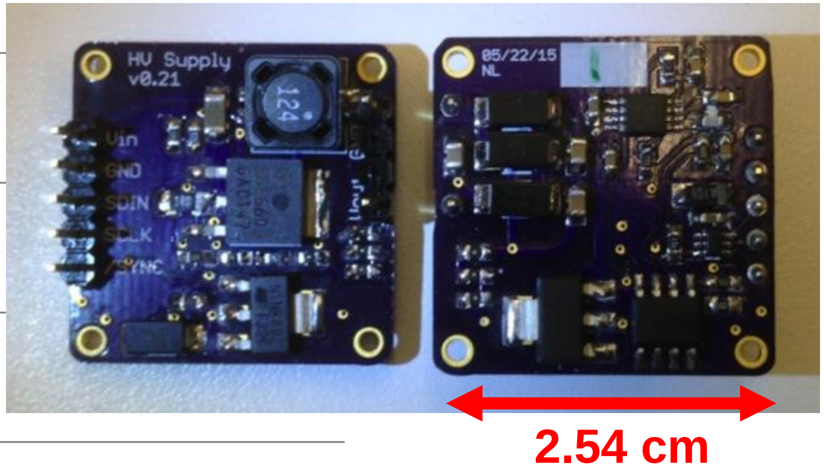
- 2 x custom switched mode HV power supply (fixed 500 V bias and variable 0–1000 V)
- Refresh electrodes sequentially



# Electrode driver test data (1)

- Good linearity in voltage control



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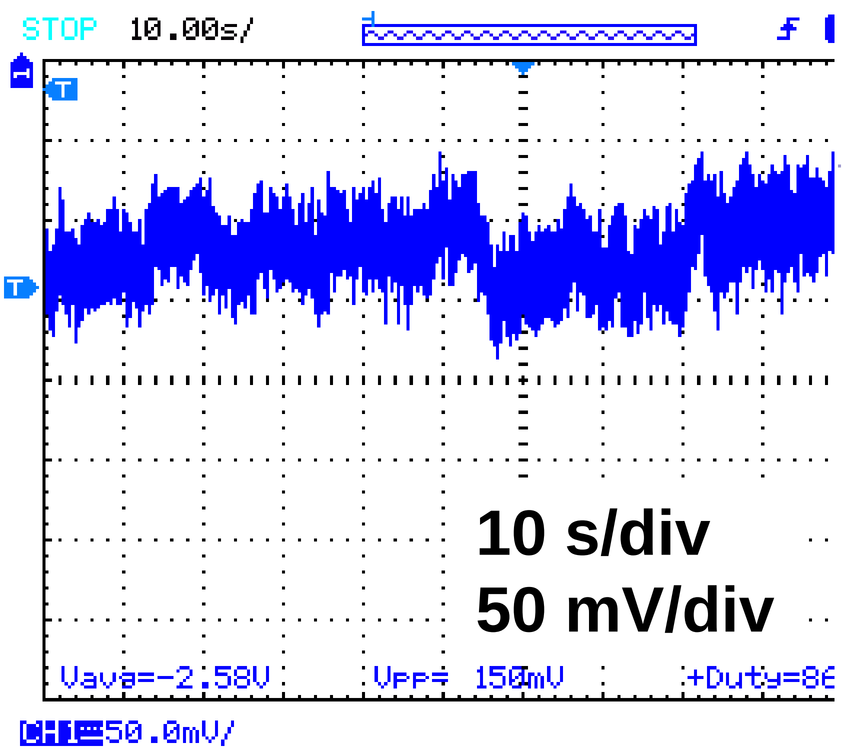
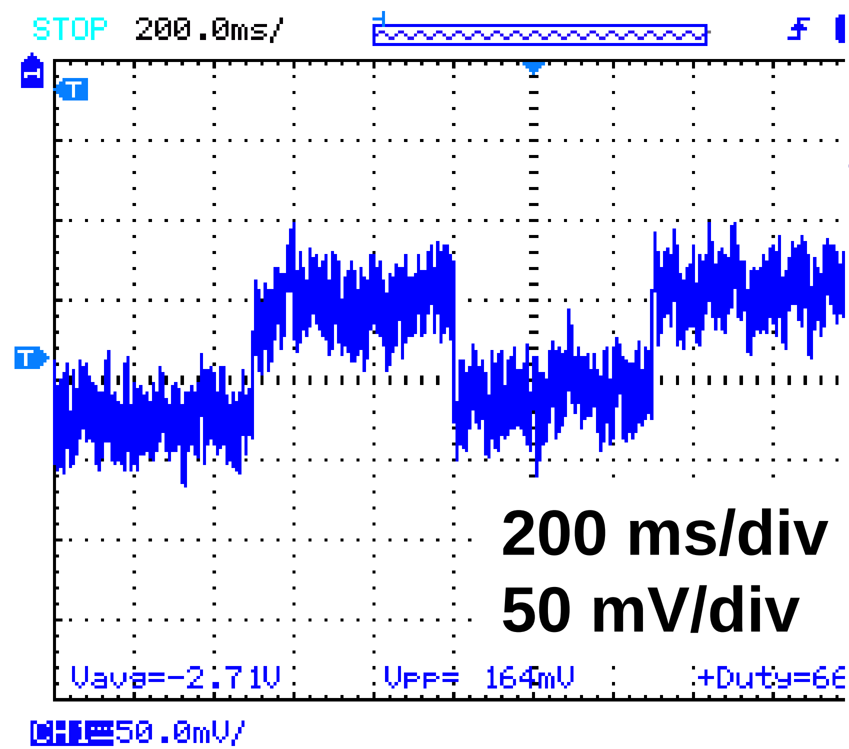
# Electrode driver test data (2)

- 150 mV peak to peak over 100 s (steady state)
- 75 mV step, DAC 0x1fff–0x1ffe (one count)



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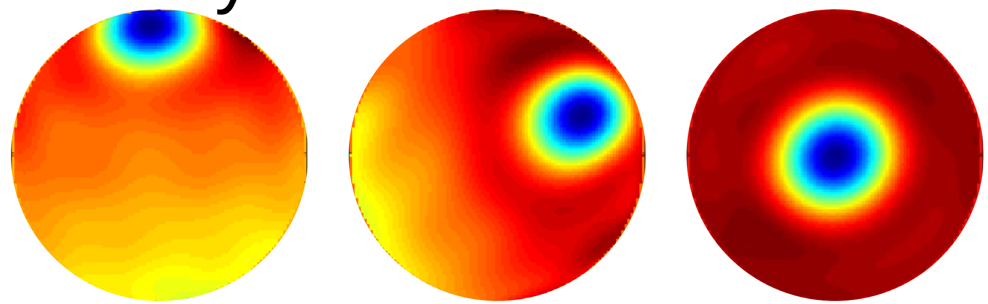
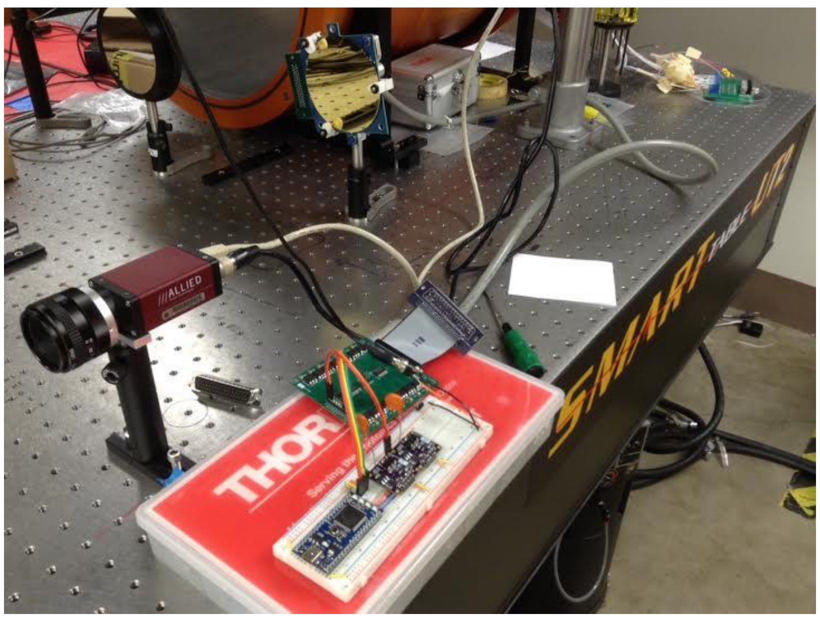
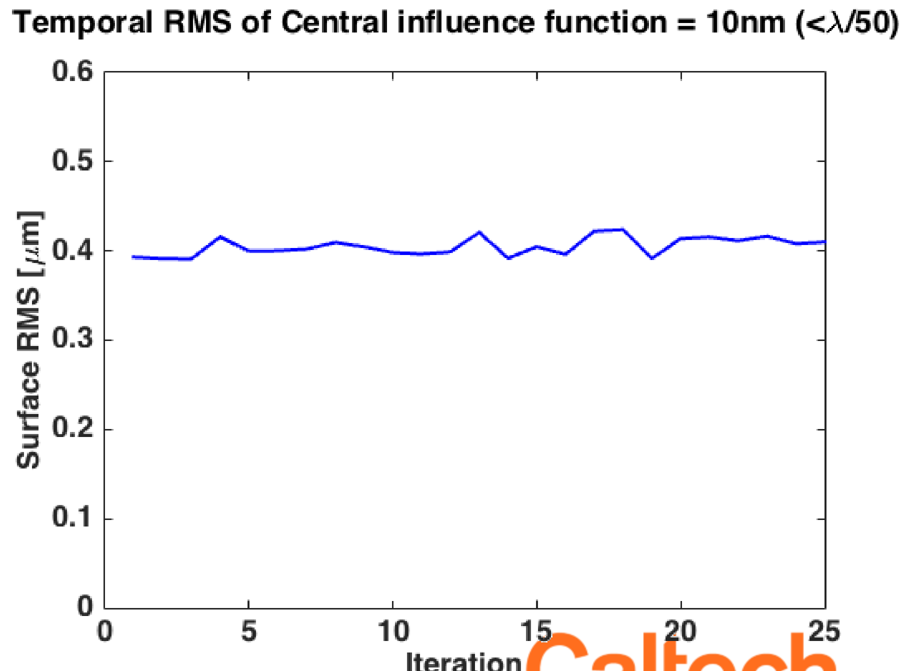
# Integrated test results

- Demonstrated optical stability of influence functions on RS-14 mirror





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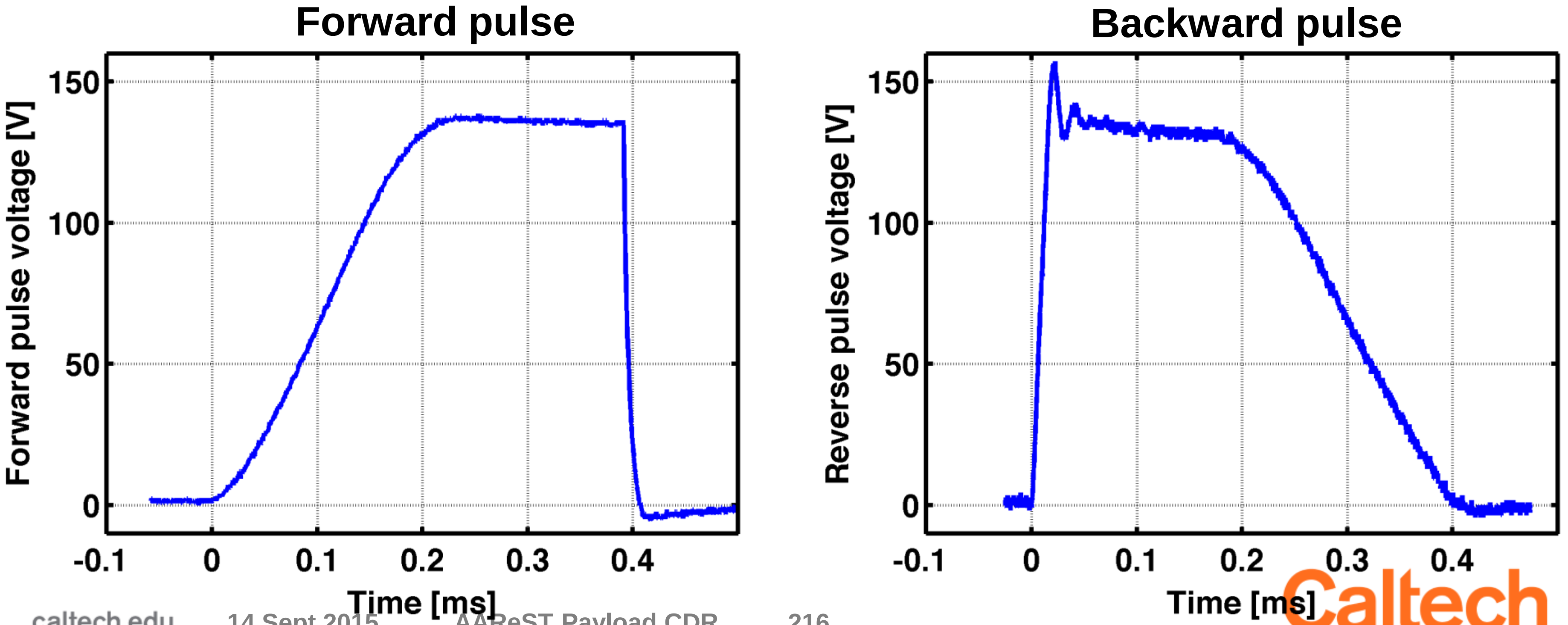
# Picomotor driver

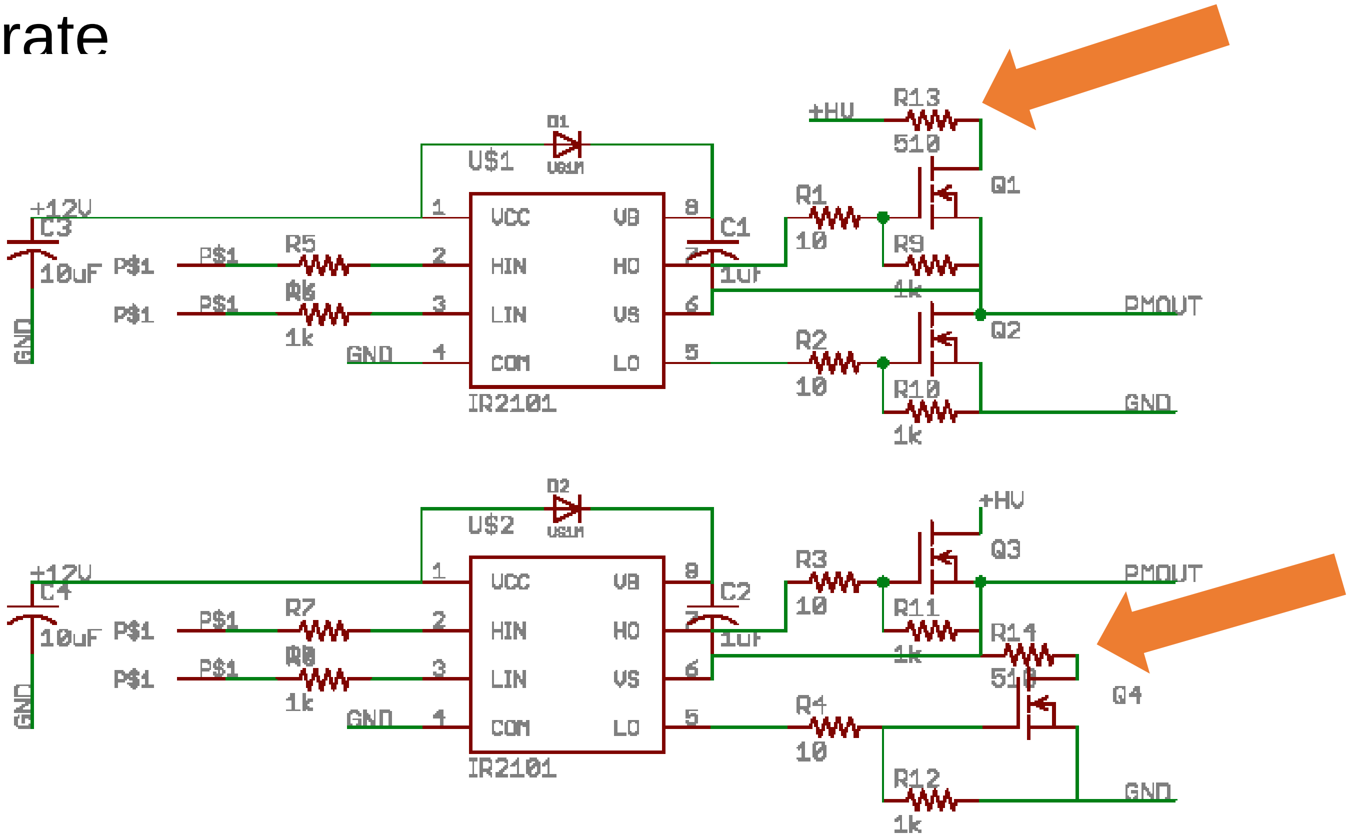
- Stick-slip mechanism with piezo element drives screw
- Need to achieve dV/dt ~ 8 V/µs (or at least > 0.7 V/µs)

**Measured Newport Picomotor controller signals**



# Picomotor driver circuit

- Low-resistance MOSFETs with high-/low-side driver
- Two separate charge/discharge paths to control voltage slew rate



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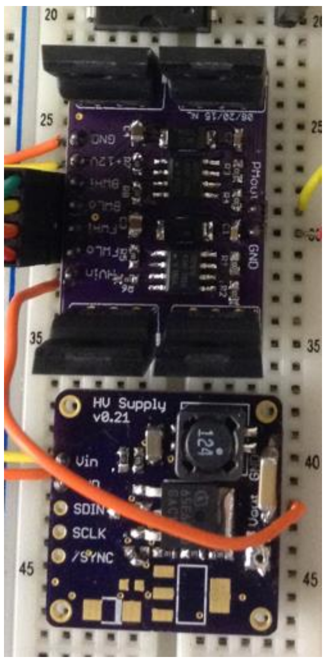
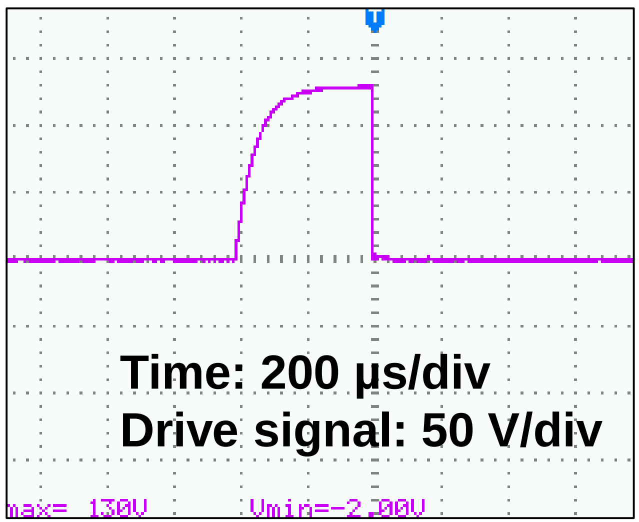
# Picomotor driver test data

- Demonstrated bidirectional operation (about 8 µm/s travel rate at 1.2 W)

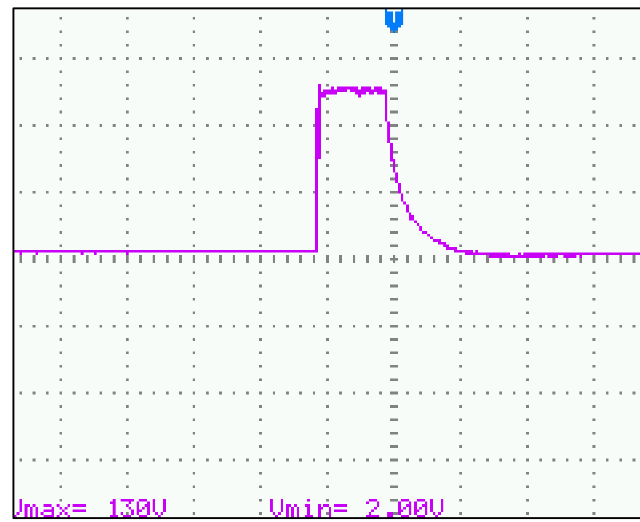



**Forward pulse**




**Time: 200 µs/div**
**Drive signal: 50 V/div**

**Backward pulse**



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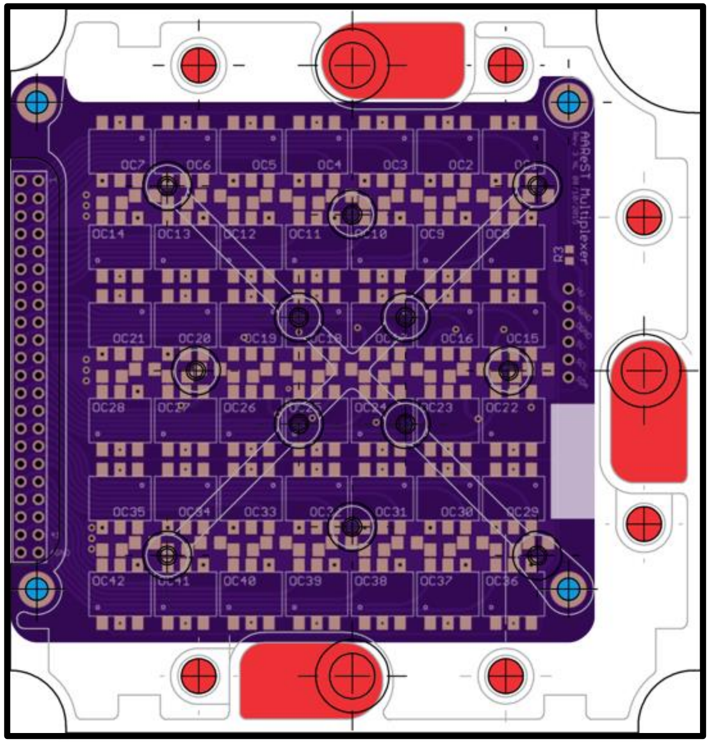
# Mirror electronics power budget

| Part | Peak (W) | Standby (W) | Picomotor mode (W) | Shaping mode (W) | Safe mode (W) |
|---|---|---|---|---|---|
| Mirror MCU | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| Electrode driver | 1.00 | 0.50 | | 0.50 | |
| Picomotor driver | 1.20 | 0.50 | 1.20 | | |
| ZigBee | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| **Total** | | | 1.45 | 1.25 | 0.25 |
| **+ Margin (10%)** | | | 1.59 | 1.37 | 0.27 |

- Electrode and picomotor power both easily scalable by adjusting refresh/pulse rates

# Mechanical constraints

- Multiplexer board layout designed to accommodate current box design



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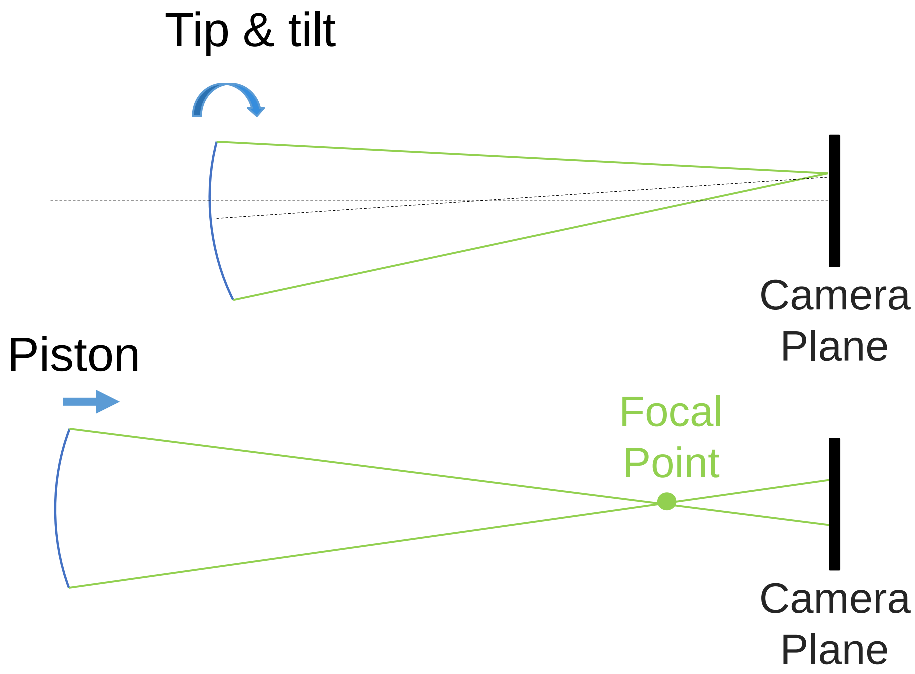
# Work to go

- Implementation and testing of health monitoring and power distribution components
- Further integrated system testing of breadboard modules with optical testbed
- PCB layout, fabrication, assembly

# Telescope Alignment & Control Algorithms

# Overview

- Write the algorithms to operate the telescope
  - Aligning
  - Shape correction
- Test on the testbed (with computer)

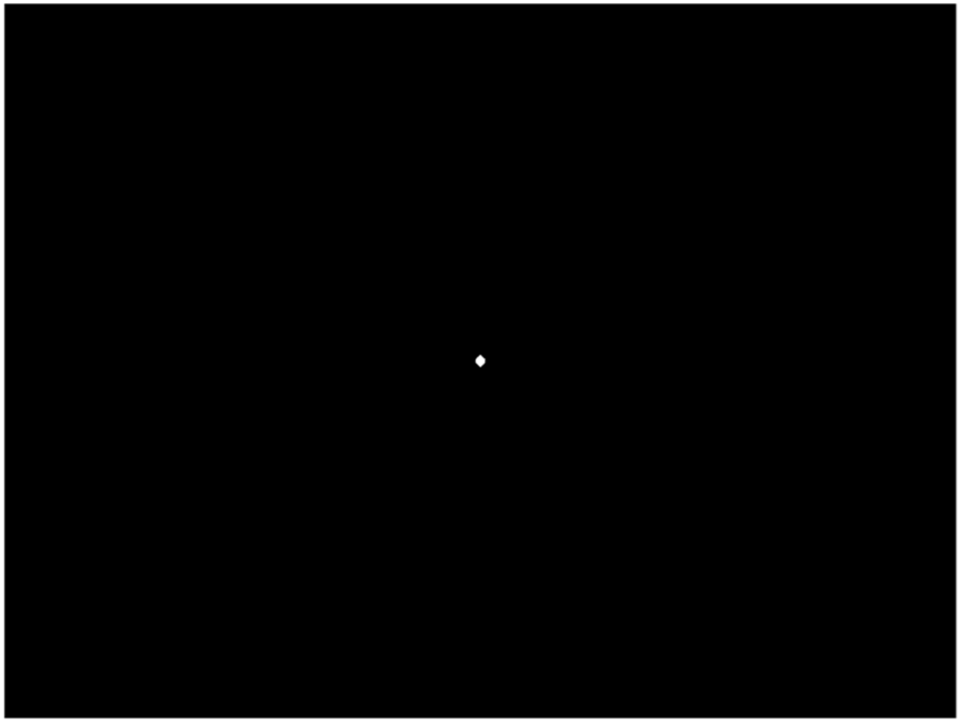



# ALIGNING

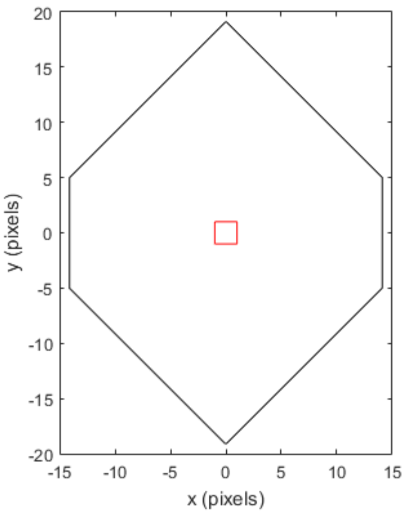
# Requirements

- Center the mirrors on the optical axis
  - Precision < 2 µm (1 pixel, 1-2 ticks on a picomotor)
- Place the mirrors on the focal plane
  - Precision on Z4 (Zernike focus coefficient) < 40 nm (λ/10, 1-2 ticks on a picomotor)

# Motivation



Uncertainty of the position of the center of a spot on the science camera



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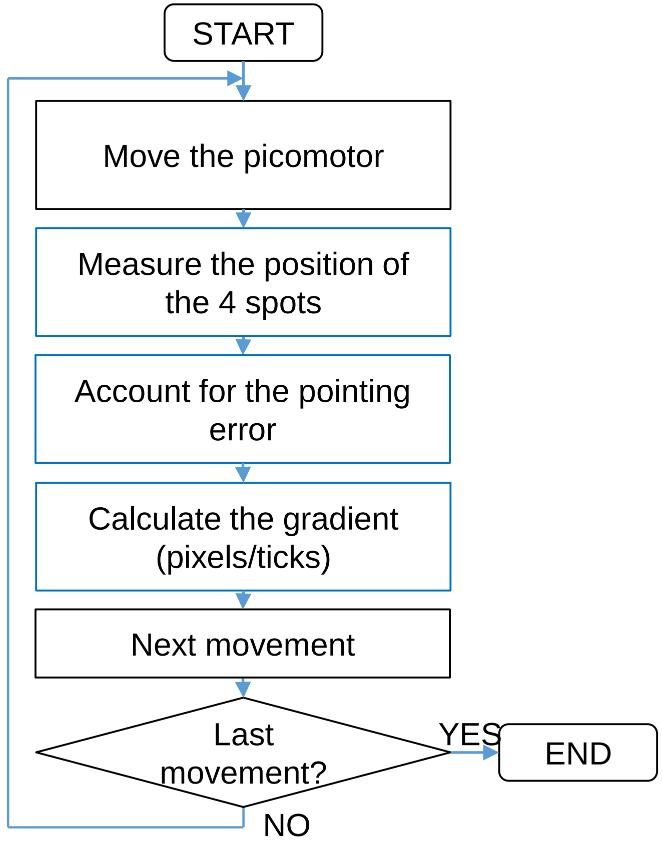
# Position gradients

**ALIGNING: Have mirrors aligned to the focal plane**

- Influence of the motion of each picomotor on the displacement of a spot



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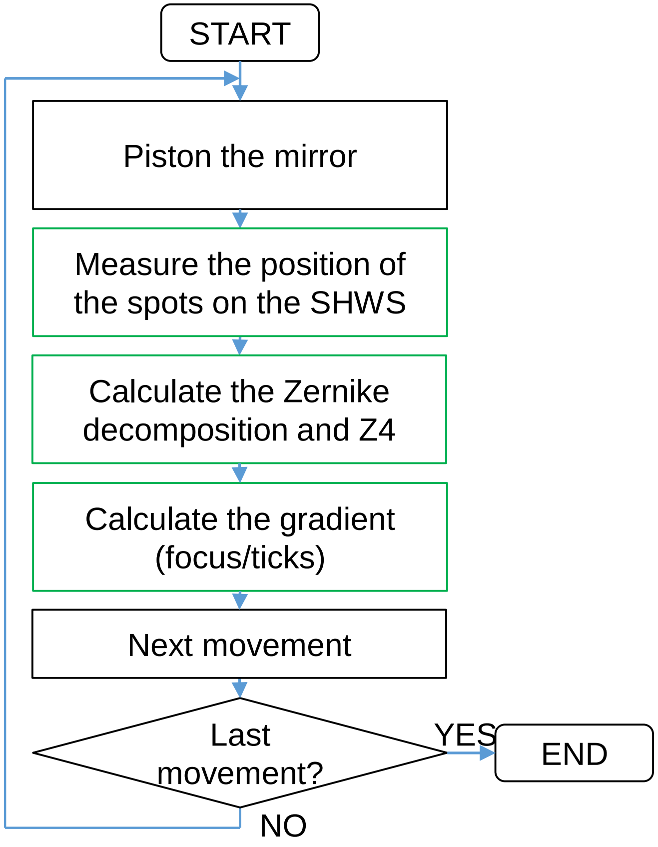
# Focus gradients

**ALIGNING: Have mirrors aligned to the focal plane**

- Influence of the piston of a mirror on the Zernike focus coefficient



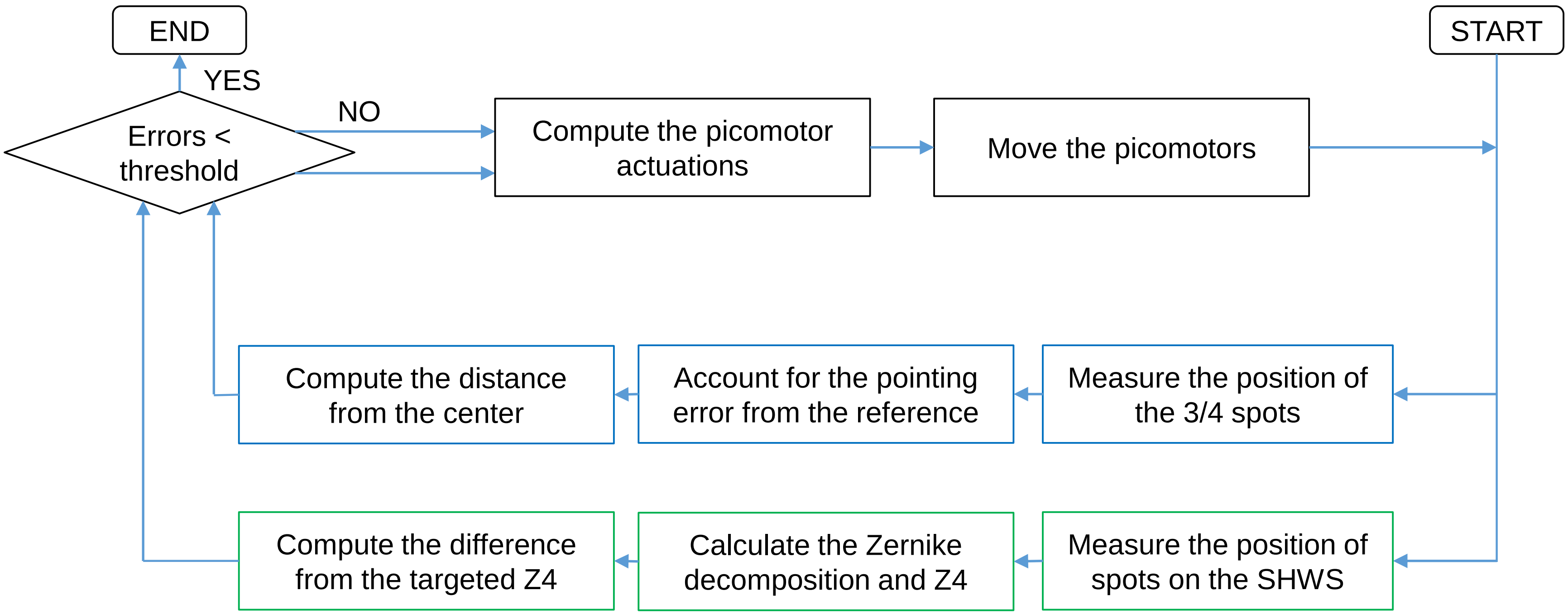
# Zero pointing error

**ALIGNING: Have mirrors aligned to the focal plane**

- Need to know the position of each spot when the star is perfectly aligned
- Get the information from the spacecraft (star trackers)
  - Doesn't account for the boom deflections
- Use the position of the reference mirrors
  - Known within 50nm with the encoders
  - ~0.002° error

# Loop

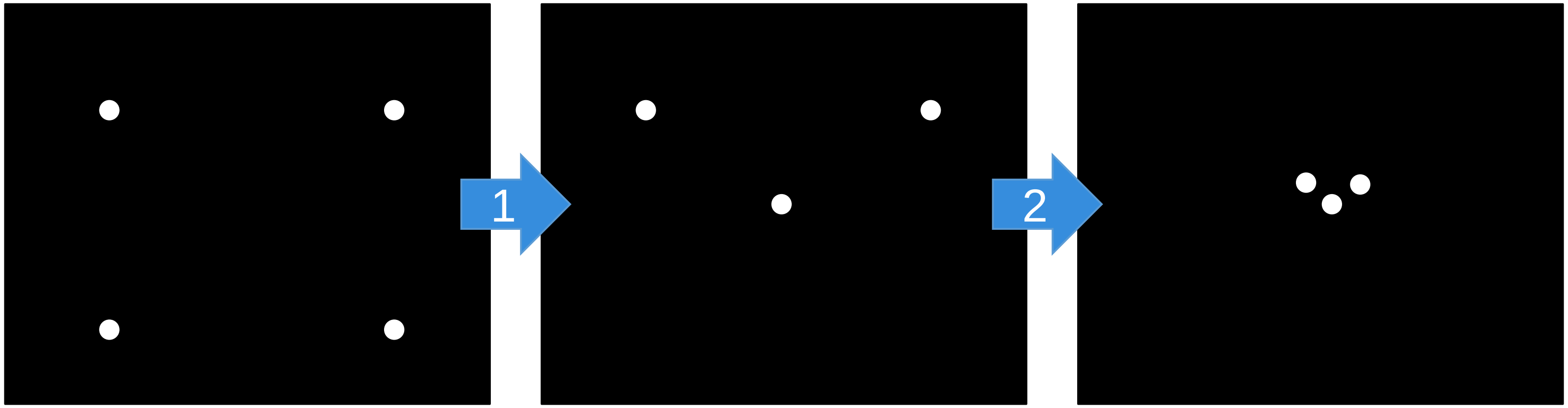
## ALIGNING: Have mirrors aligned to the focal plane



# Concept of operation

**ALIGNING: Have mirrors aligned to the focal plane**

1. Focus/Center the deformable mirrors
2. Focus/Bring the reference mirrors close
   – Need 2 points to account for pointing errors
3. Final open loop centering of the reference mirrors



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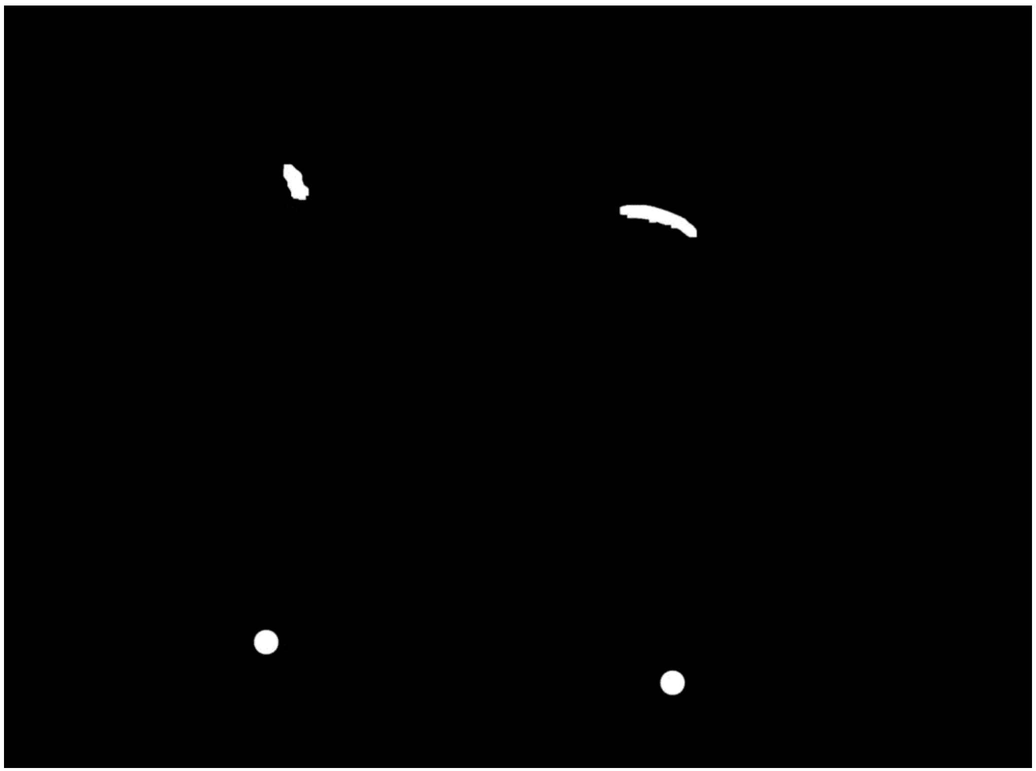
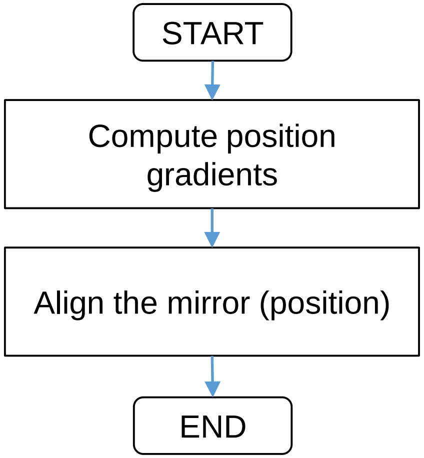
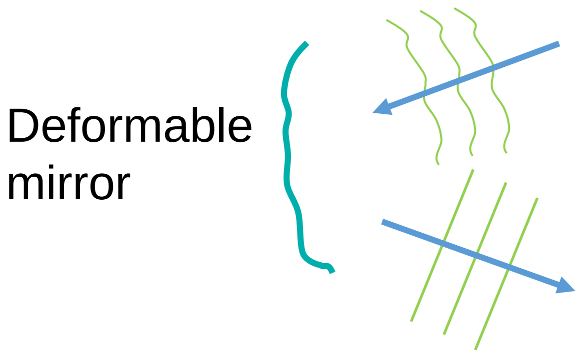
# Test

**ALIGNING: Have mirrors aligned to the focal plane**





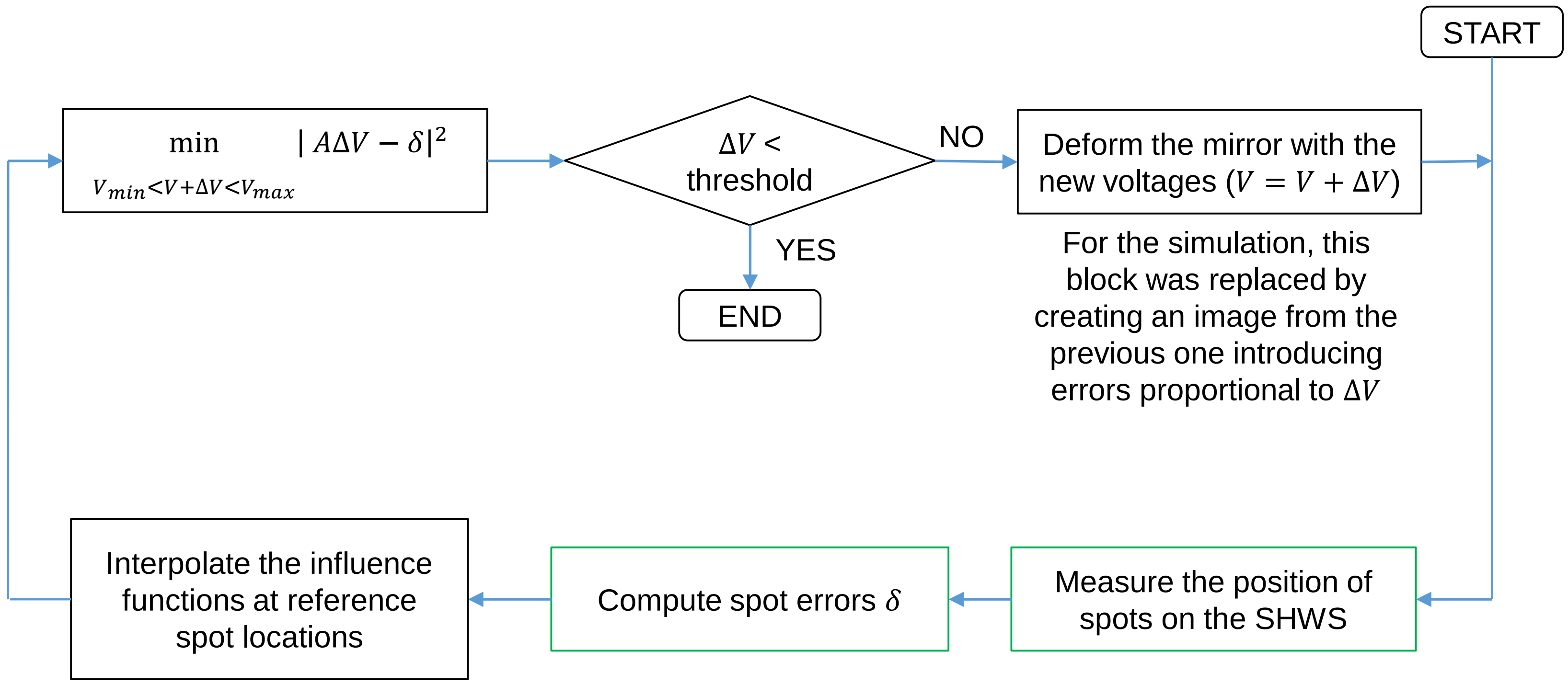

2 picomotors / mirror
2 mirrors




# SHAPE CORRECTION

# Loop

## SHAPE CORRECTION: Correct shape of the deformable mirrors



# Conclusion

## What has been done

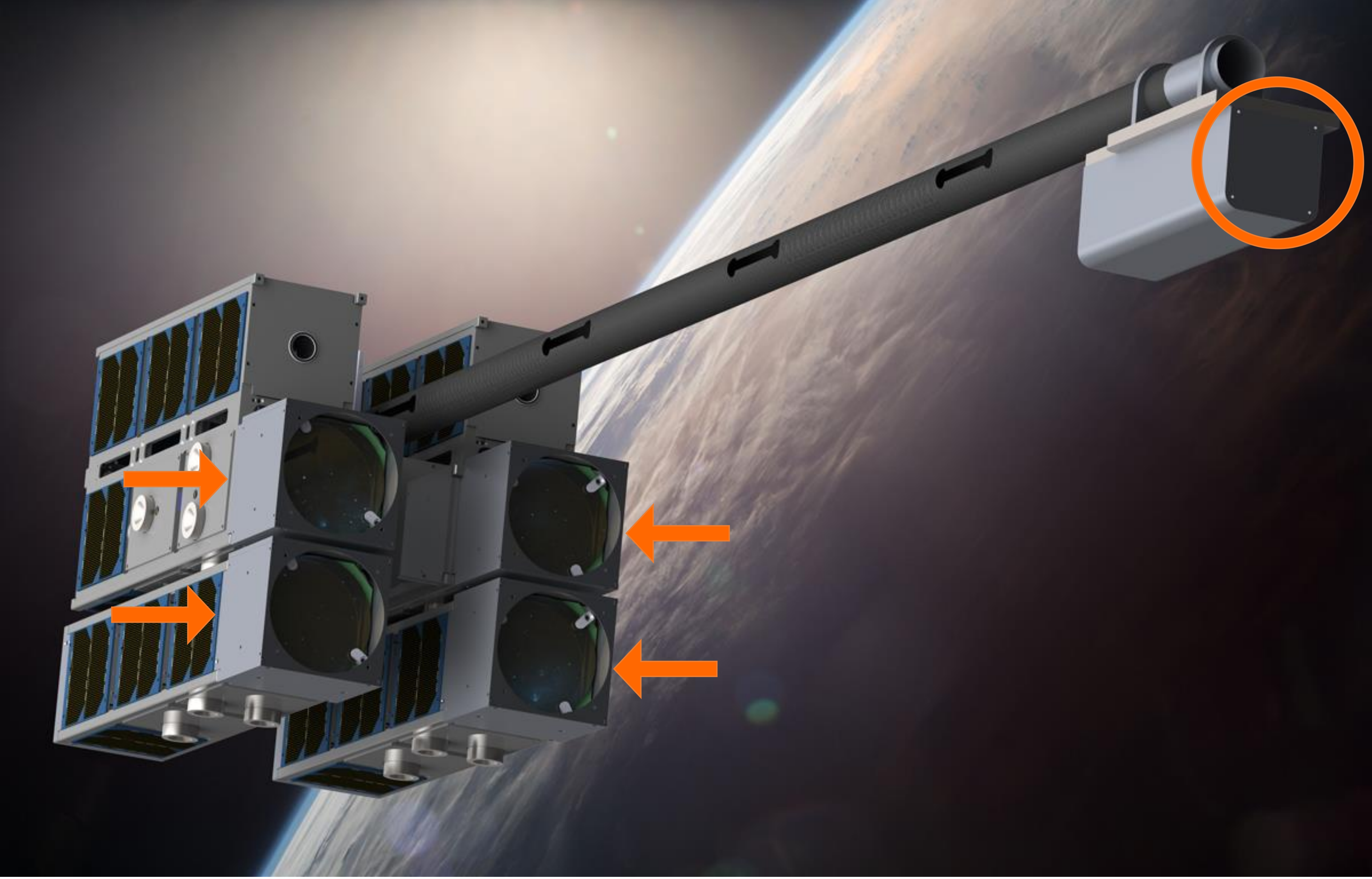
- Algorithms written
- Tested on a computer
  - Off-the-shelf hardware & drivers

## What needs to be done

- Include mirror boxes and hardware into the loop
- Test the shape correction algorithm
- Tests on the flight CPU

# AAReST Onboard Software

Yuchen Wei
Finn Carlsvi





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# Outline

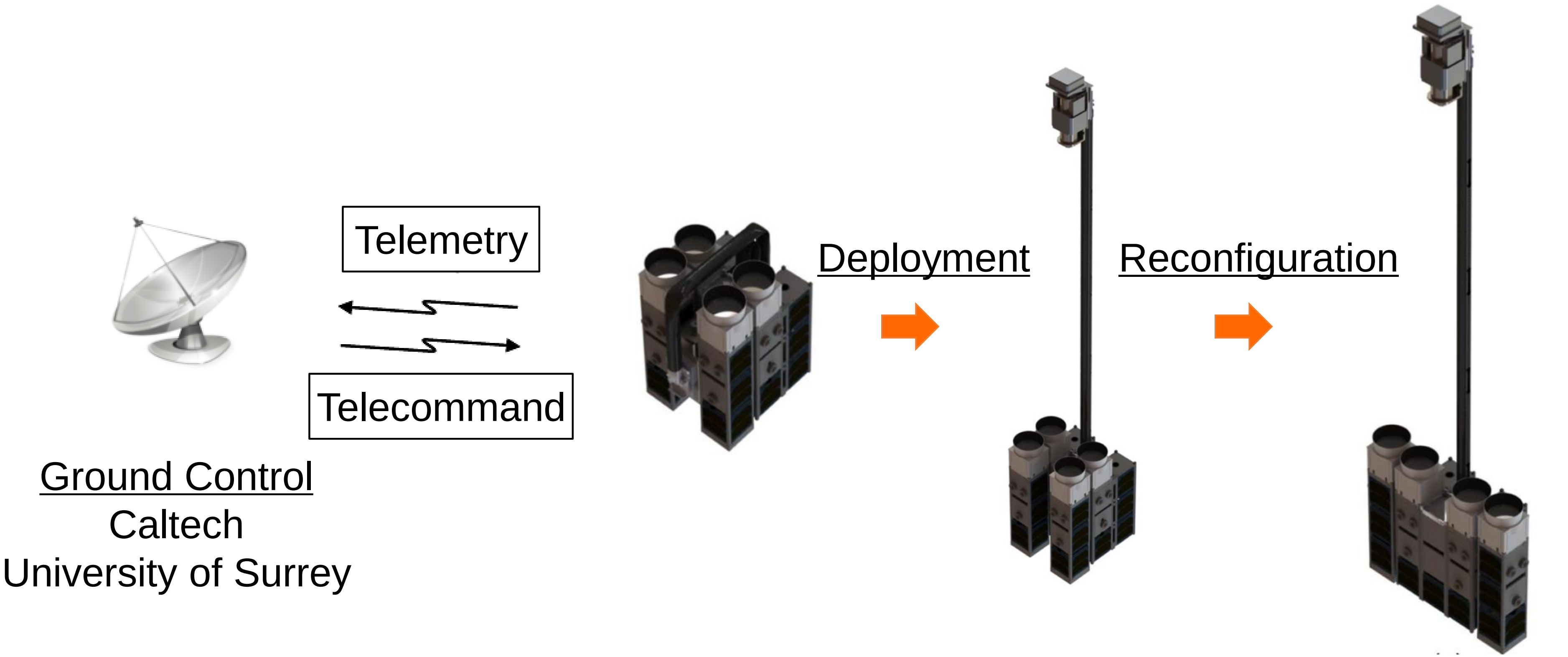
- Objective
  - State Based Operation
  - Purpose of OBSW
  - Onboard Computer
- Onboard Software Design
  - Camera OBSW
  - Mirror OBSW
  - Communication Design and Data Budget
- Test
- Future Work

# AAReST Mission Operation

Objective
Design
Test

## Operation Timeline

Post Launch → Deploy-ment → Calib-ration → Imaging → Reconfi-guration → Cali-bration → Imaging → Extended Mission



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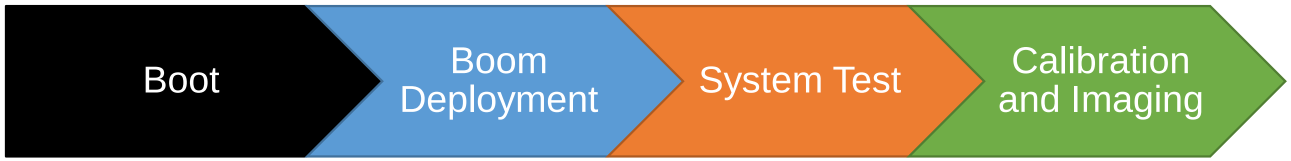
# AAReST Mission Operation

- Operation of AAReST can be divided into different Onboard States:




- Transition between states will be triggered by ground command or automatically

Based on current state:

- Hardware operation
- Command and data handling, fault protection

Need to be performed automatically

# Purpose of AAReST OBSW

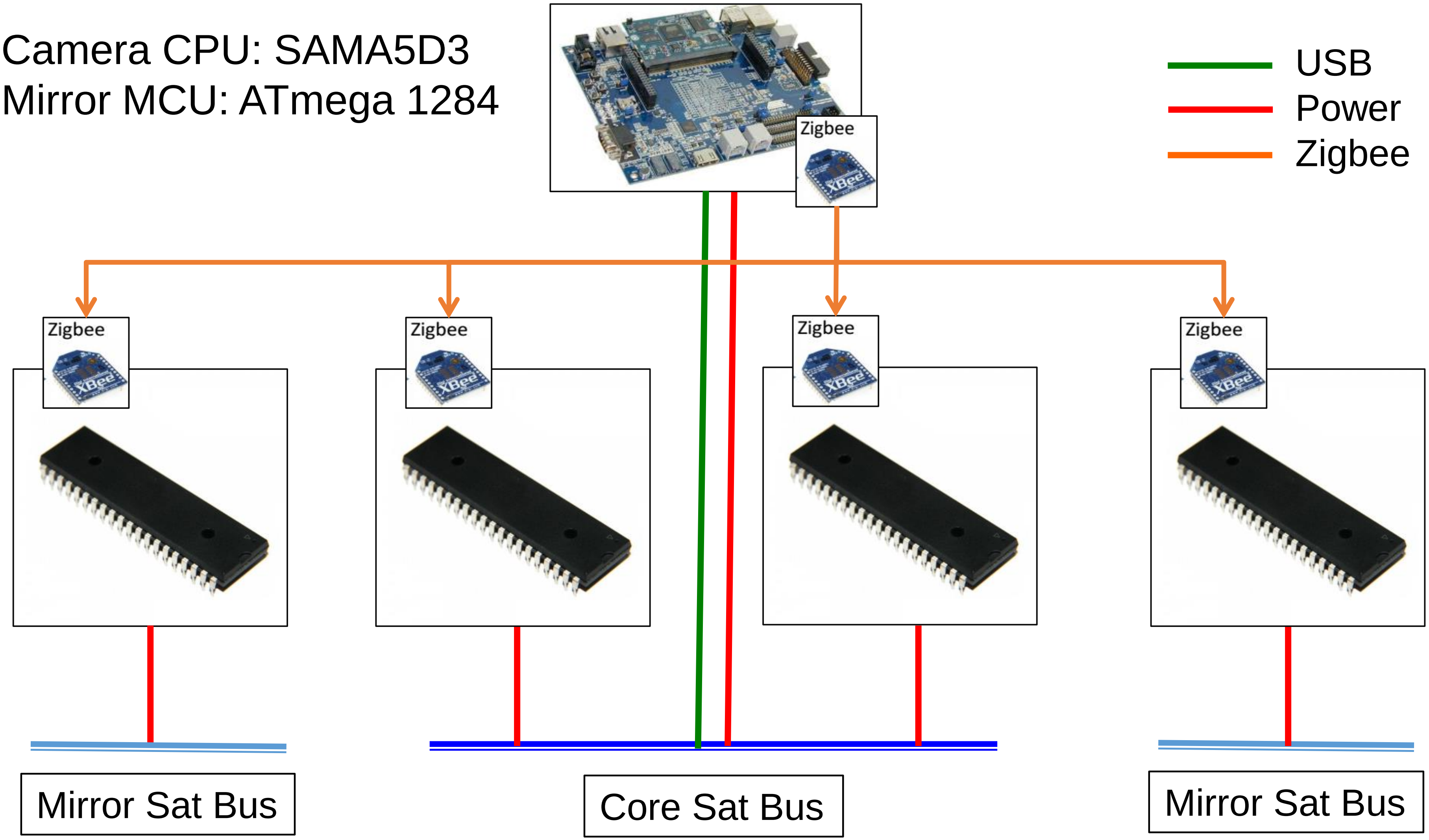
<u>OBSW is the “Brain ” of the science payloads</u>

- Implement state-based operation
- Control payload hardware
- Relay science and engineering data for camera/mirror boxes
- Fault detection and recovery
  - Health monitoring
  - Event logging
  - Safe mode and recovery

# Onboard Computer Assembly

Objective
Design
Test

Camera CPU: SAMA5D3
Mirror MCU: ATmega 1284



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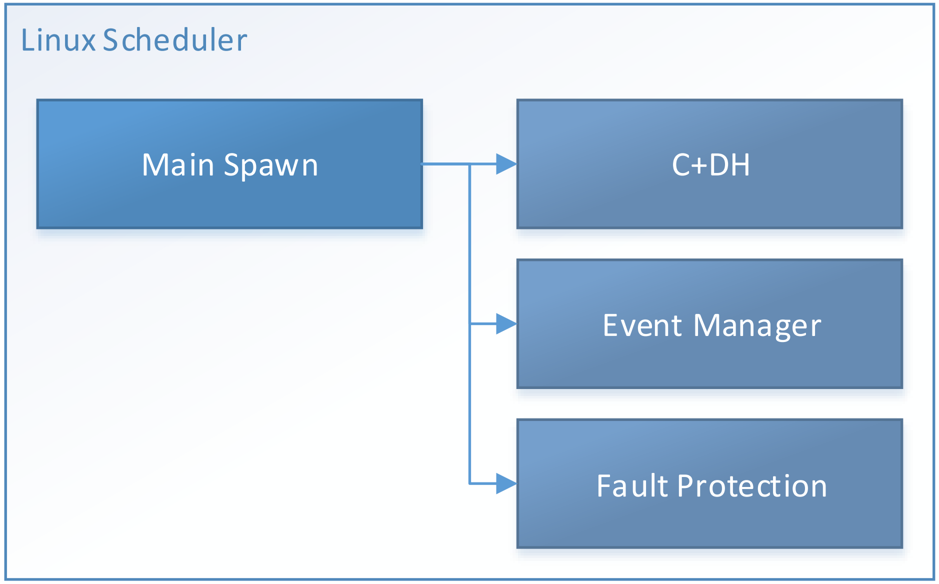
# Camera OBSW Architecture

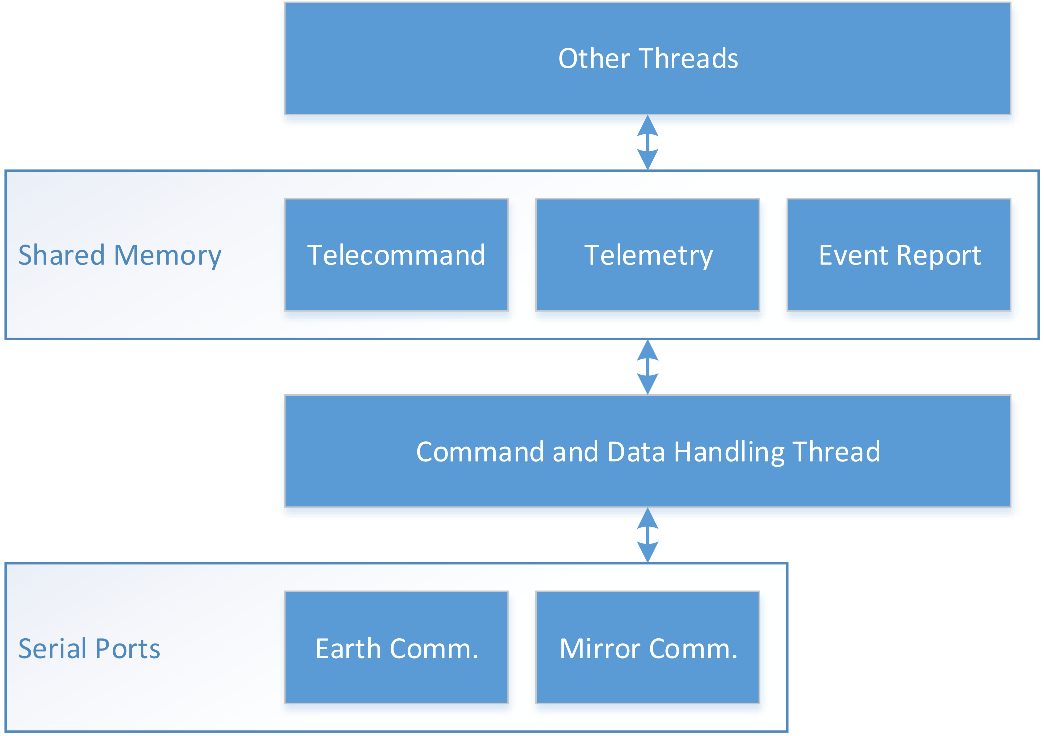
- Linux OS
- Three main threads



# Command and Data Handling

Objective
Design
Test


- Handles all external communication



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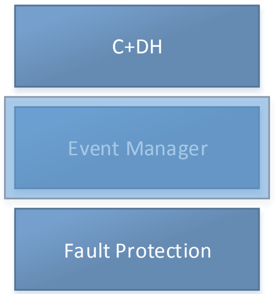
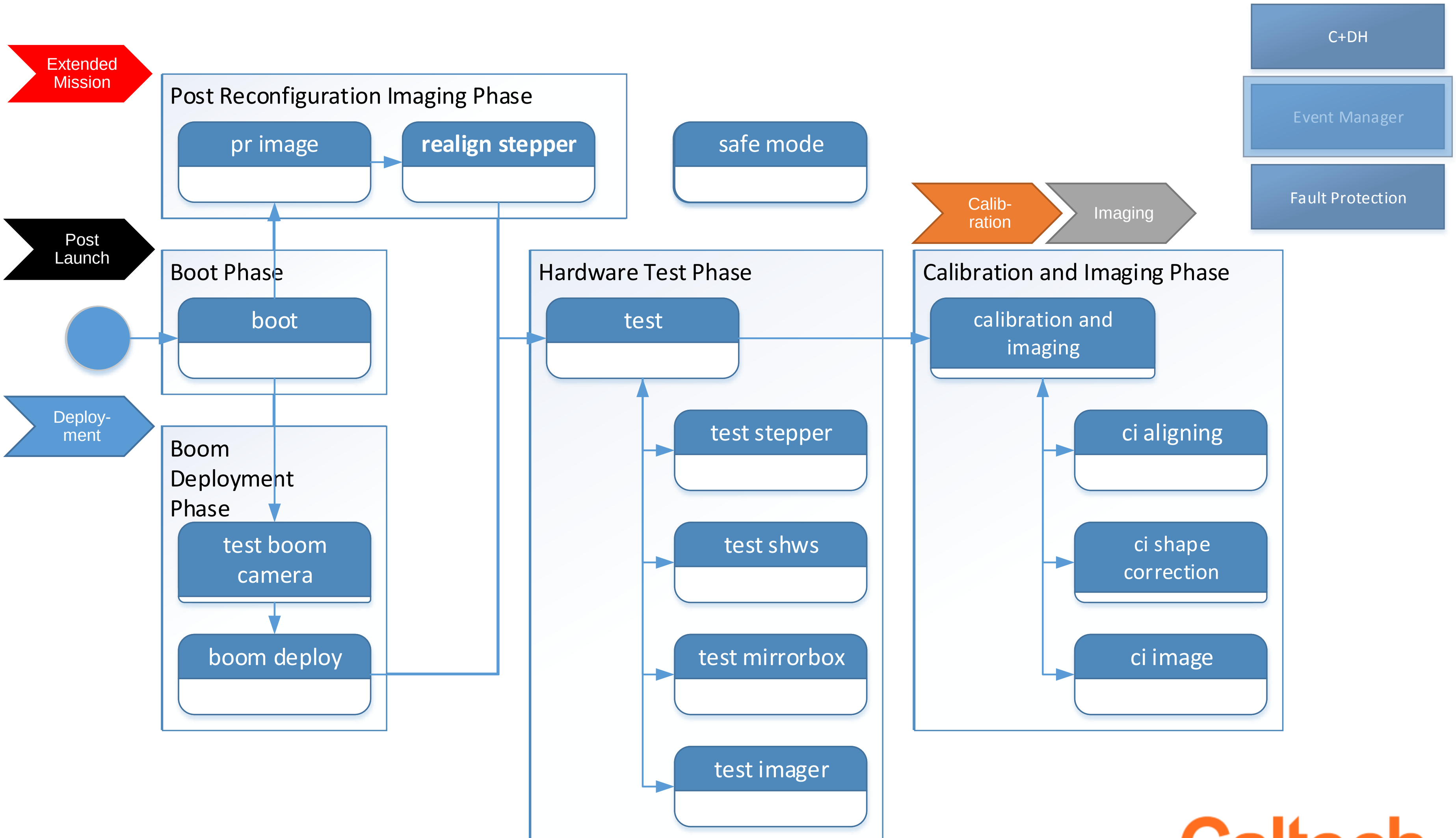
# Event Manager




- Implement State-Based operation
- Executes functions based on:
  – Telecommands
  – Mirror Telemetry
  – Satellite State
  – Software and Hardware Events

# Event Manager State Diagram

Objective
Design
Test



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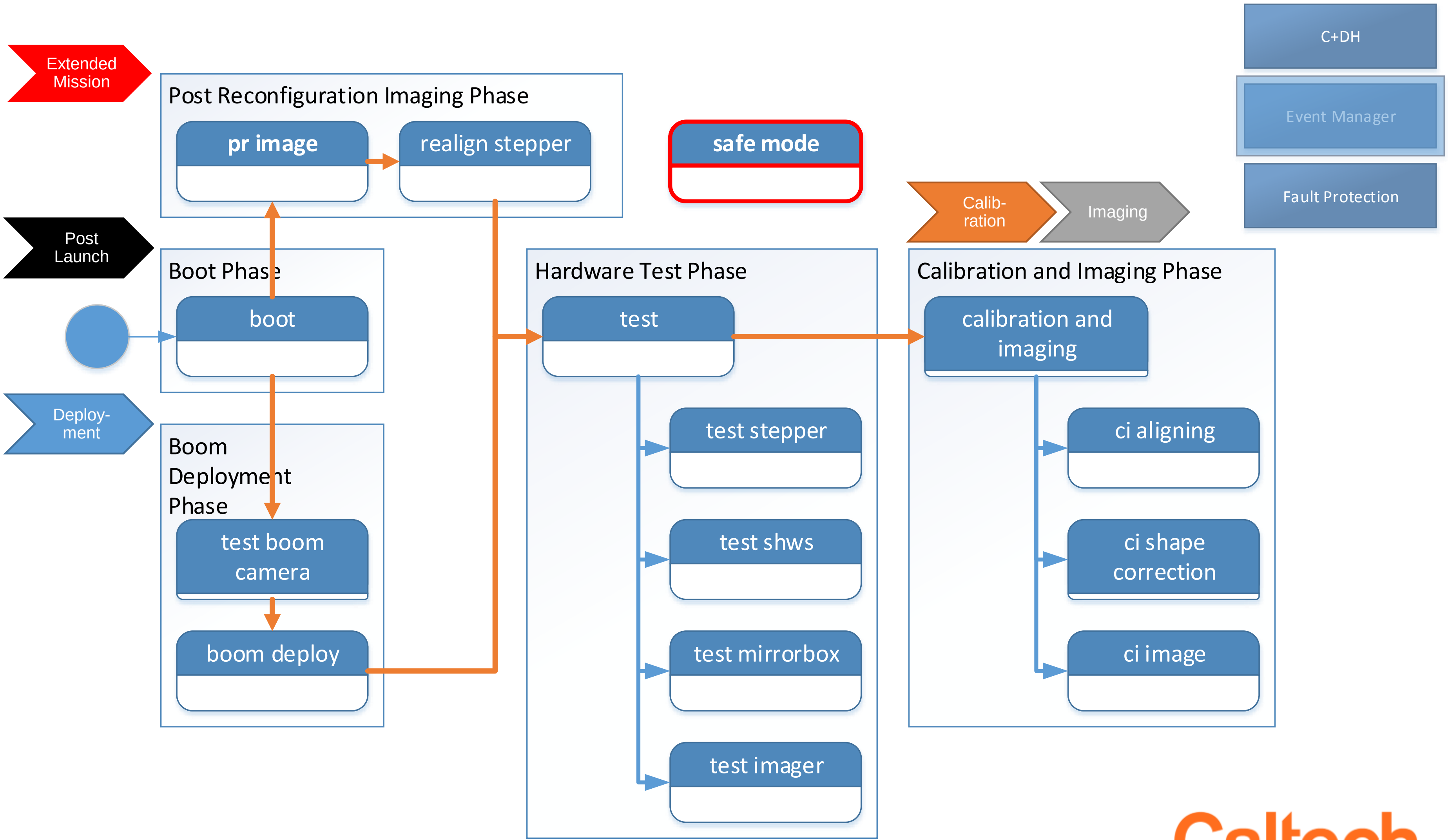
# Event Manager State Diagram

Objective
Design
Test



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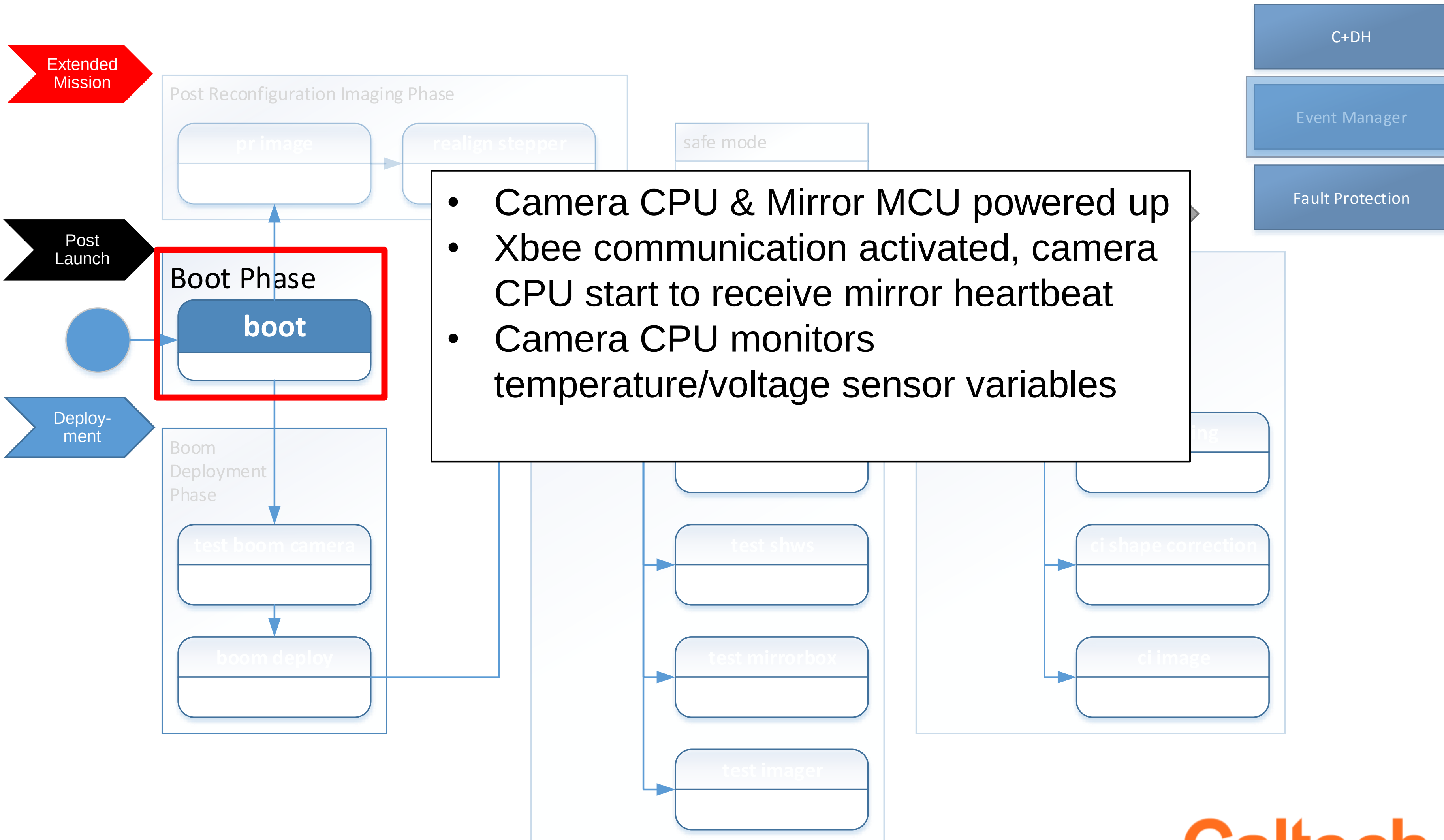
# Event Manager State Diagram

Objective
Design
Test




- Camera CPU & Mirror MCU powered up
- Xbee communication activated, camera CPU start to receive mirror heartbeat
- Camera CPU monitors temperature/voltage sensor variables



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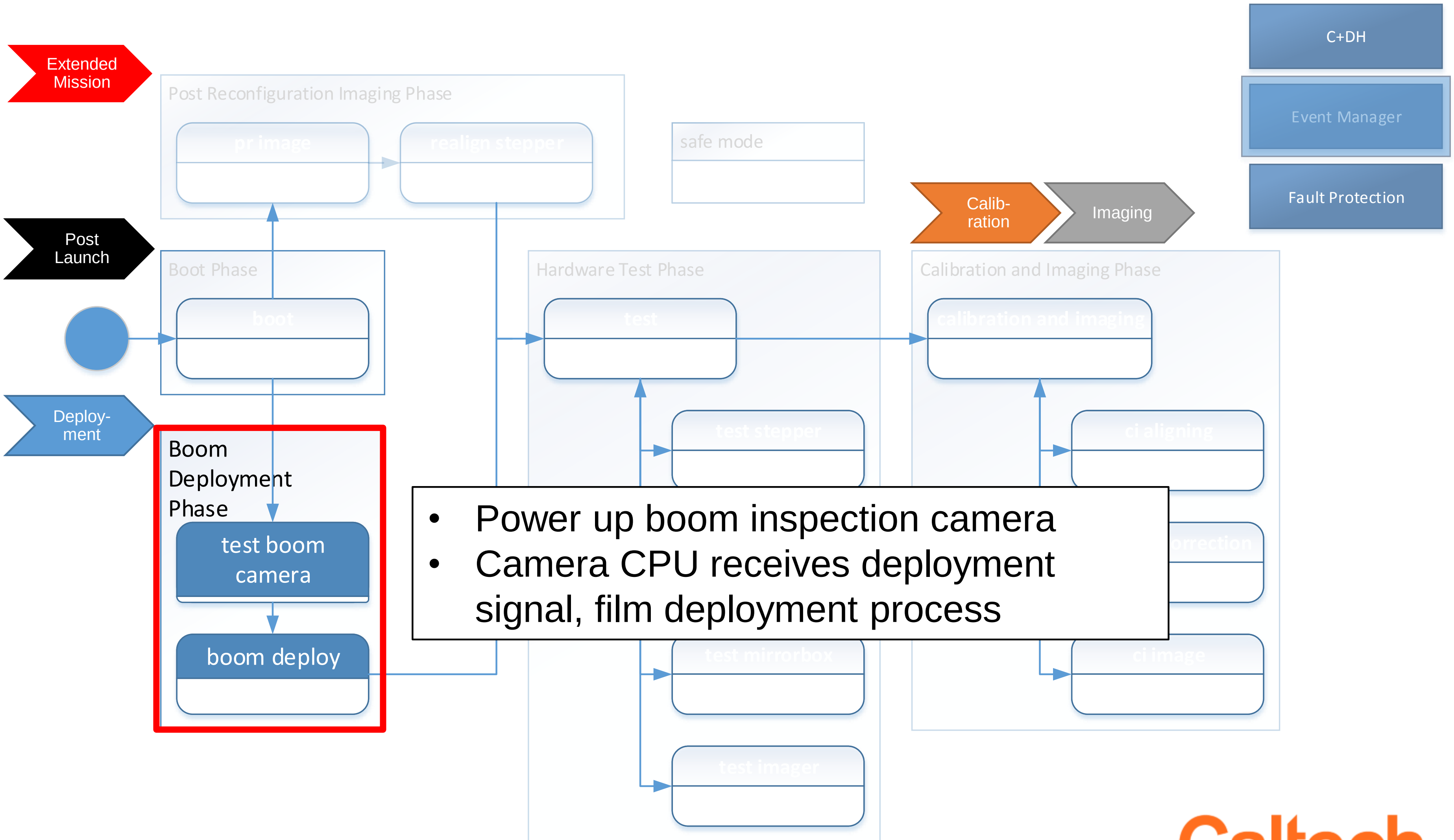
# Event Manager State Diagram



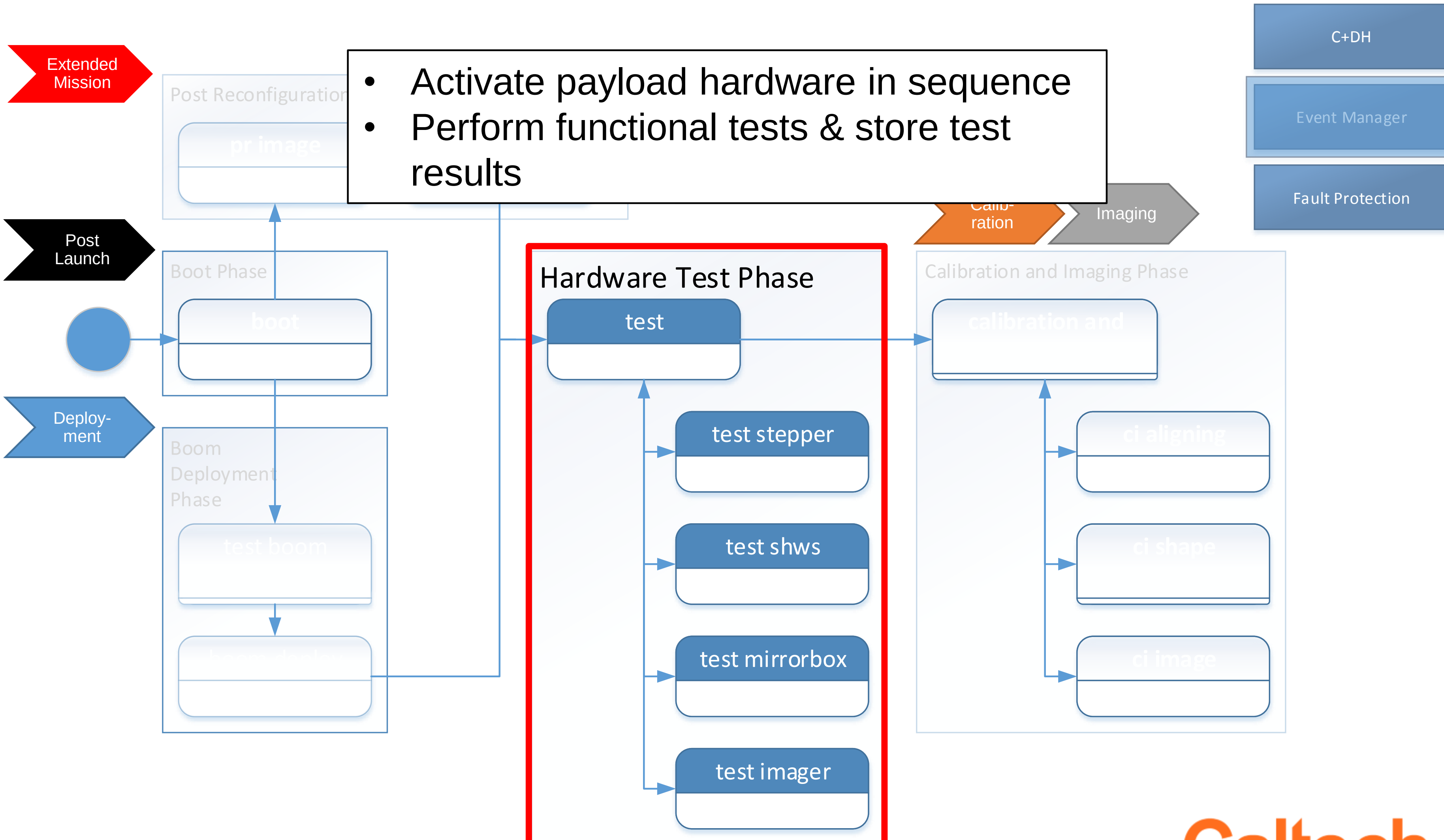



- Power up boom inspection camera
- Camera CPU receives deployment signal, film deployment process

# Event Manager State Diagram

Objective
Design
Test

- Activate payload hardware in sequence
- Perform functional tests & store test results



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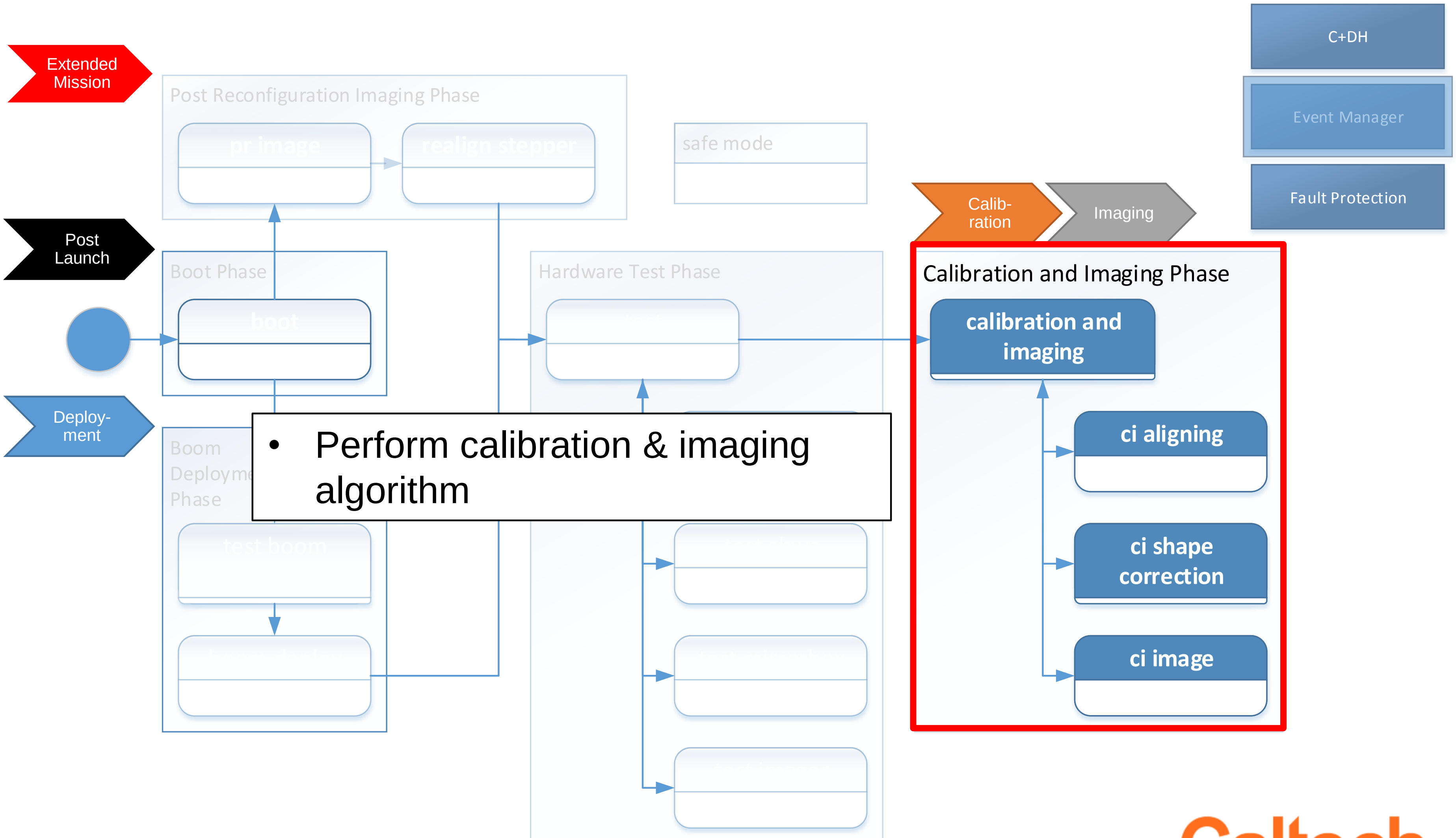
# Event Manager State Diagram

Objective
Design
Test




- Perform calibration & imaging algorithm



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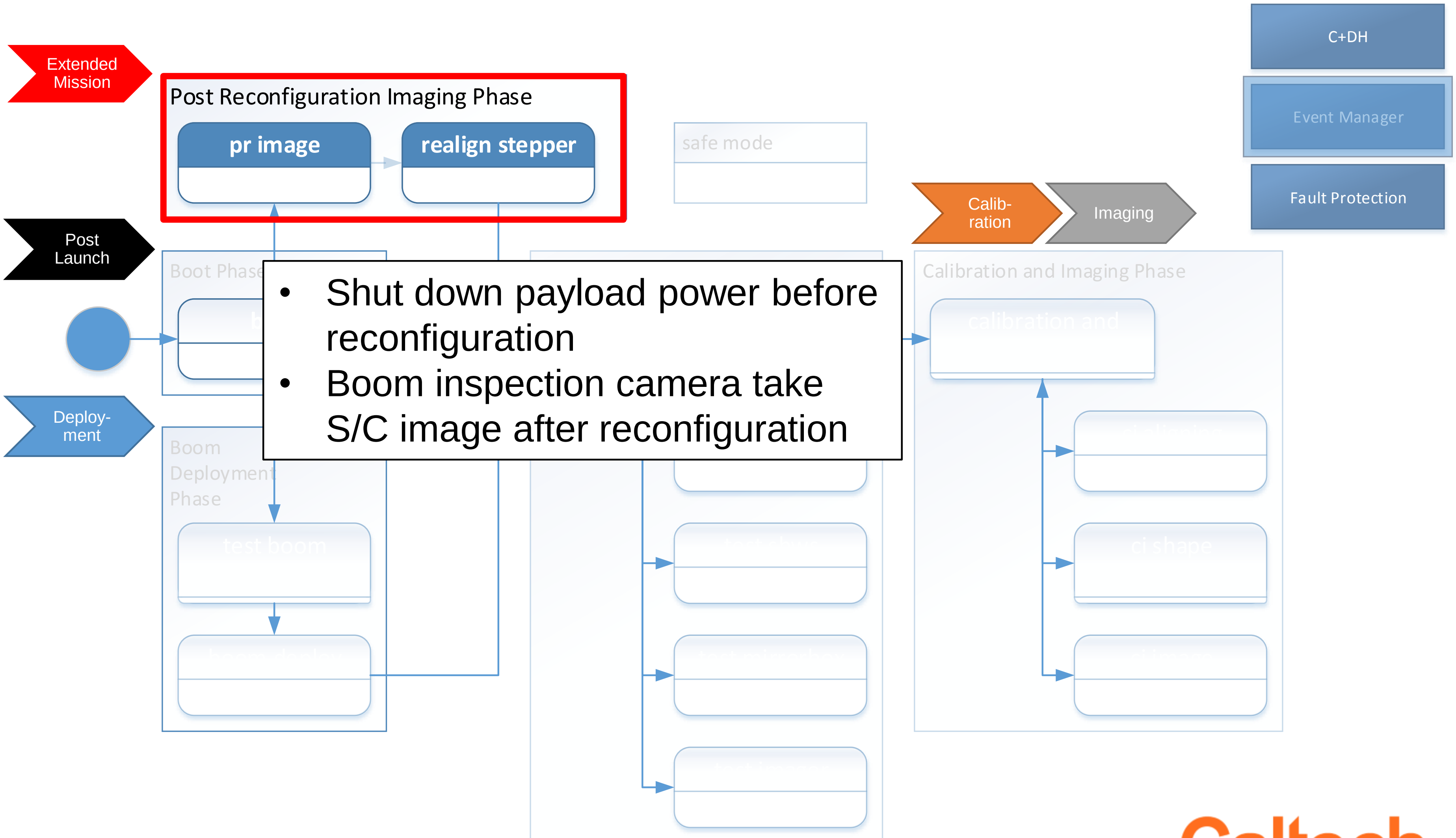
# Event Manager State Diagram

Objective
Design
Test




- Shut down payload power before reconfiguration
- Boom inspection camera take S/C image after reconfiguration



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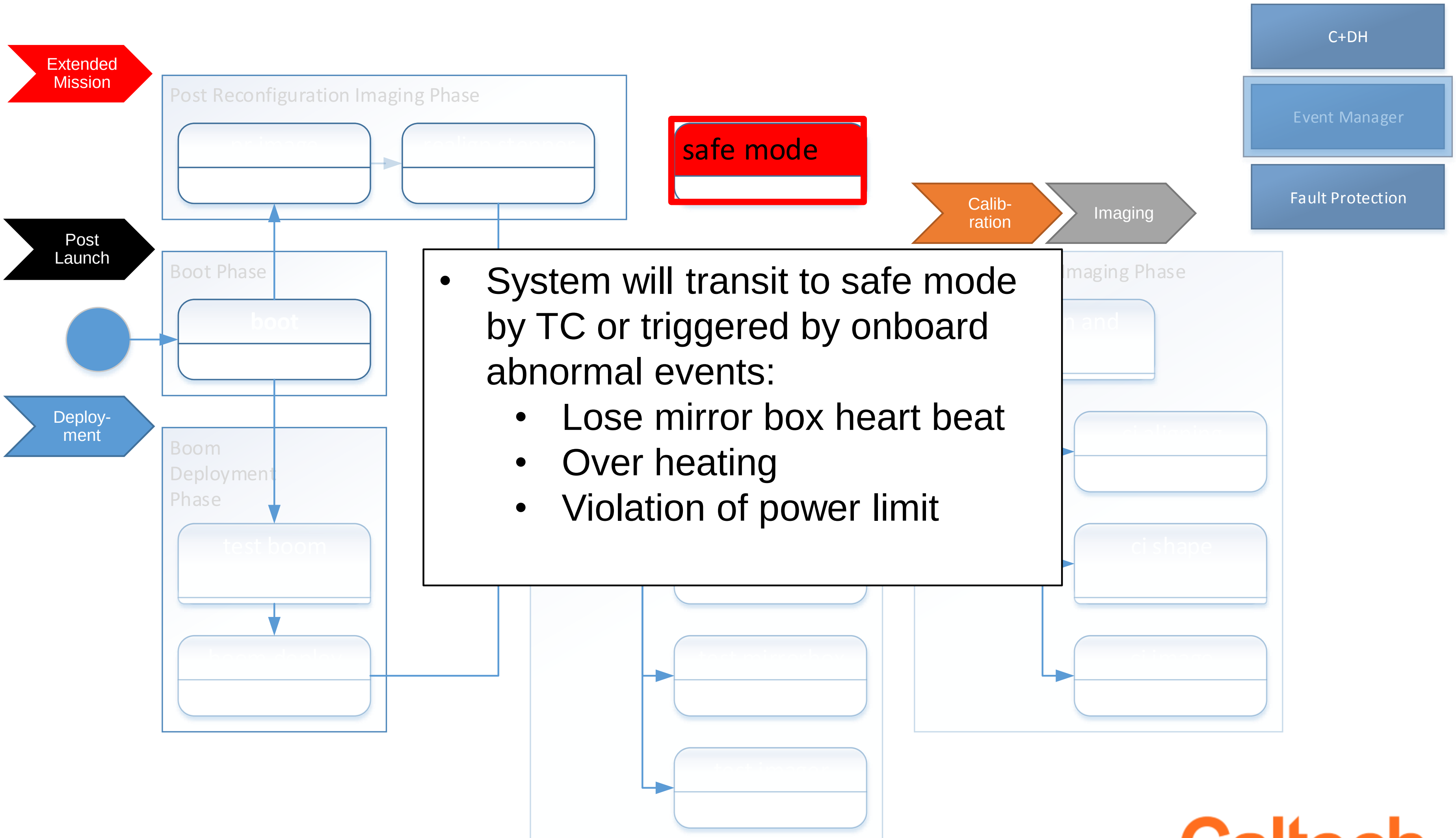
# Event Manager State Diagram

Objective
Design
Test




- System will transit to safe mode by TC or triggered by onboard abnormal events:
  - Lose mirror box heart beat
  - Over heating
  - Violation of power limit



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# Event Manager Auto Coder





## State List

| Group | State | State Name |
|---|---|---|
| *BEGIN READ* | | |
| Boot | Boot | Boot |
| BoomDeployment | BD_Test | Test |
| | BD_Idle | Idle |
| | BD_Deploy | Deploy |
| SystemTest | ST_Imager | Imager |
| | ST_SHWS | SHWS |
| | ST_Stepper | Stepper |
| | ST_Mirrorbox | Mirrorbox |
| | ST_Idle | Idle |
| RealignStepper | RealignStepper | Realign Stepper |
| CalibrationAndImaging | CI_BlindSearch | Blind Search |
| | CI_Centering | Centering |
| | CI_Pistoning | Pistoning |
| | CI_ShapeCorrectior | Shape Correction |

## Transition Table

| Legend | Description |
|---|---|
| COMMAND | User commands a change of state |
| FORCE_COMMAND | User commands a forced change of state |
| FAULT | The fault detection code recognized that an error has occurred |

**Transitions**

| Initial State | Action | Final State |
|---|---|---|
| *BEGIN READ* | | |
| Boot | COMMAND | BD_Test |
| Boot | COMMAND | PR_Test |
| | | |
| BD_Test | COMMAND | BD_Idle |
| | | |
| BD_Idle | COMMAND | BD_Test |
| BD_Idle | COMMAND | BD_Deploy |
| BD_Idle | COMMAND | ST_Imager |
| | | |
| BD_Deploy | COMMAND | BD_Idle |
| | | |
| PR_Test | COMMAND | PR_Idle |

## Power State Table

| | Variable | Name | State | | | |
|---|---|---|---|---|---|---|
| | | | Boot | BD_Test | BD_Idle | BD_Deploy |
| **Camera Box** | **motor_controller** | Motor Controller | OFF | OFF | OFF | OFF |
| | | Limit Switches | OFF | OFF | OFF | OFF |
| | **shws_1** | SHWS 1 | OFF | OFF | OFF | OFF |
| | **shws_2** | SHWS 2 | OFF | OFF | OFF | OFF |
| | **camera_telescope** | Imager Camera | OFF | OFF | OFF | OFF |
| | **camera_inspection** | Boom Insp. Cam. | OFF | ON | ON | ON |
| | **boom_wire_cutter** | Boom wire cutter | OFF | OFF | OFF | ON |
| **Reference Mirror Box** | | Voltage Divider | OFF | OFF | OFF | OFF |
| | | HV Board | OFF | OFF | OFF | OFF |
| | | Electrodes | OFF | OFF | OFF | OFF |
| **Deformable Mirror Box** | | Voltage Divider | OFF | OFF | OFF | OFF |
| | | Limit Switches | OFF | OFF | OFF | OFF |
| | | HV Board | OFF | OFF | OFF | OFF |
| | | Pico Motors | OFF | OFF | OFF | OFF |
| | | Electrodes | OFF | OFF | OFF | OFF |

## Python Autocoder

## C++ Headers

```
// Group: Boot
// State: Boot
// Description: Initial state of the system at bootup
class StateBoot : public State {
public:
  StateBoot();
  State* RequestState(uint8_t requested_state);
  State* RunState();
  char const* Description();
  uint8_t GetState();
};

// Group: BoomDeployment
// State: Test
// Description:
class StateBD_Test : public State {
public:
  StateBD_Test();
  State* RequestState(uint8_t requested_state);
  State* RunState();
  char const* Description();
  uint8_t GetState();
};
```

## C++ Code

```
#include "state.h"

// Group: Boot
// State: Boot
// Description: Initial state of the system at bootup
StateBoot::StateBoot() {

}

State* StateBoot::RequestState(uint8_t requested_state) {
  State* return_state = this;

  if(requested_state == STATE_BD_TEST) {
    delete this;
    return_state = new StateBD_Test;
  }
  else  if(requested_state == STATE_PR_TEST) {
    delete this;
    return_state = new StatePR_Test;
  }

  return return_state;
}
```



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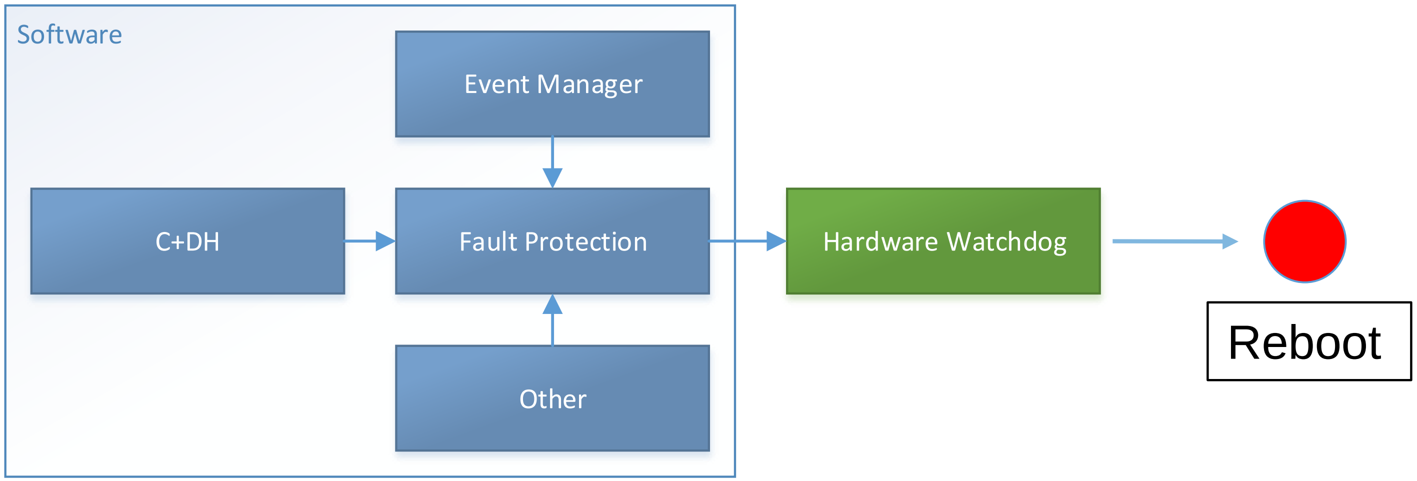
# Fault Protection



- Acts as software watchdog



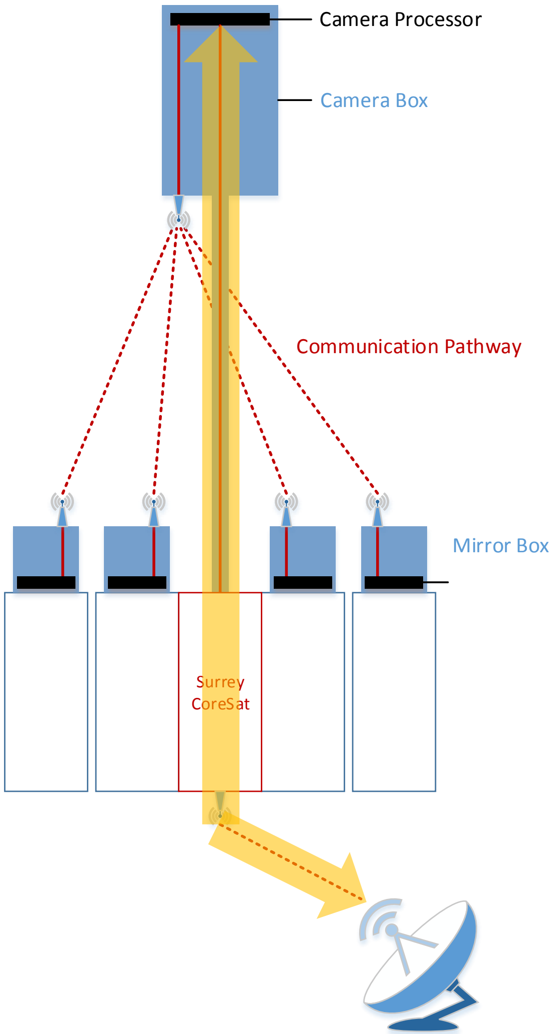

- Monitors engineering data
  - Temperature, Voltage, and Current

# Mirror OBSW Architecture



- Real-time Scheduler
  - Uses timer overflow interrupt ticks
  - Runs processes based on:
    1. Countdown ticker
    2. Priority
  - Uses interrupts for receiving data

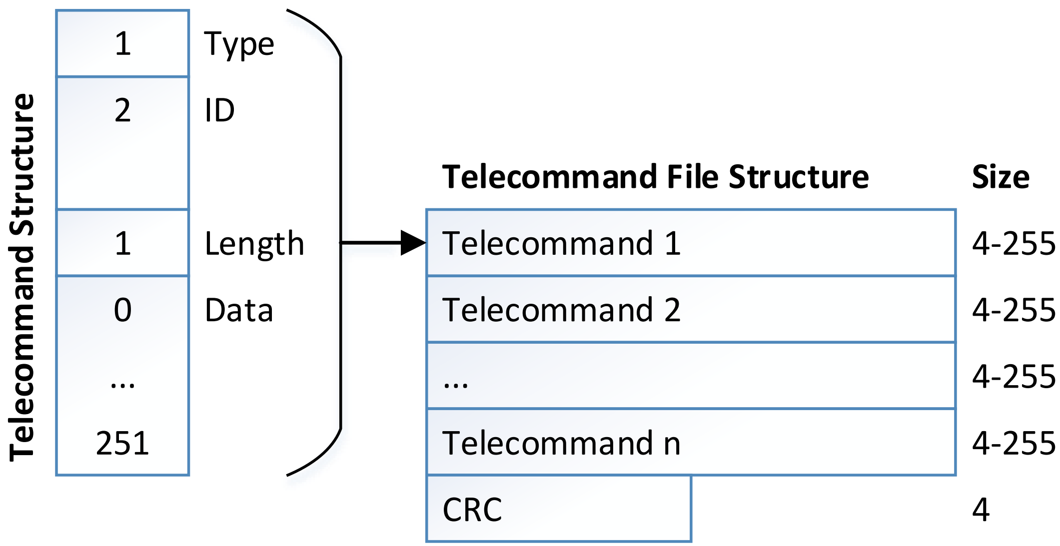
# Communication




| | From | To |
|---|---|---|
| **Telecommands** | Caltech | Camera OBSW |
| **Telemetry** | Camera OBSW | Caltech |
| | | |
| **Mirror Commands** | Camera OBSW | Mirror OBSW |
| **Mirror Telemetry** | Mirror OBSW | Camera OBSW |

# Communication - Telecommands

## Caltech to Camera OBSW




- Telecommand type
  - Regular
  - Special
- Telecommand identifier

4 kB = 16-1023 telecommands / message



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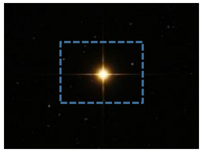
# Communication - Science Data Downlink

1. Image taken on AAReST
2. Thumbnails selected for downlink
3. Area of interest of image transmitted to AAReST
4. Image area cropped and downlinked in full resolution

1
Full image on AAReST

2
Image thumbnail

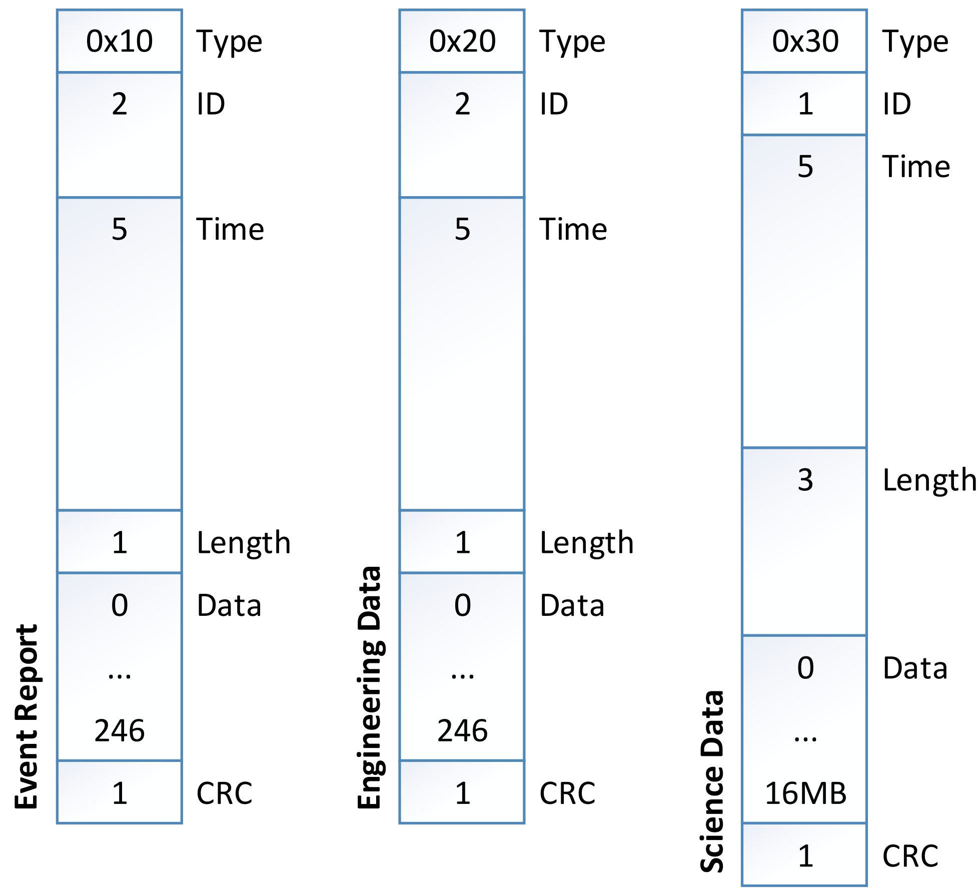
3
Area selected



4
Full resolution image area

# Communication - Telemetry

## Camera OBSW to Caltech




- Telemetry type
- Telemetry identifier
- 1ms time accuracy
- Science data payloads up to 16MB
- 8 bit CRC



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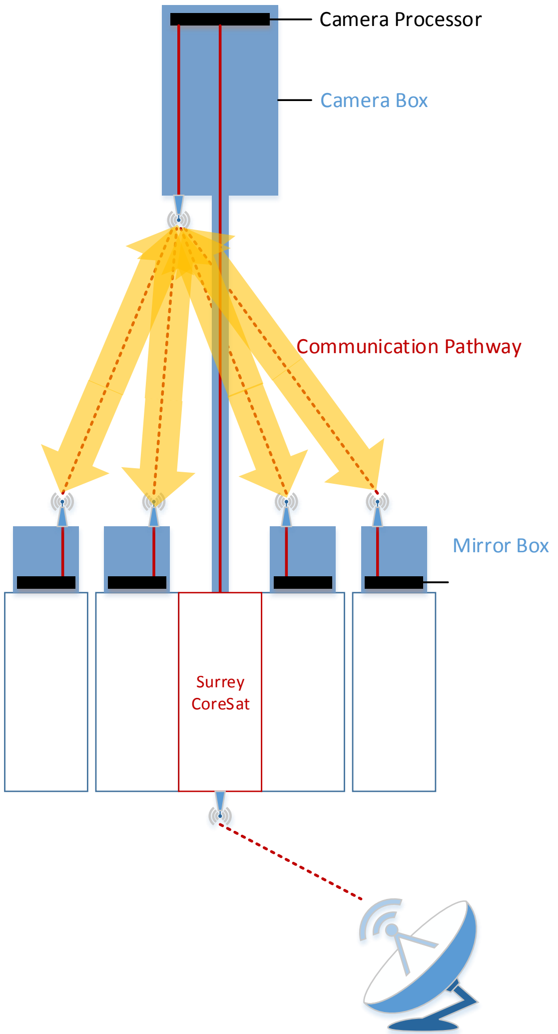
# Communication




| | From | To |
|---|---|---|
| **Telecommands** | Caltech | Camera OBSW |
| **Telemetry** | Camera OBSW | Caltech |
| | | |
| **Mirror Commands** | Camera OBSW | Mirror OBSW |
| **Mirror Telemetry** | Mirror OBSW | Camera OBSW |



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Objective
Design
Test

# Communication - Mirror Commands and Telemetry

- Commands and Telemetry:
  - State Commands and Telemetry
  - Mirror Electrode Settings
  - Piezo Actuators
- 0.1% Duty Cycle

**Mirror Electrode Settings**

| | |
|---|---|
| 41 | Electrodes |
| 2 | Byte precision |
| 7 | Byte overhead |
| 89 | Byte total |
| 9.3 | ms Transmission Time |

**Piezo Actuators**

| | |
|---|---|
| 3 | Actuators |
| 2 | Byte precision |
| 7 | Byte overhead |
| 13 | Byte total |
| 1.4 | ms Transmission Time |

| | |
|---|---|
| 10 | second transmission period |
| 9600 | baud |
| 0.1% | duty cycle |



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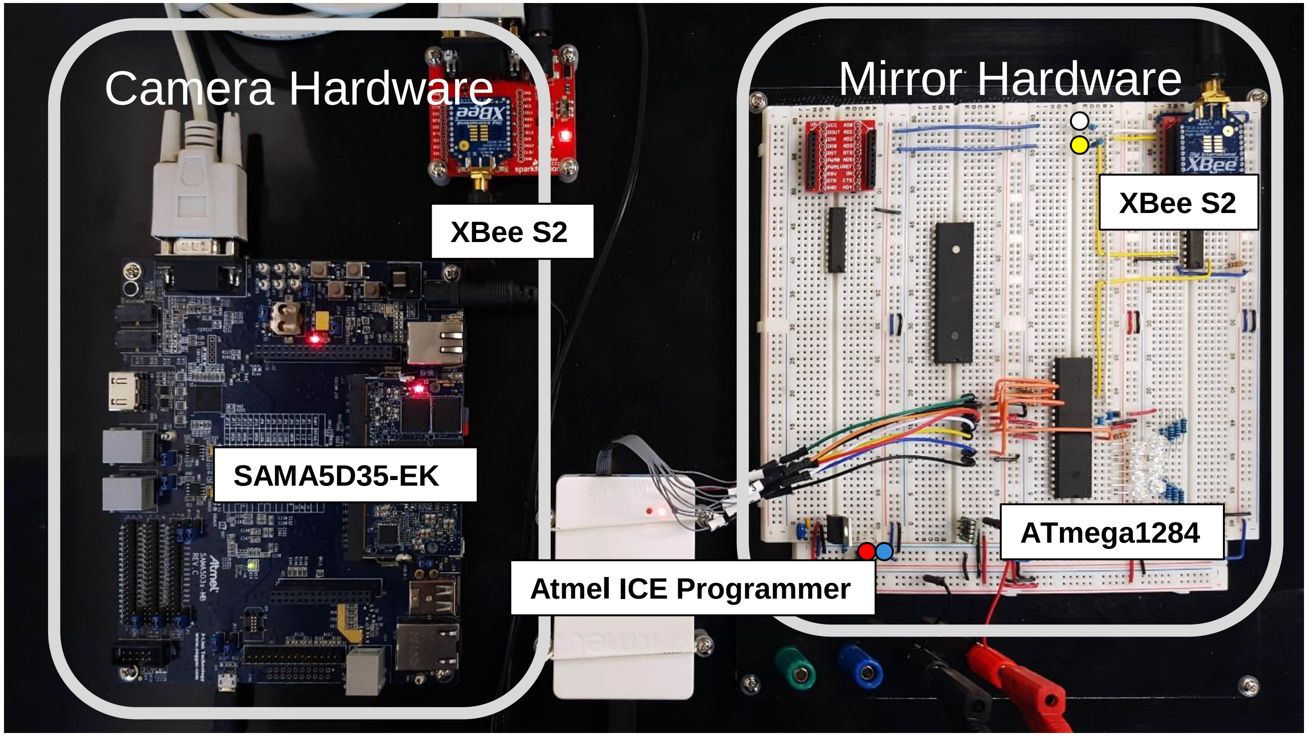
# OBSW Test

- Tests and test success criteria are formulated based on the Software Requirements Specification
- All tests are performed on flight hardware



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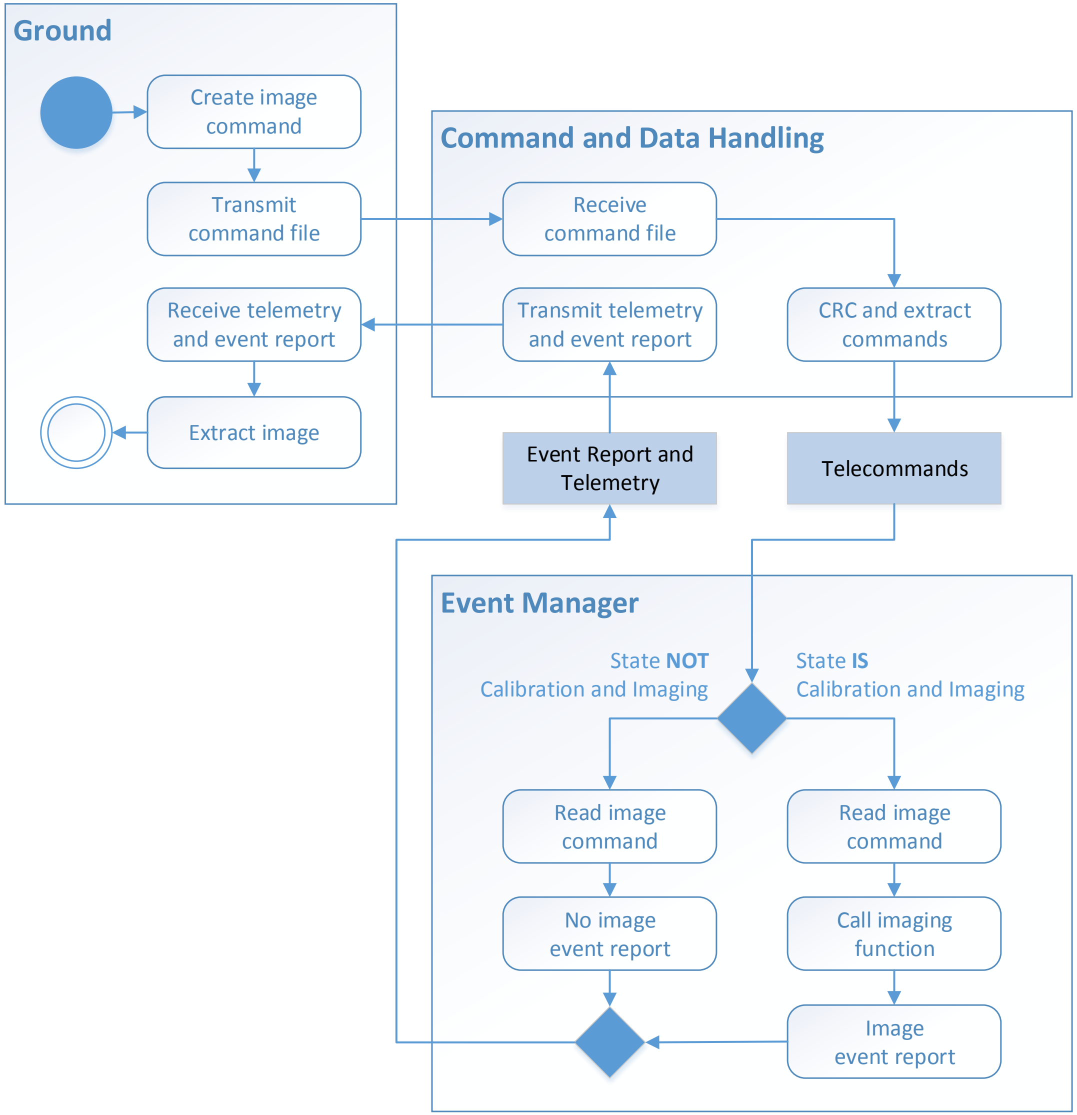
# Fault Injection

- Simulates hardware failure
  - Infinite loops
  - Memory corruption
  - Temperature out of range
  - Power levels out of range
  - Unexpected reboots

- Activated using special telecommands
- Used in both Camera and Mirror OBSW

# Image Acquisition



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# OBSW Test Sum-up

- OBSW passed all Use Case tests

| | Test Name | Test Description |
|---|---|---|
| State Operation | Change State | Request change of state |
| | Force State | Force change of state |
| Fault Detection and Recovery | Fault Injection | Manually disturb onboard process, force S/C into safe mode |
| | Safe mode Recovery | Recover from safe mode to designated state |
| Communi-cation | Retrieve Engineering/Science Data | Download stored onboard data by request |
| | Camera CPU – Mirror MCU Communication | Exchange TC/TM through XBee |
| Payload Operation | Image Acquisition | Retrieve stored image from telescope |

# Future Work

- Memory error detection & correction
  - Use of Hamming encoder
- Integration with payload control software
- Payload hardware in the loop test