Presentation Agenda

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

AAReST Telescope Overview

Kathryn Jackson

Caltech

Outline

- Review of Optomechanical Design
- Telescope Requirements
  - Field of View
  - Encircled Energy
  - Throughput/SNR
- Optical Systems status
  - RMs, DMs, Camera Lens Assembly
  - Alignment and Integration
- Overview of Active Element Control
  - Rigid Body Actuation
  - DM actuator control and measurement with SHWFS

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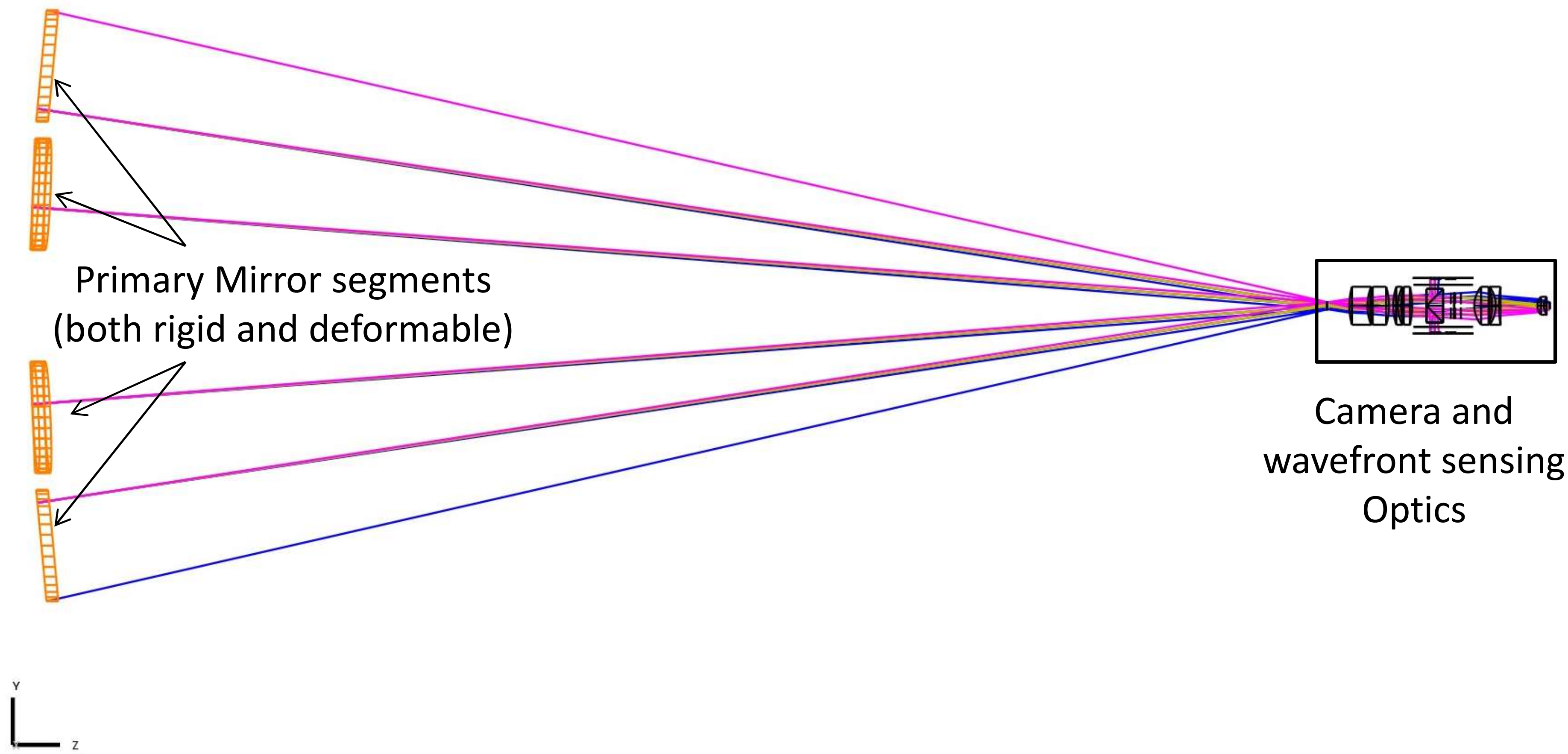
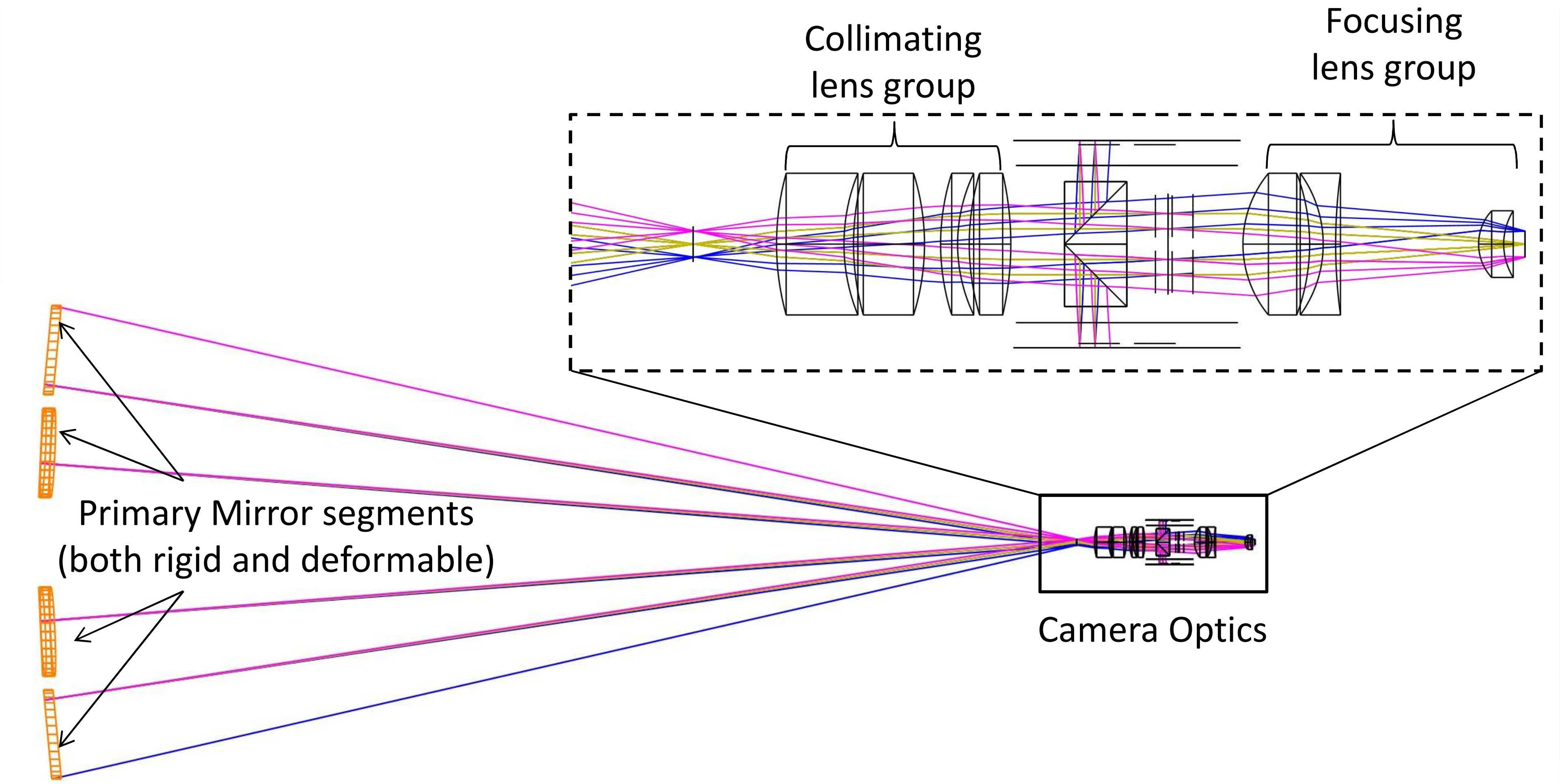
Optical System Overview



Caltech

Optical System Overview



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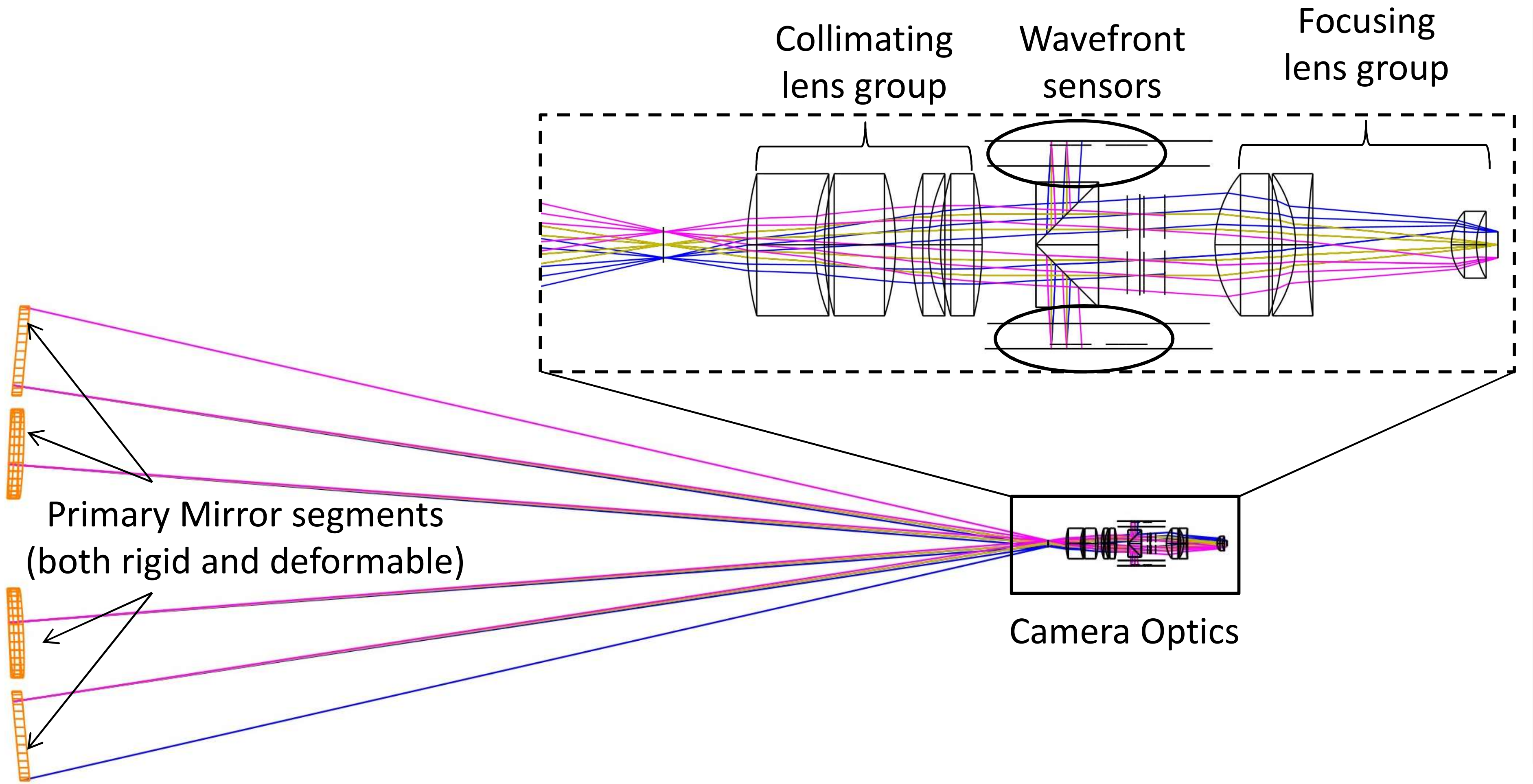
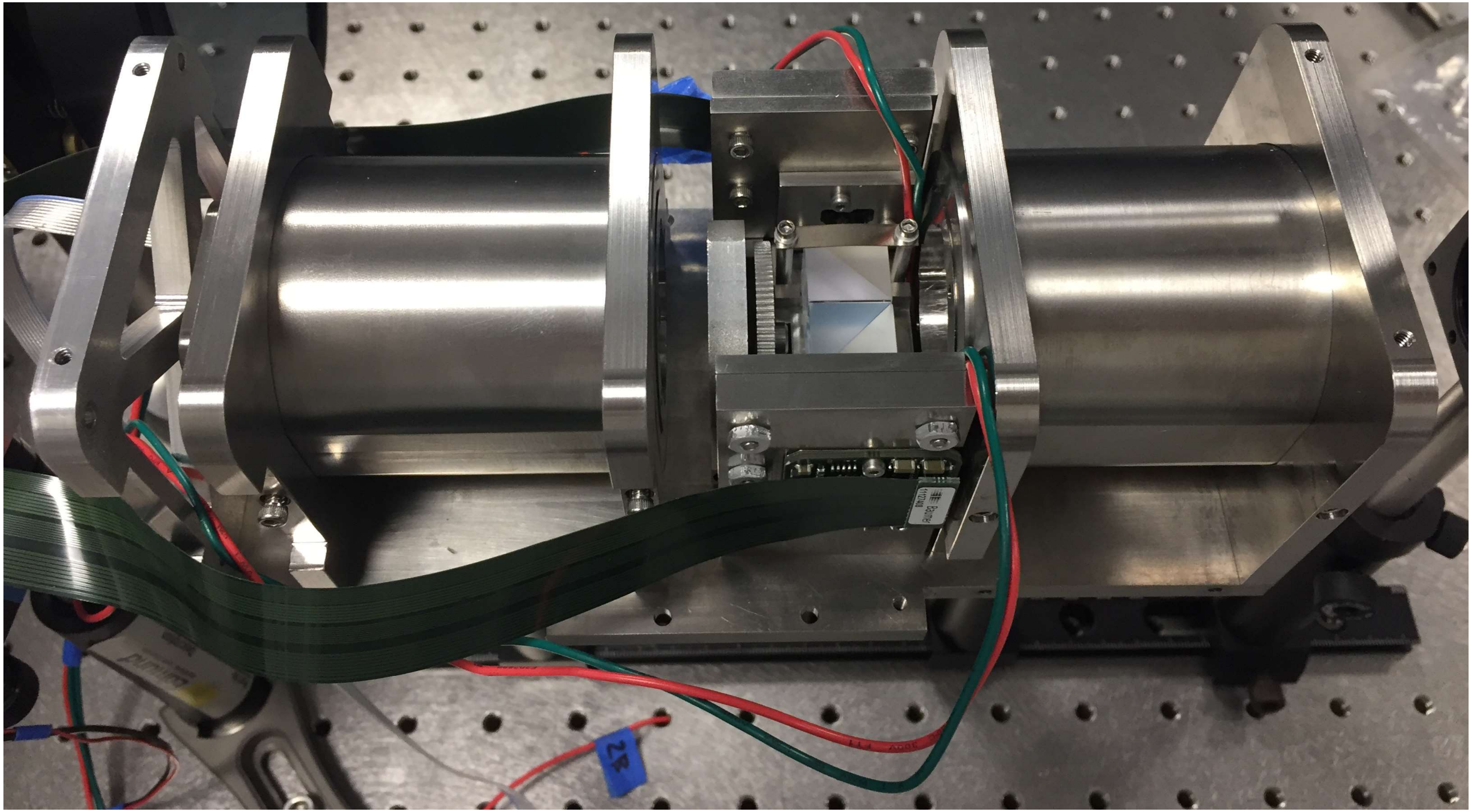
Optical System Overview



Camera



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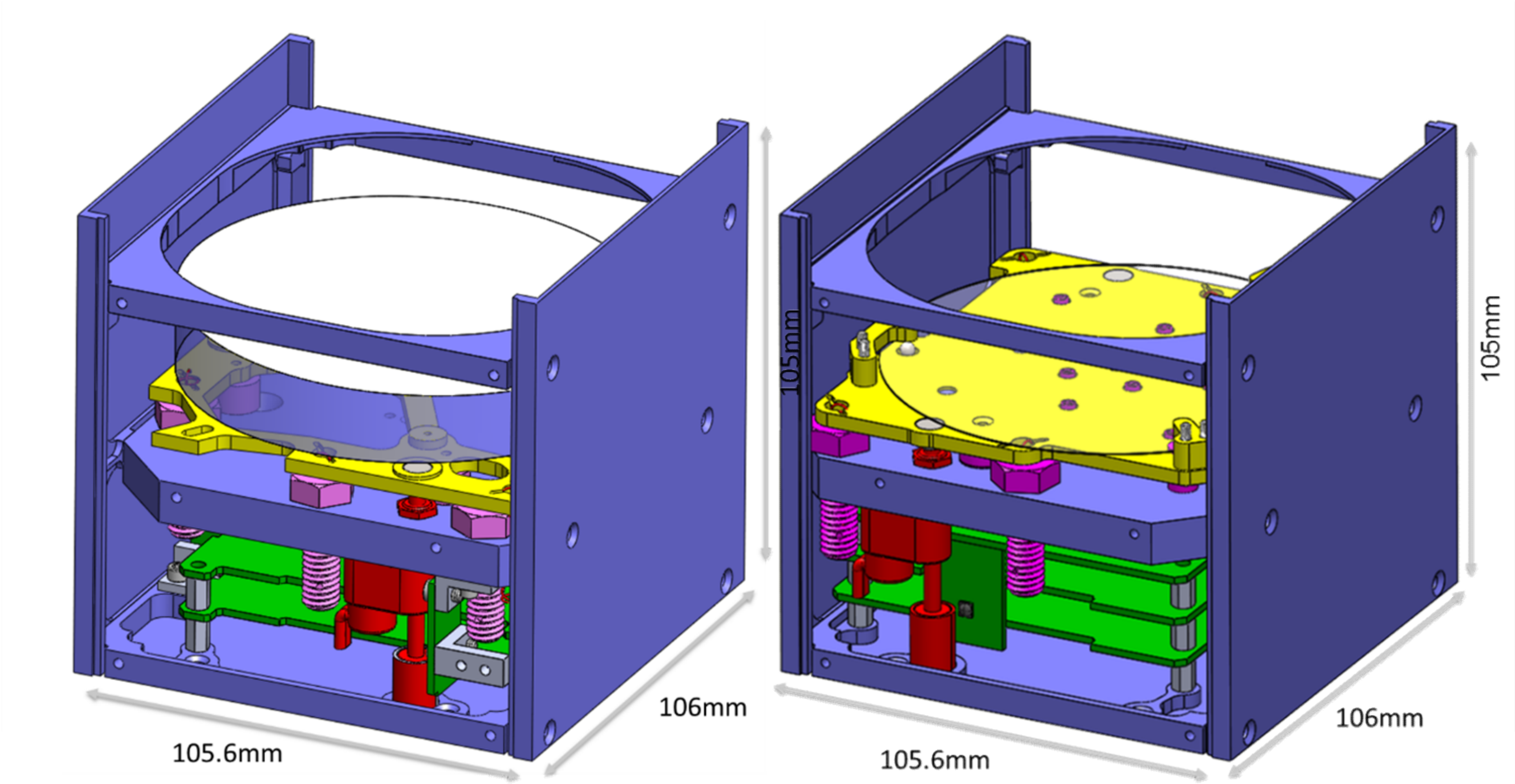
Mirror Boxes



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Baseline Requirements

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

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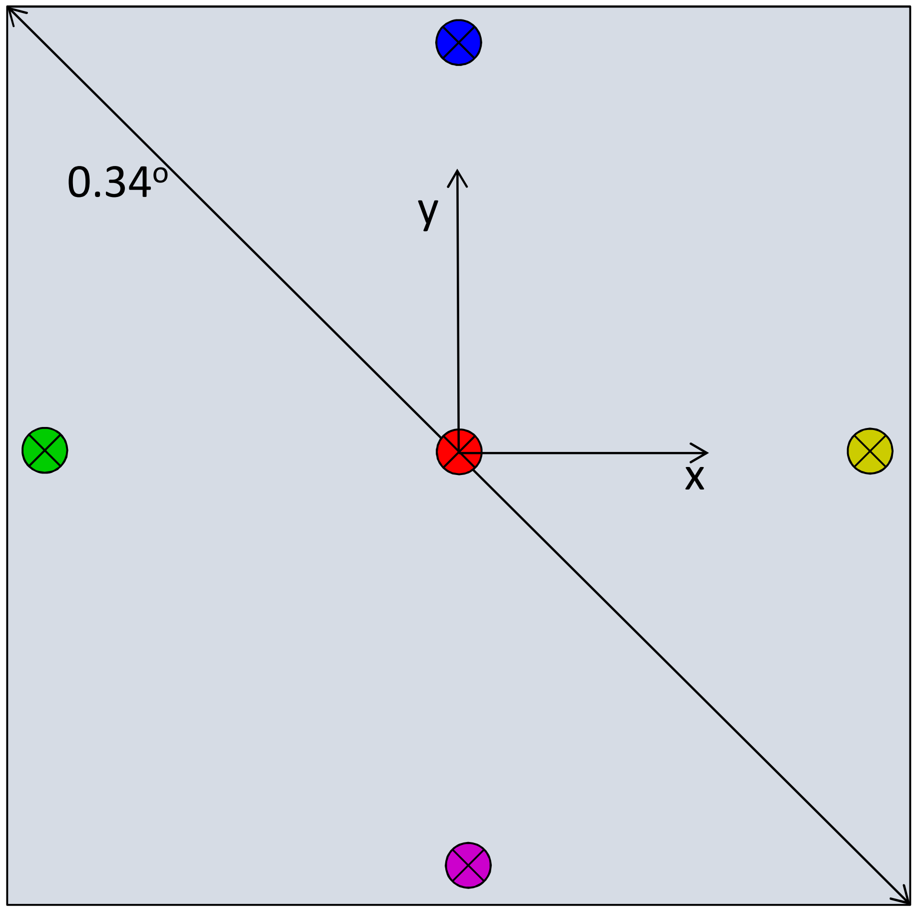
Requirement: Field of View

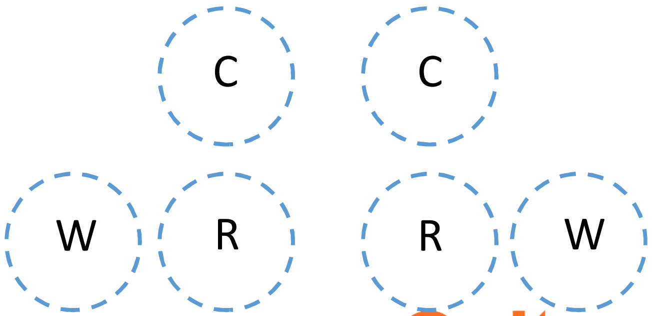


Detector

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

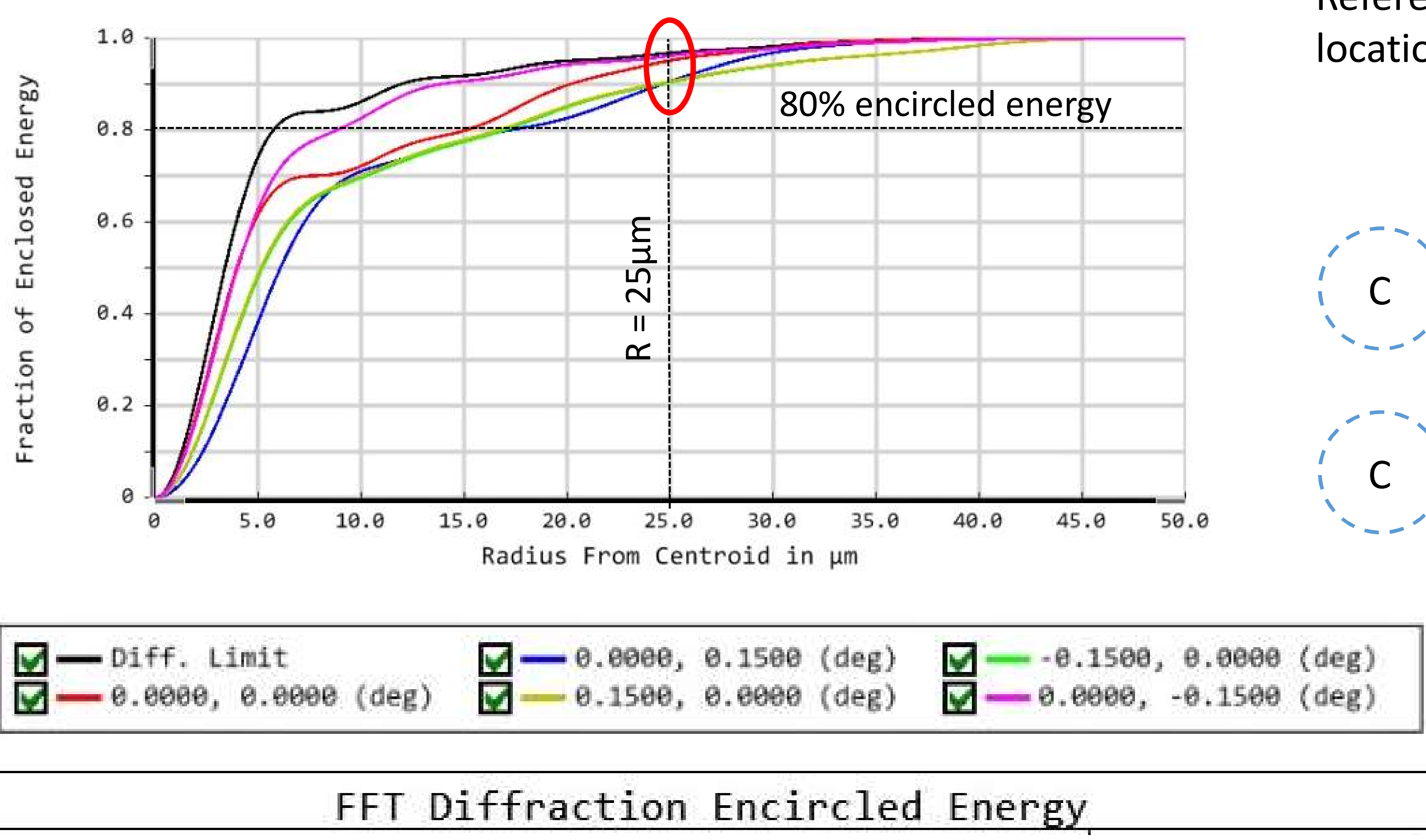
Simulations were done for individual mirror segments at each of three segment locations:

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

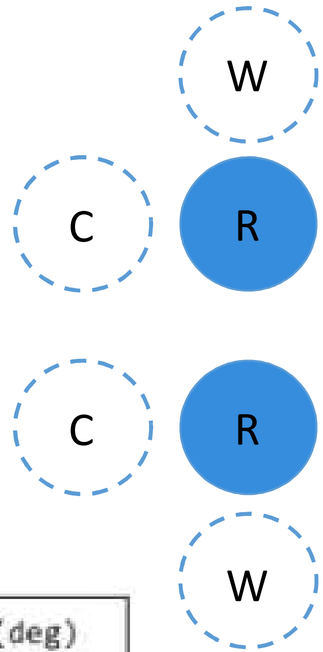


Requirement: PSF

80% encircled energy within 50µm diameter for each segment over entire FoV

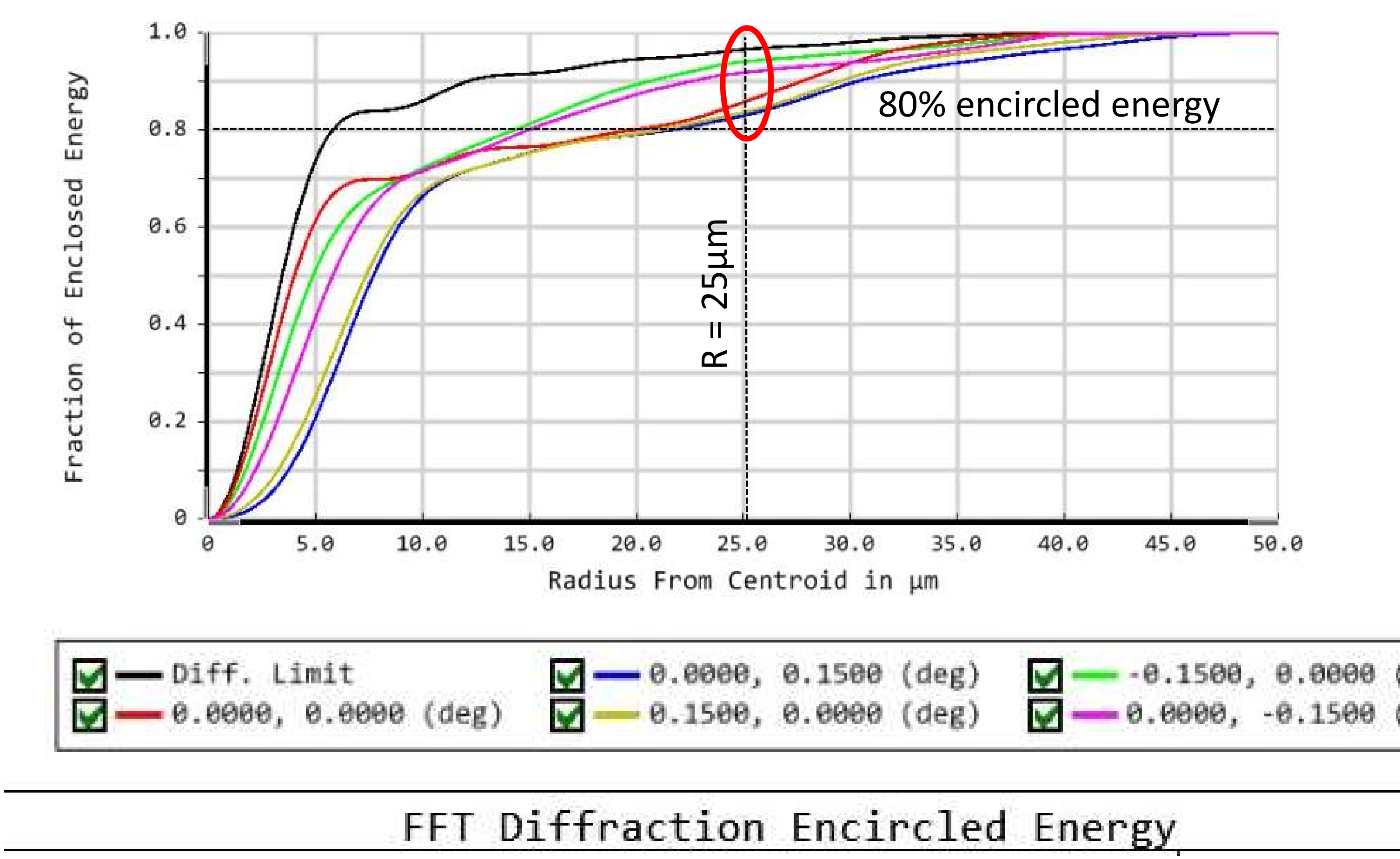


Reference Mirror location:

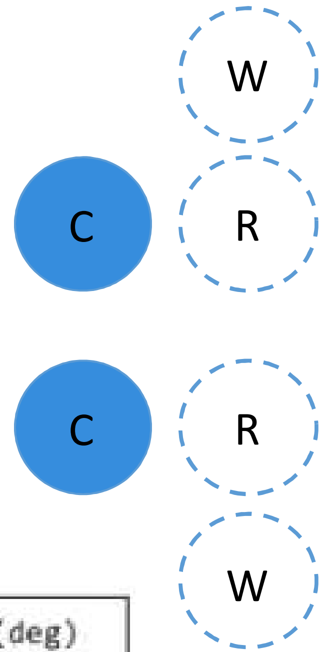


Requirement: PSF

80% encircled energy within 50μm diameter for each segment over entire FoV

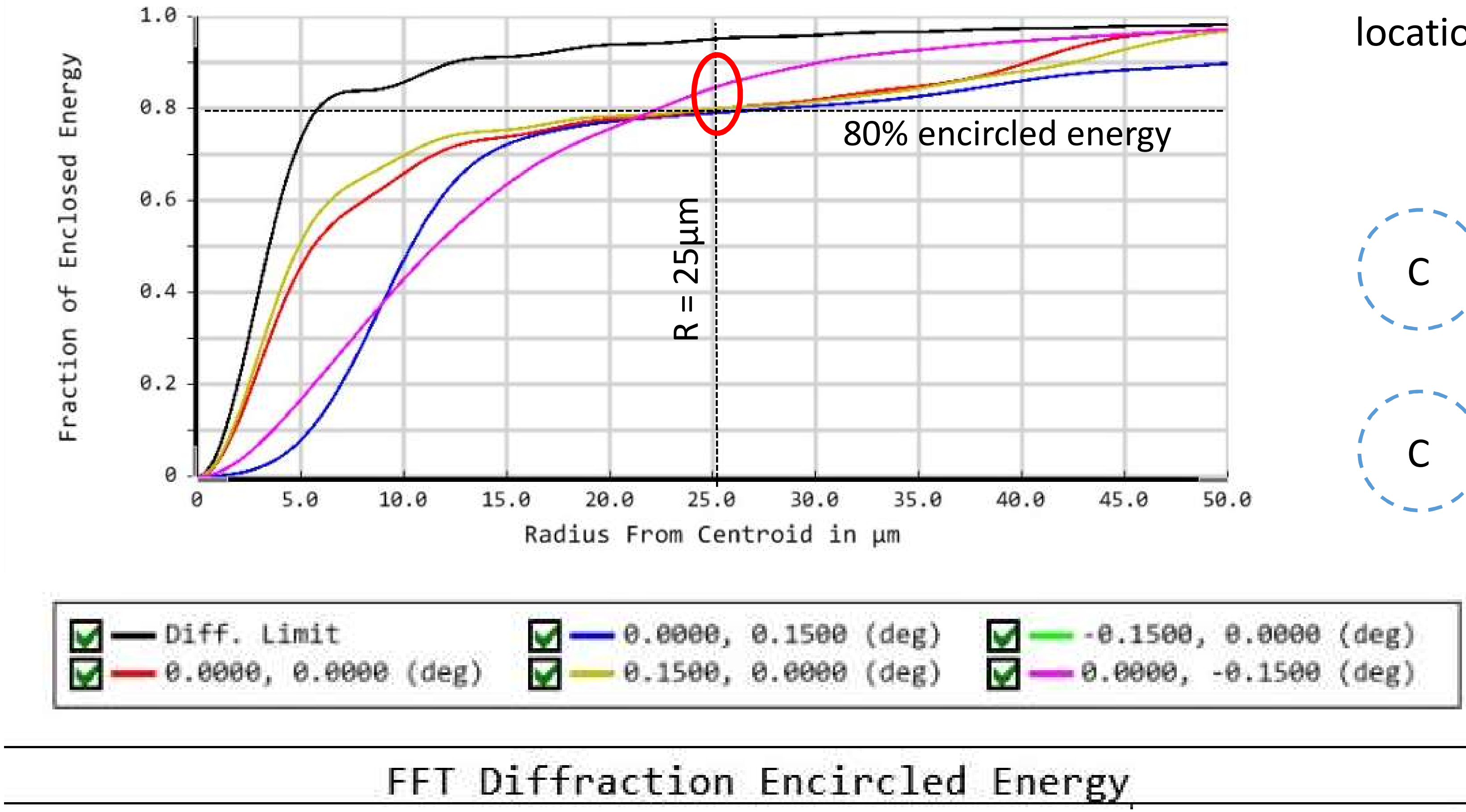


Compact/Narrow Mirror location:

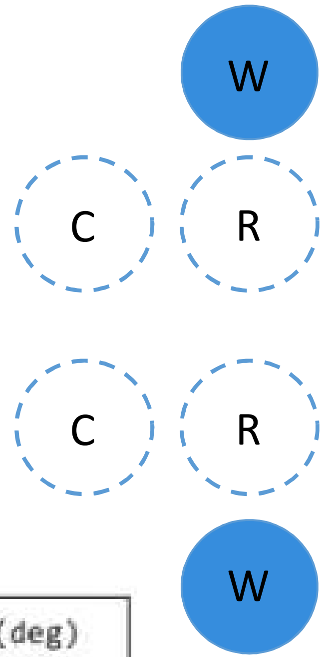


Requirement: PSF

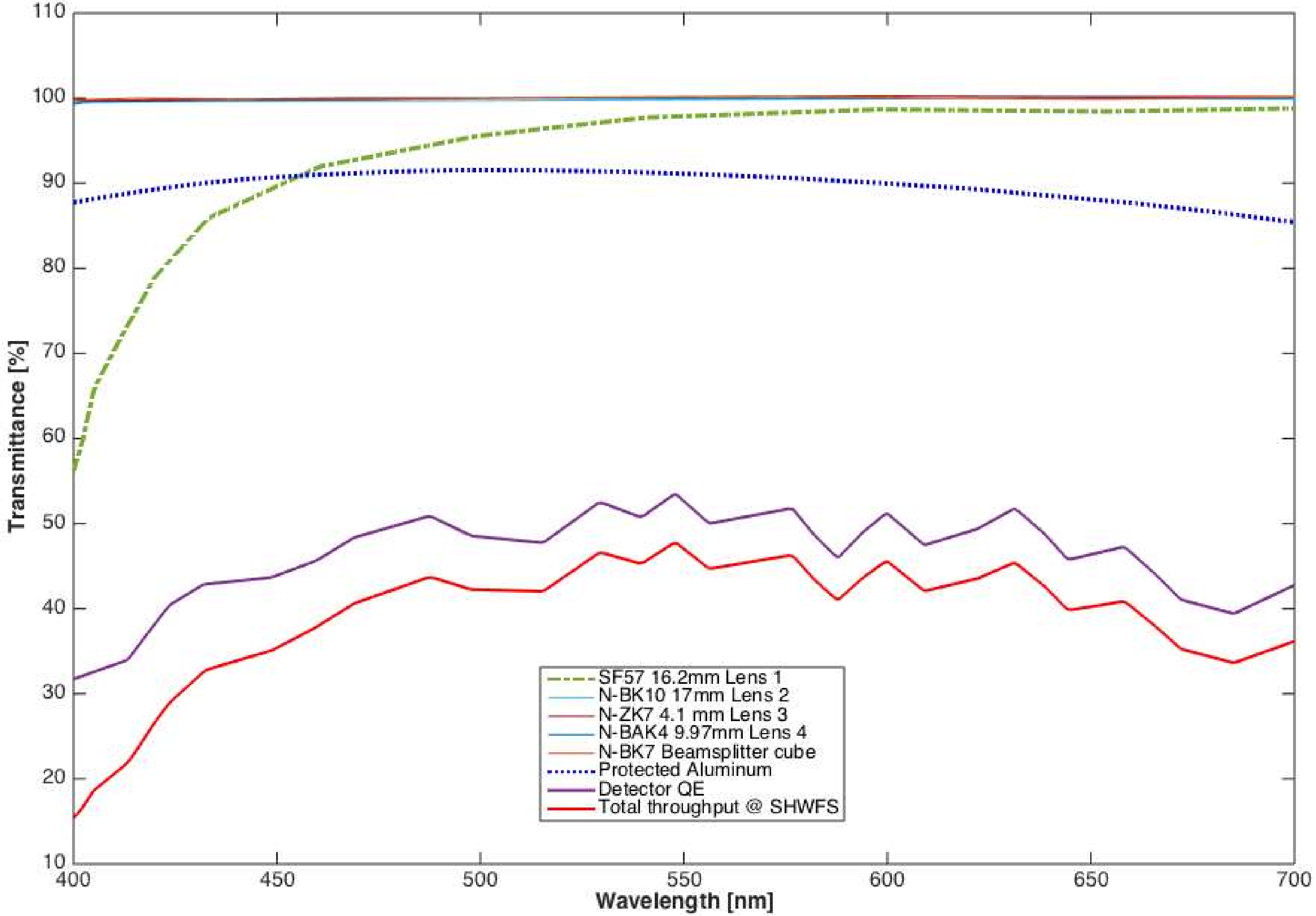
80% encircled energy within 50μm for each segment over entire FoV



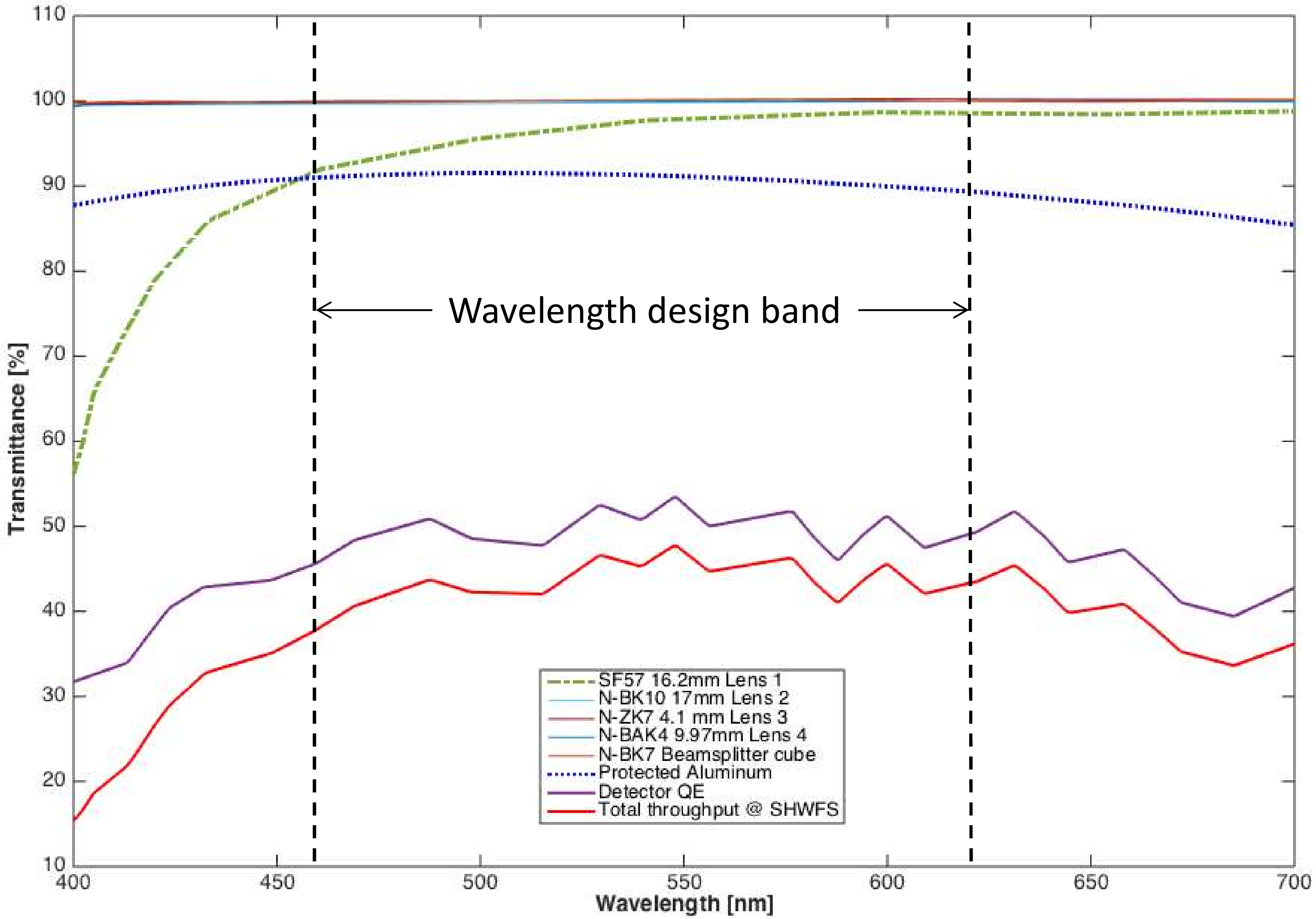
Wide Mirror location:



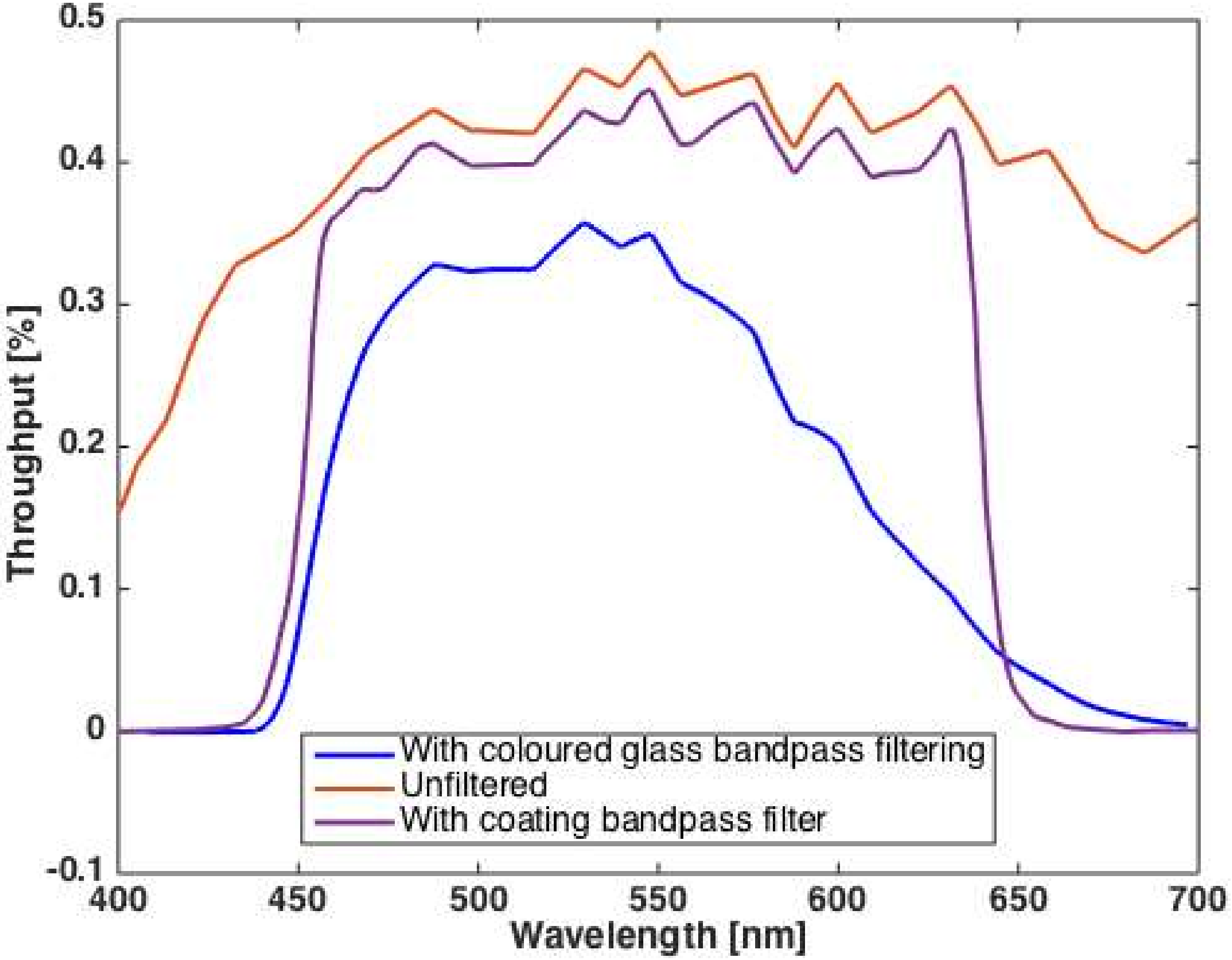
Requirement: Throughput



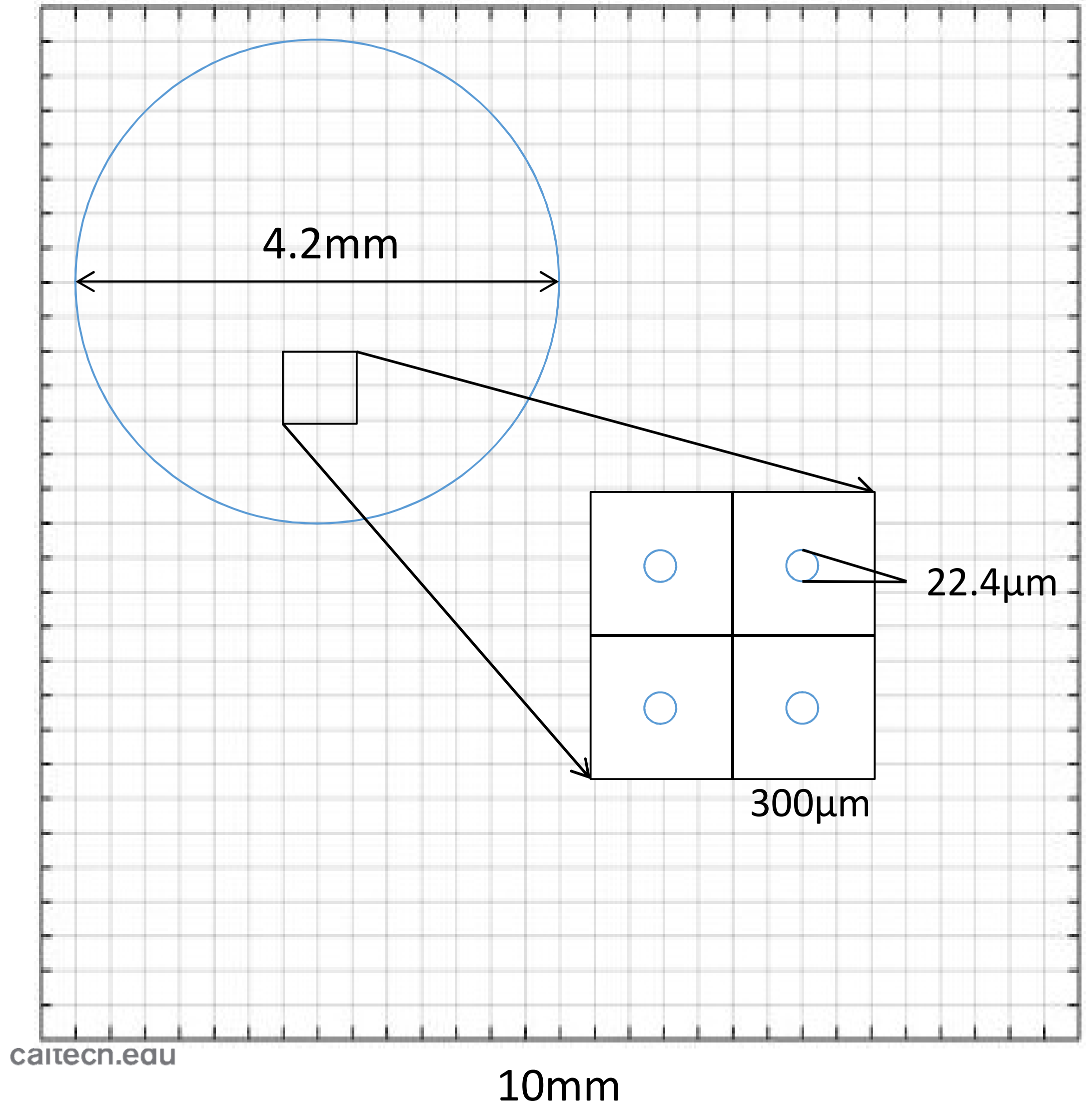
Requirement: Throughput



Bandpass Filter



WFS Geometry



- Lenslet Array = 10mmx10mm
- lenslet pitch = 300µm
- 30x30 lenslets in total
- 14x14 lenslets per segment pupil
- Detector pixel size = 5.5µm
- 300µm/5.5µm = 55x55 pixels per subaperture

- Spot size:

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

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

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

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WFS SNR with a 2nd Magnitude star for a 50ms exposure for a single mirror segment

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

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

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

$$N_\rho = \sqrt{S}$$

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

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

WFS SNR with a 2nd Magnitude star for a 50ms exposure for a single mirror segment

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

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

$$S = 3.4 \times 10^6 \frac{\nu}{cm^2 s} \cdot 50 \times 10^{-3} s \cdot \eta \cdot \frac{63.6 cm^2}{nPix}$$

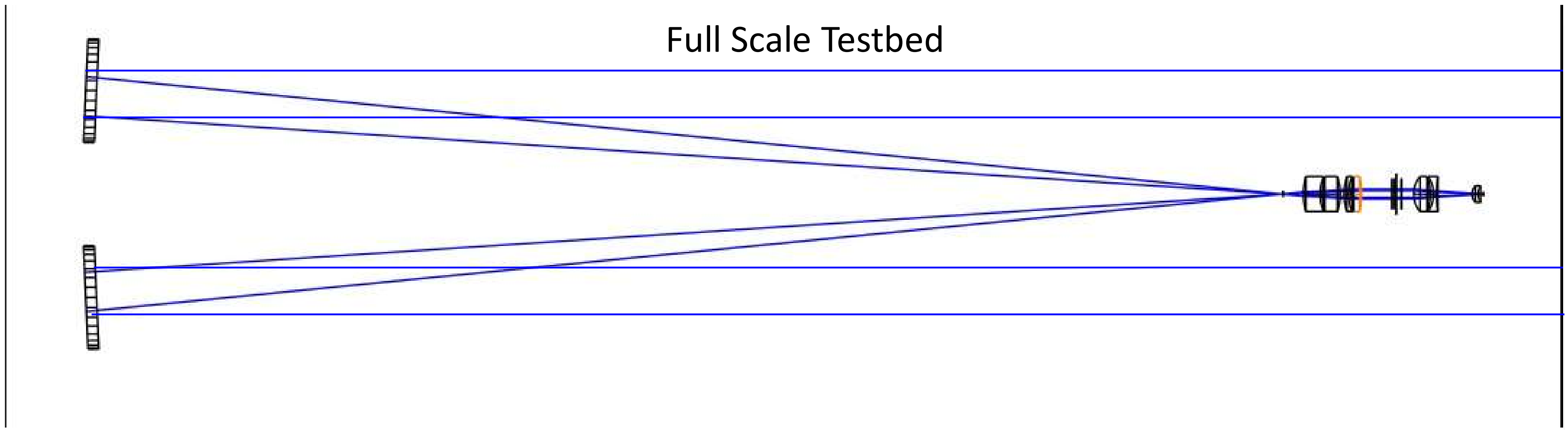
SHWFS	Science Cam
$\eta \sim 0.35 \frac{e^-}{\nu}$ $SNR = 110 / lenslet$	$\eta \sim 0.035 \frac{e^-}{\nu}$ $SNR = 116$

Optical Systems Status

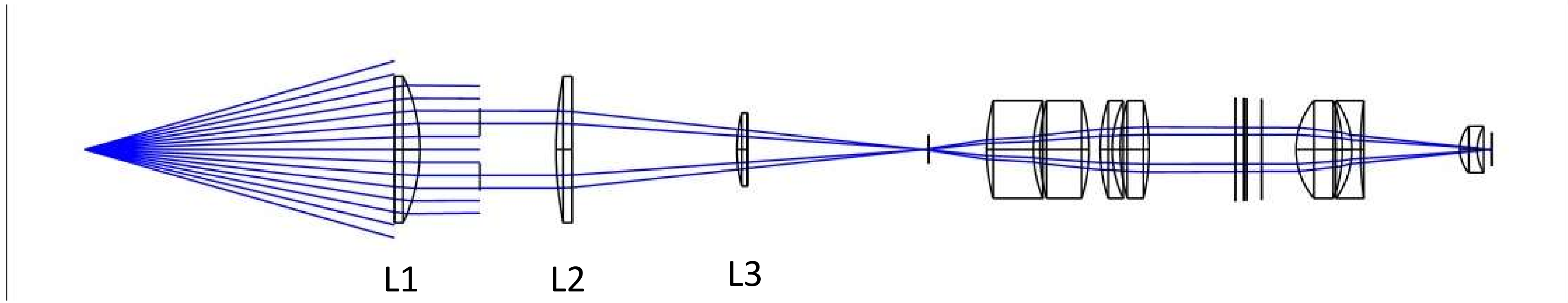
- Camera Lens assembly
  - Verify lenses are manufactured and aligned correctly
- Rigid Mirrors
  - Integration into testbed with science imager for coarse alignment and SHWFS for fine WFE measurement
- Deformable Mirrors
  - Characterization using high order wavefront sensing
  - Integration into testbed with SHWFS readout
  - Active control in testbed using some flight like electronics.

Camera Lens Assembly Verification

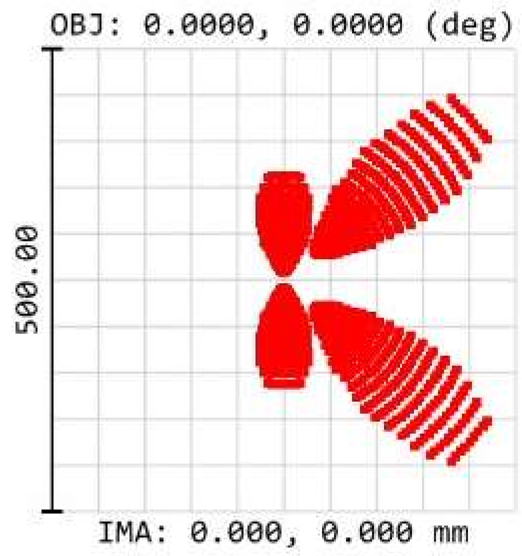
Full Scale Testbed



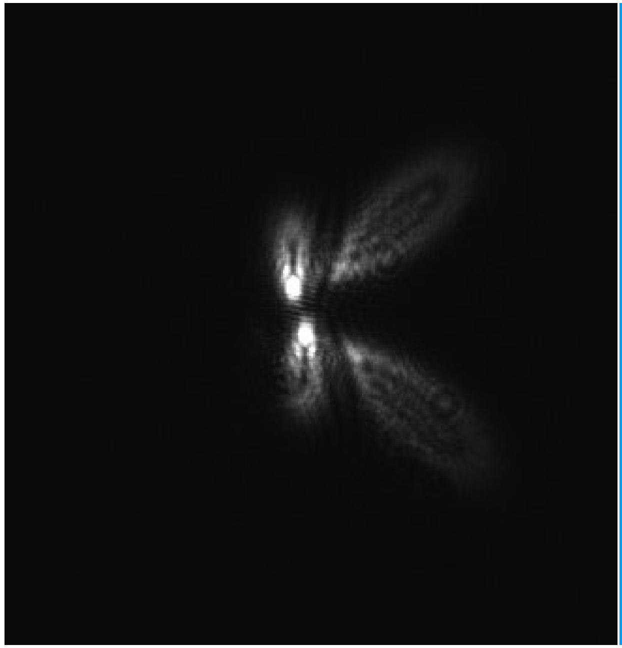
Primary Mirror Simulator using off the shelf lenses



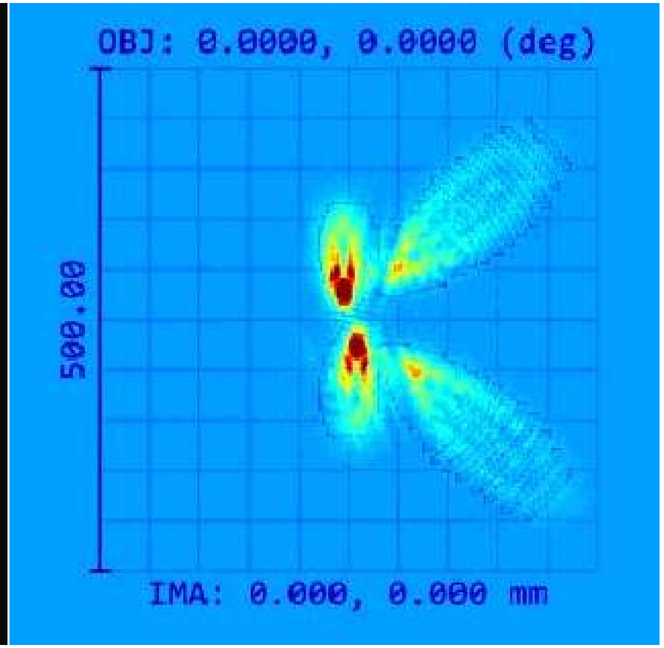
Simulation and Measurement



Telescope simulator raytrace.

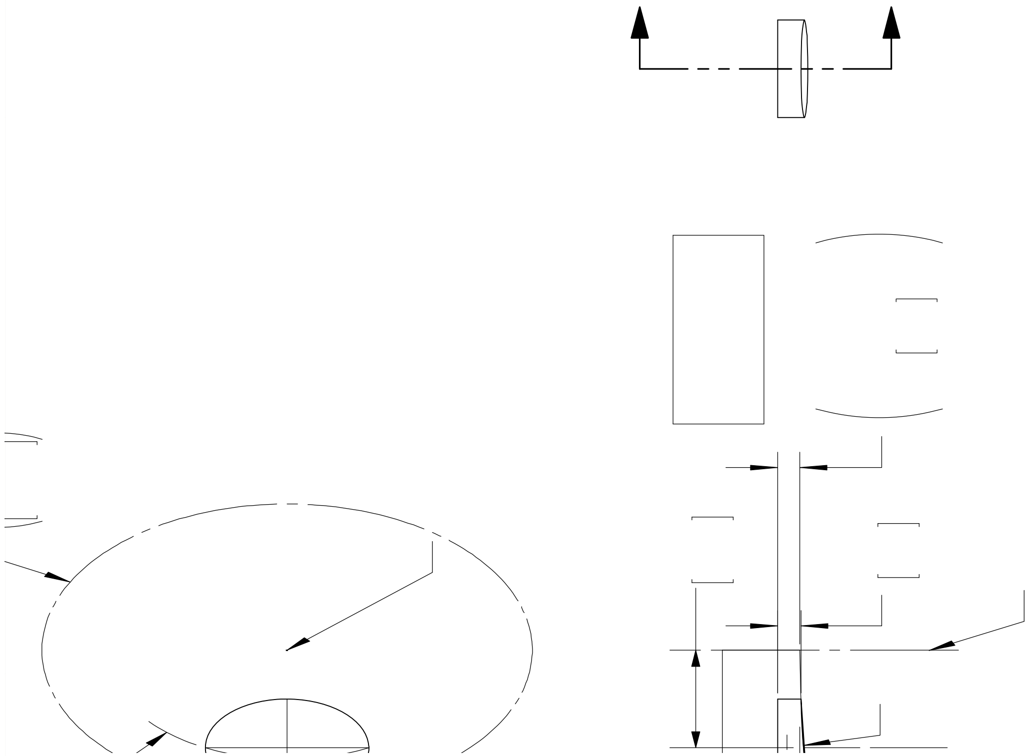


Telescope simulator camera measurement.



Measurement overlaid on raytrace.

Rigid Mirrors



- Matched off-axis hyperboloidal mirrors cored from single parent.

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

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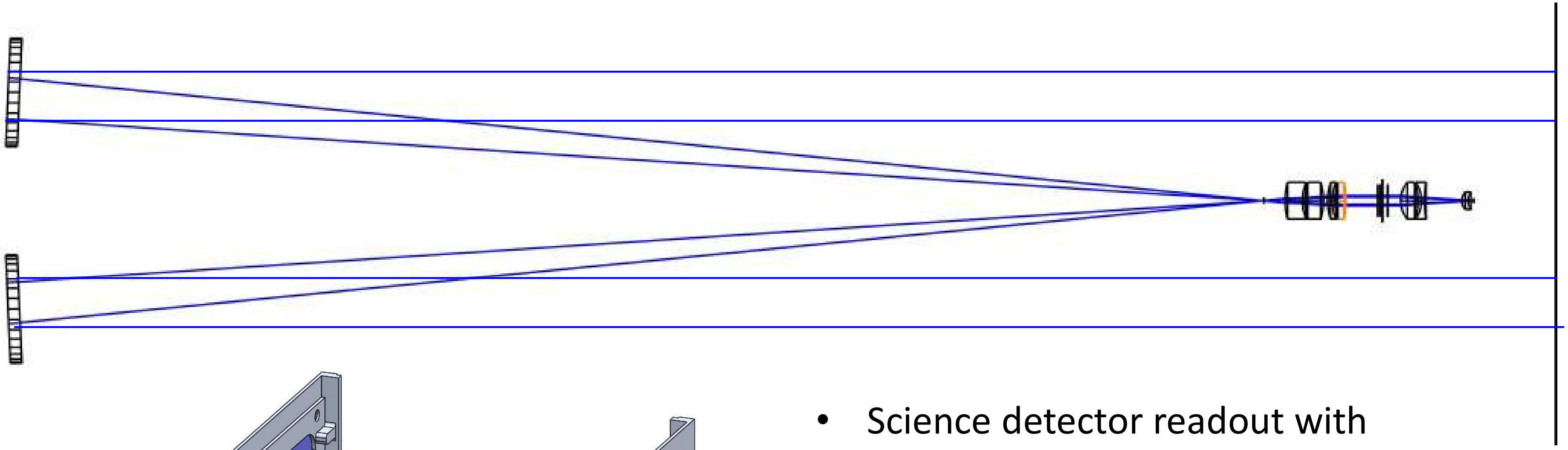
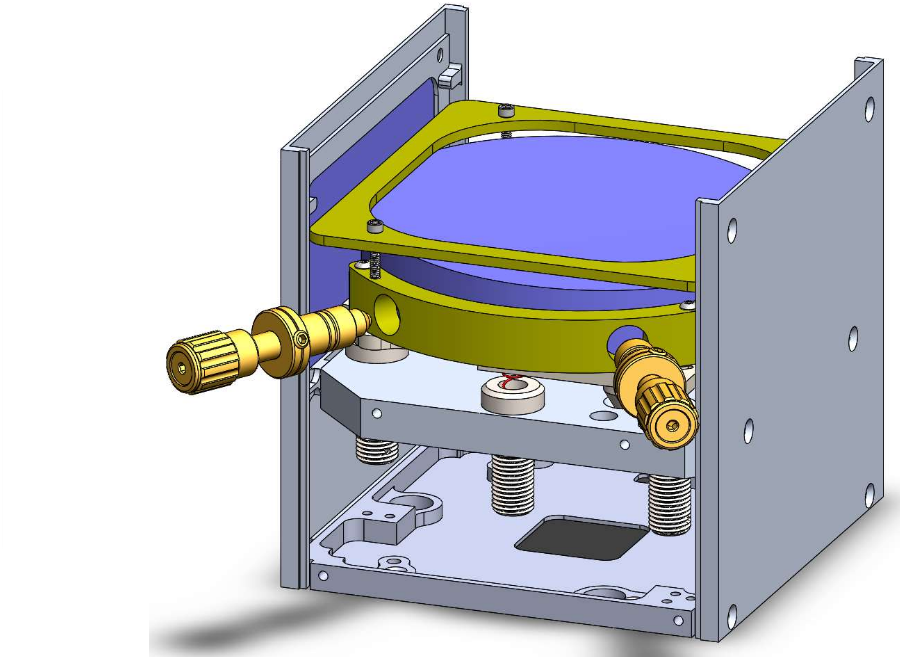
Rigid Mirrors: Validation in Testbed





- Science detector readout with single rigid mirror in place.
- Mirror is held with a temporary mount which provides rotational freedom and fine x/y position adjustment
- Spot is positioned in the camera using mirror box linear actuators

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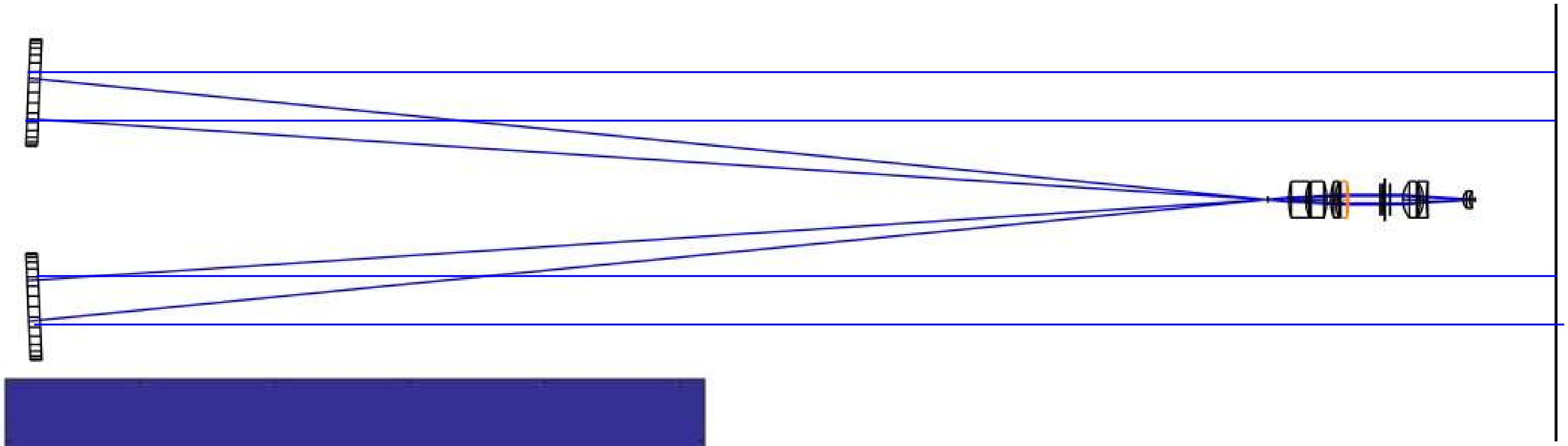
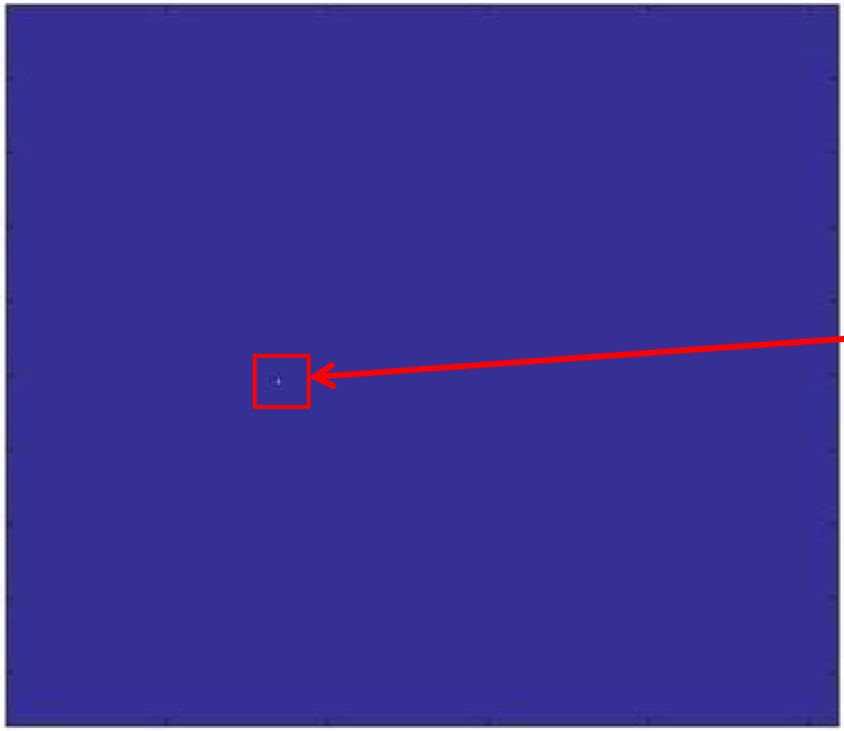
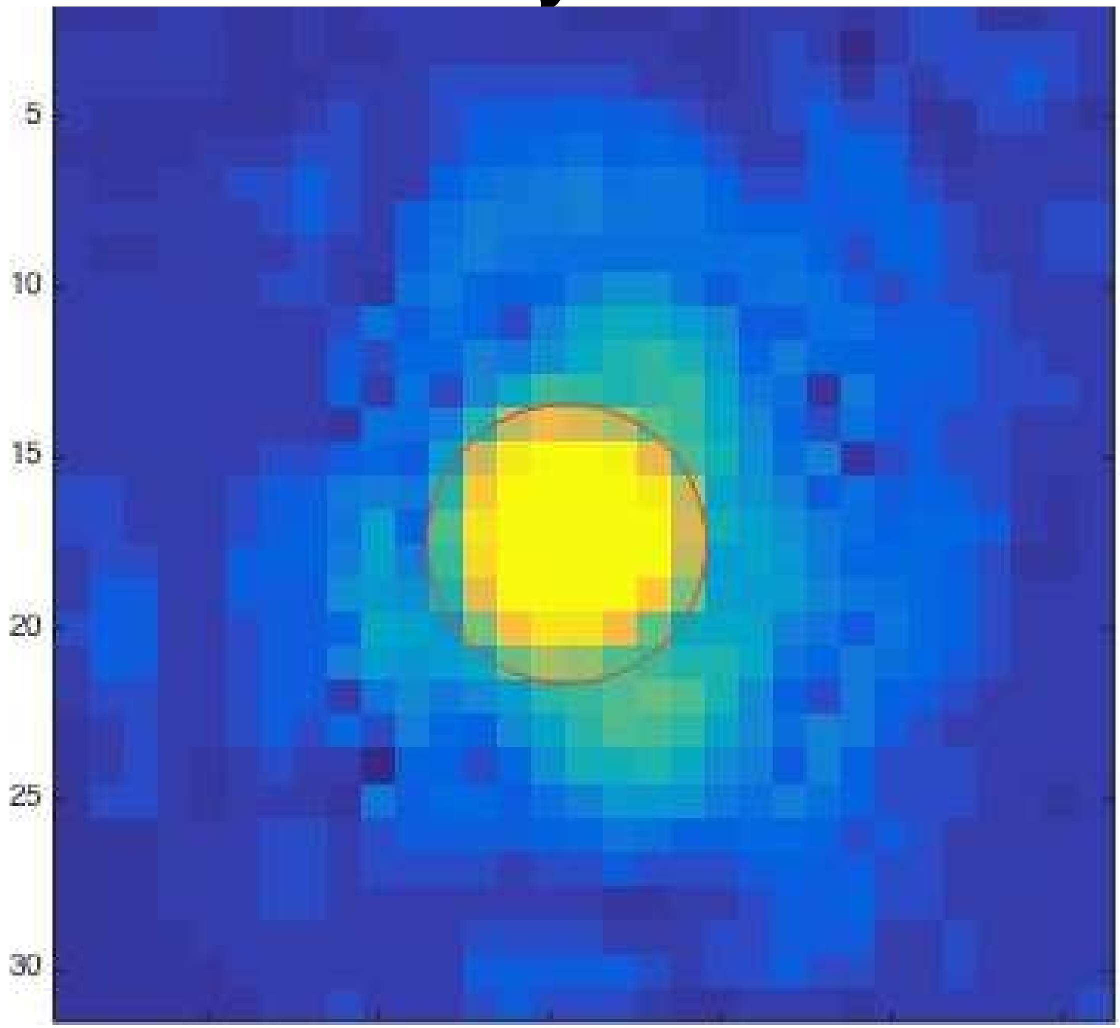
Rigid Mirrors: Validation in Testbed





Science detector readout with single rigid mirror in place.

Rigid Mirror image with expected Airy Disc



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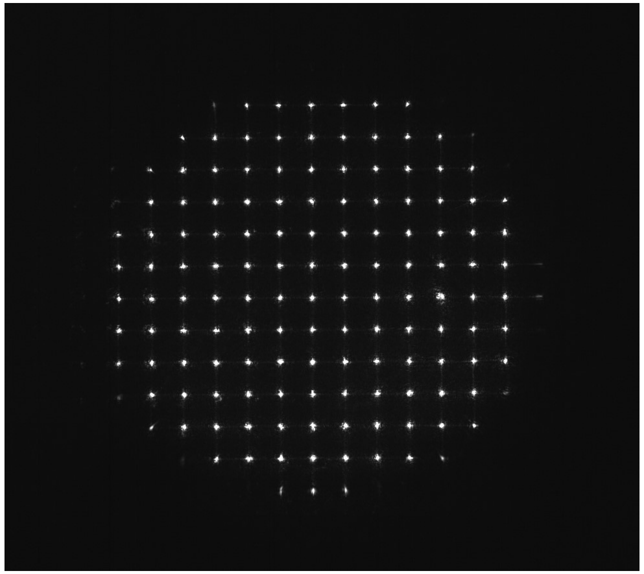
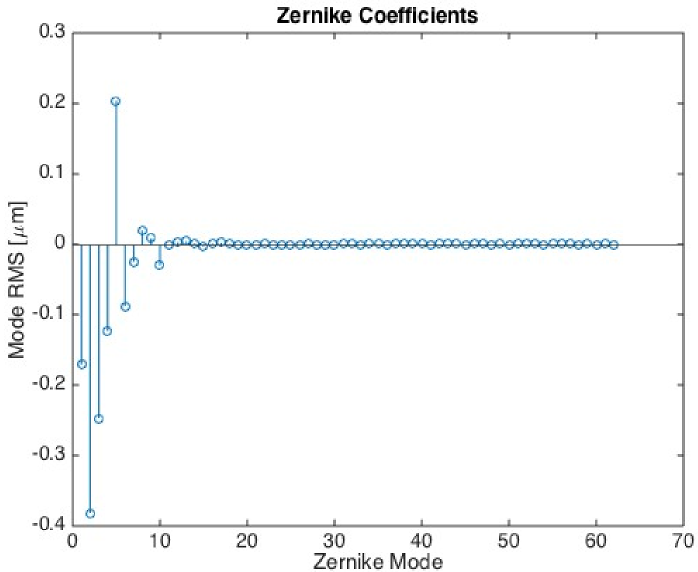
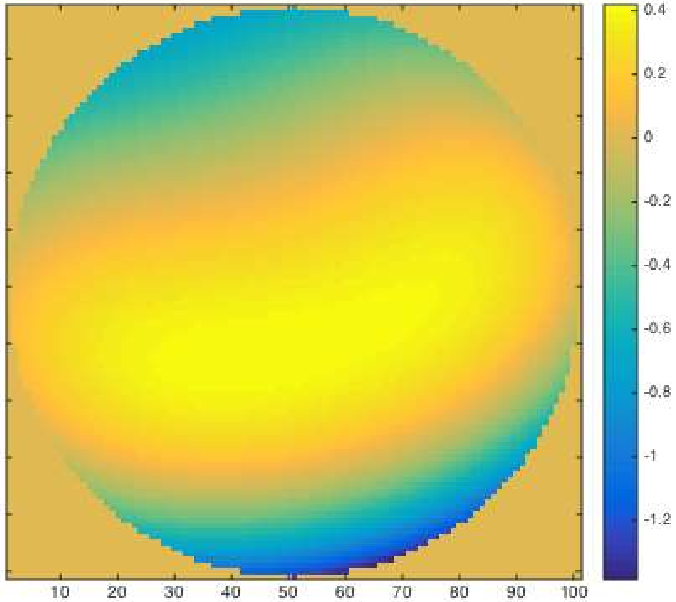
Rigid Mirror in SHWFS

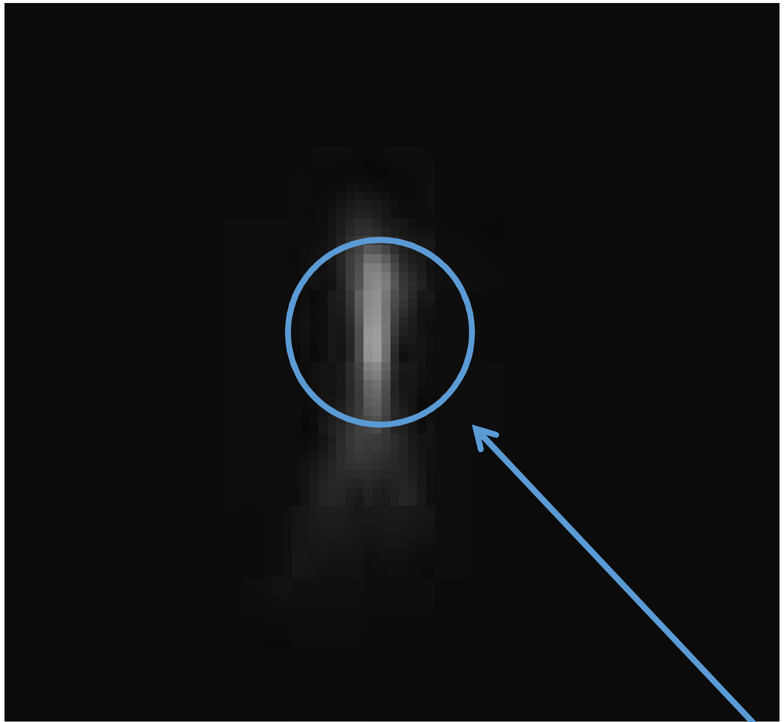


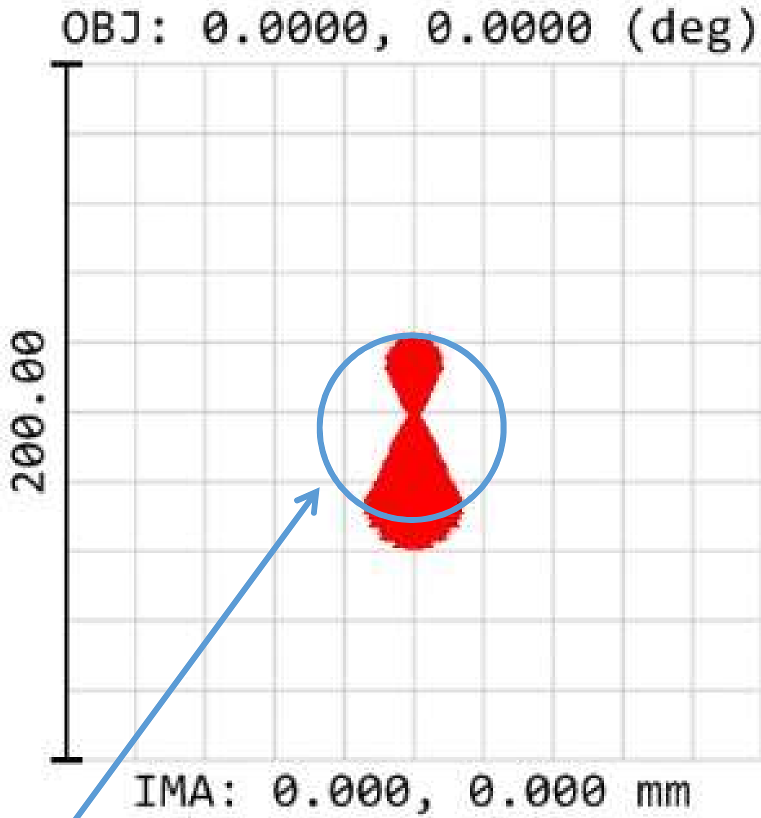


RMS = 353nm
(T/T/F removed)



White Light (Wide Band)





50µm Encircled
energy boundary

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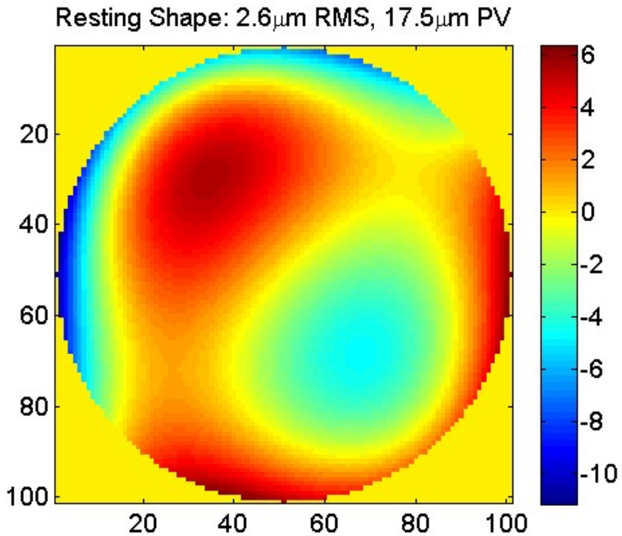
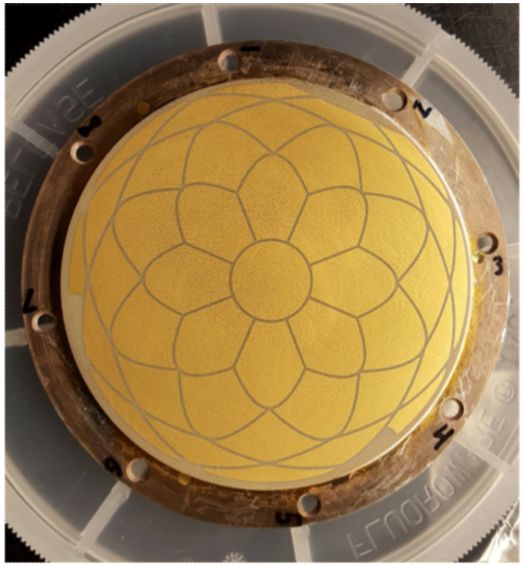
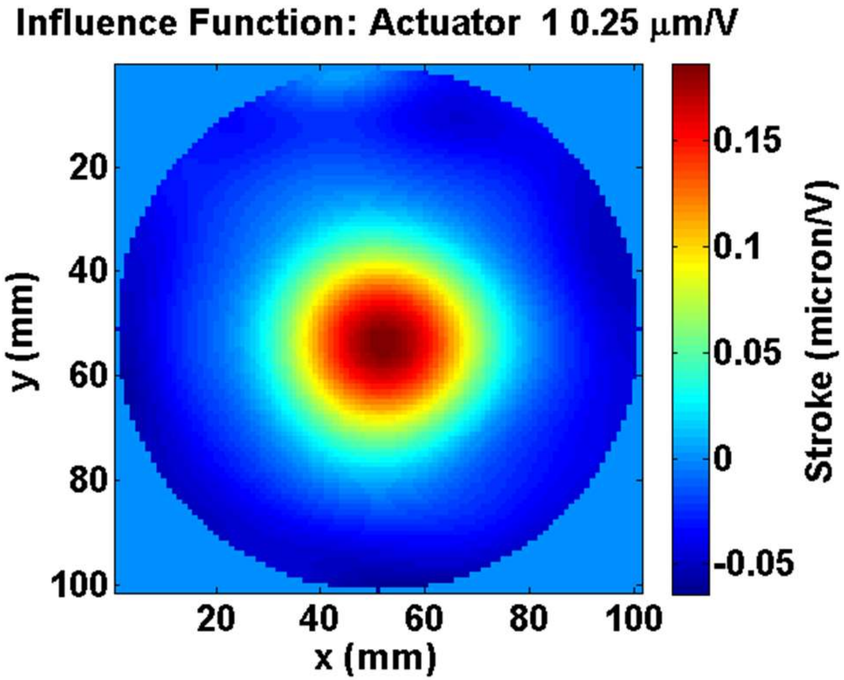
Deformable Mirrors







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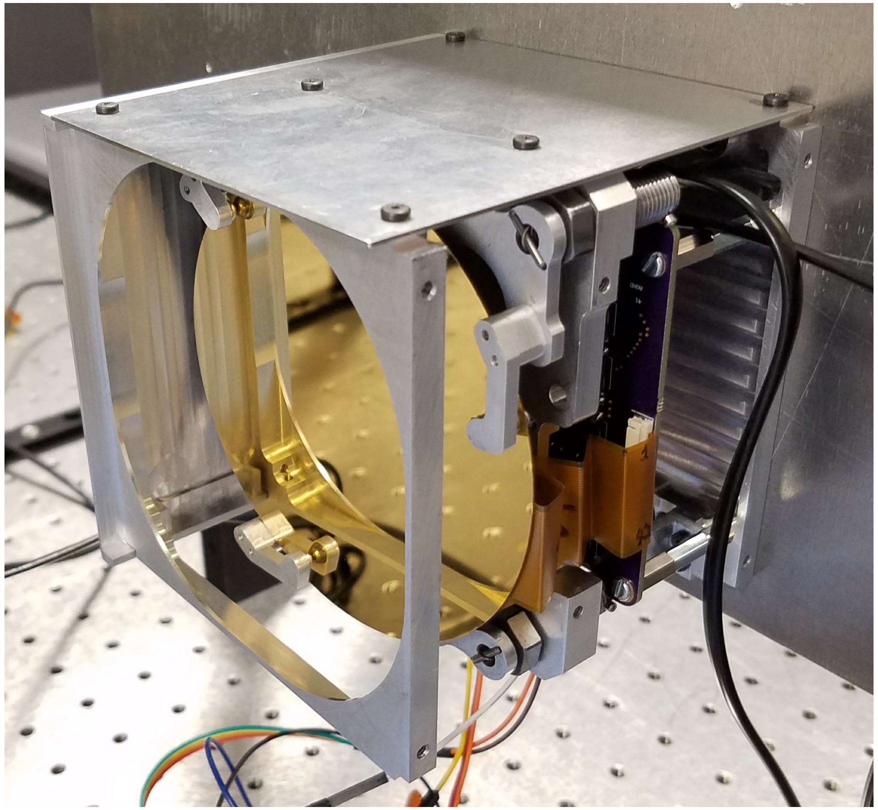
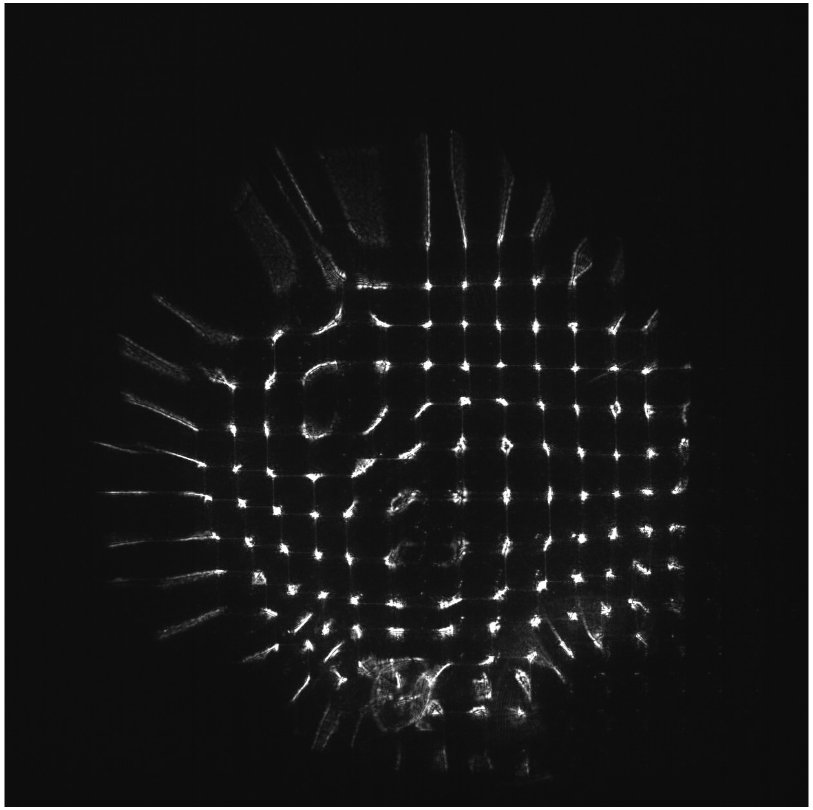
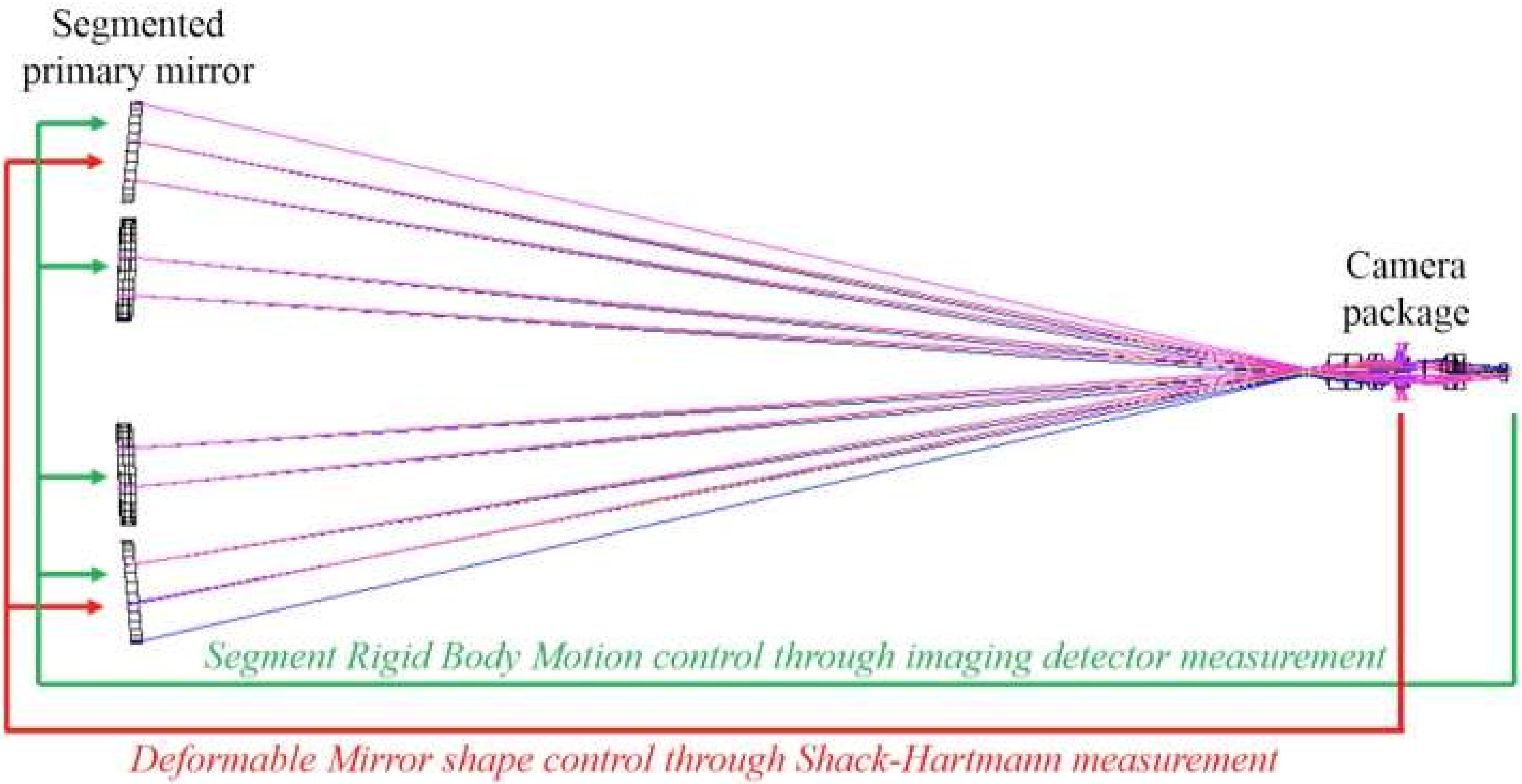
DM In testbed measured by SHWFS





Active Element Control



Active Element Control

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

Summary

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

Future Work

- Manufacture remaining mirror boxes and integrate all four mirror segments into testbed
- Fix rigid mirrors to mirror box and remove temporary mounts
- Execute calibration and closed loop control of DMs using flight camera and SHWFS.

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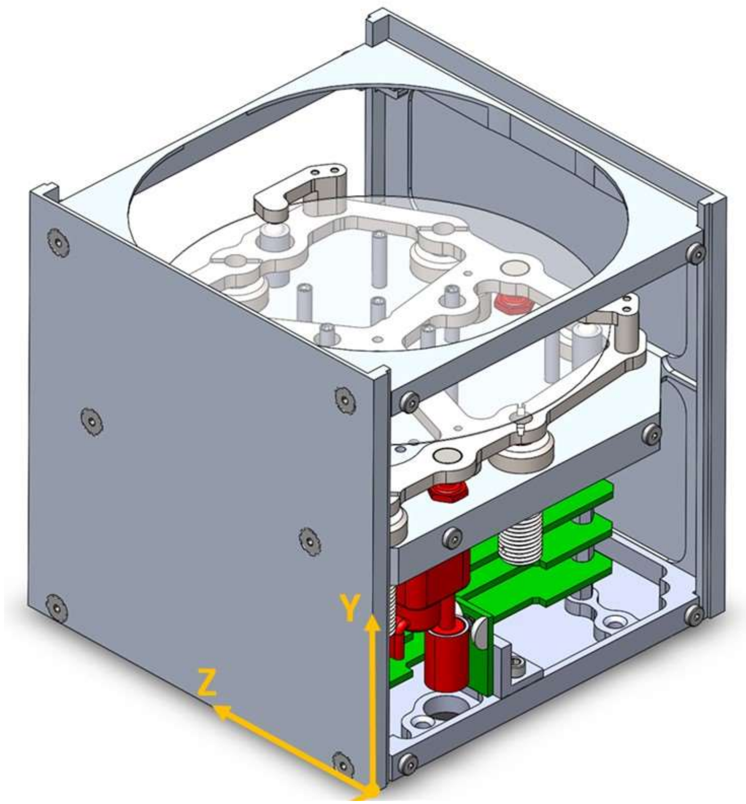
AAReST Deformable Mirrors

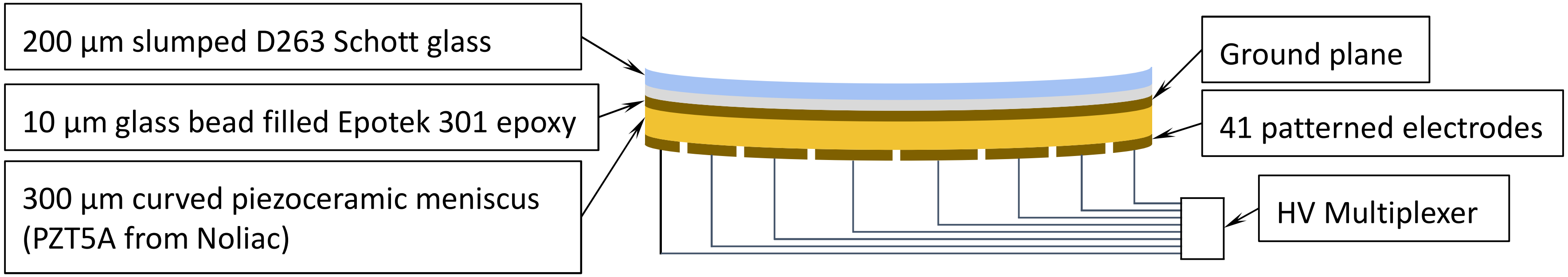
Stephen Bongiorno and Kathryn Jackson

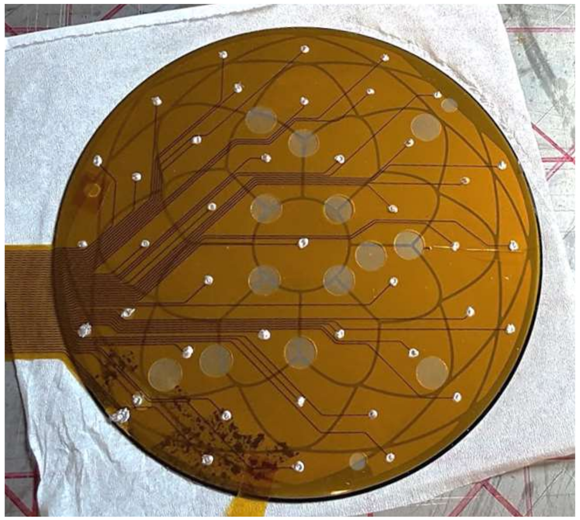
Outline

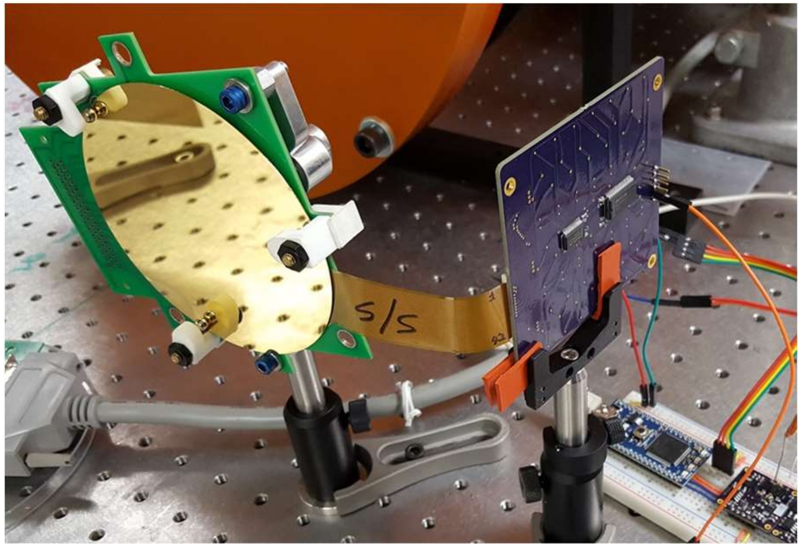
- Deformable mirror (DM) overview
- Requirements
- Shape measurement tool description
- Results from two working mirrors
- Flight mirror fabrication timeline



DM overview


200 µm slumped D263 Schott glass
10 µm glass bead filled Epotek 301 epoxy
300 µm curved piezoceramic meniscus (PZT5A from Noliac)
Ground plane
41 patterned electrodes
HV Multiplexer





Requirements

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

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

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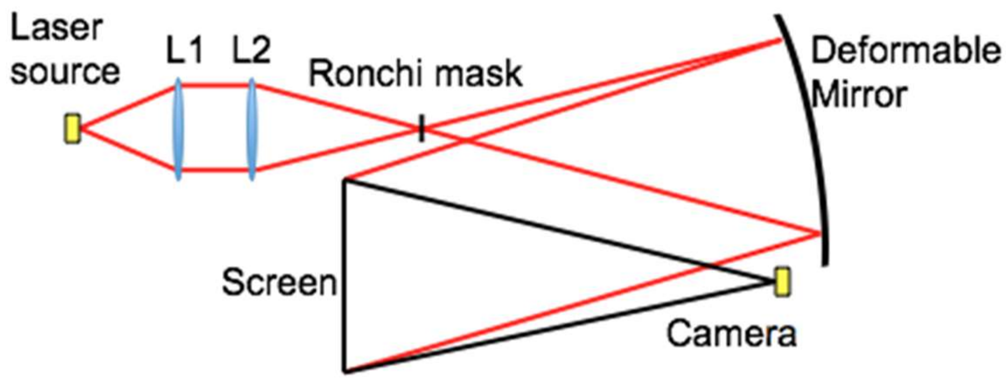
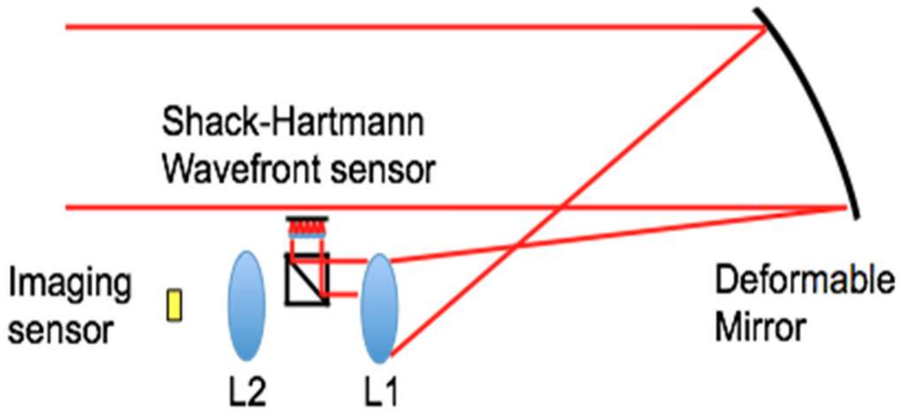
Optical shape measurement

Reverse-Hartmann



Shack-Hartmann



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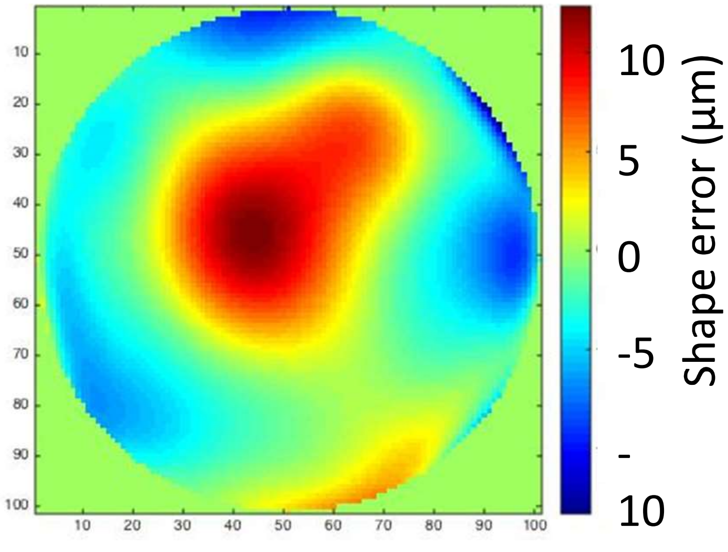
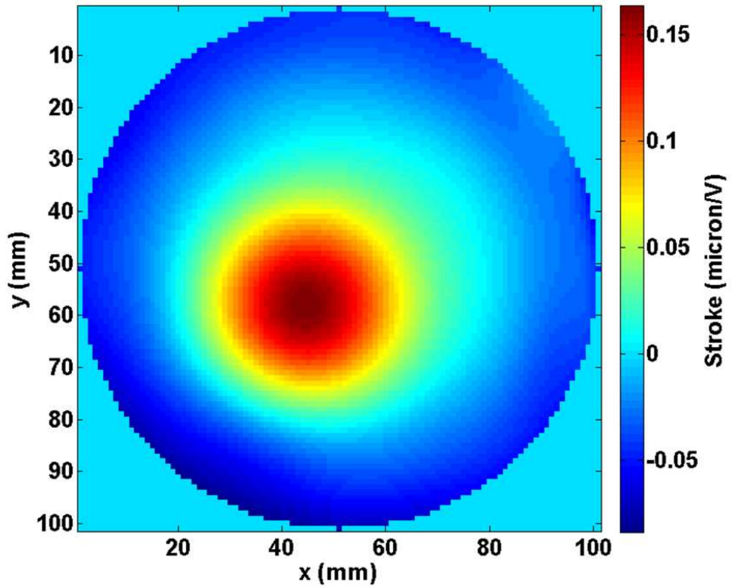
pzt3gs16 - Shape and influence

PZT3GS16 RMS=4.7 µm PV=25.6 µm



Influence function: Actuator 1 0.2475 µm/V P-V



- Unactuated mirror shape is well within range of actuation

- 59.4 µm P-V at 240V max actuation
- Note: mirror was not centered in RH testbed

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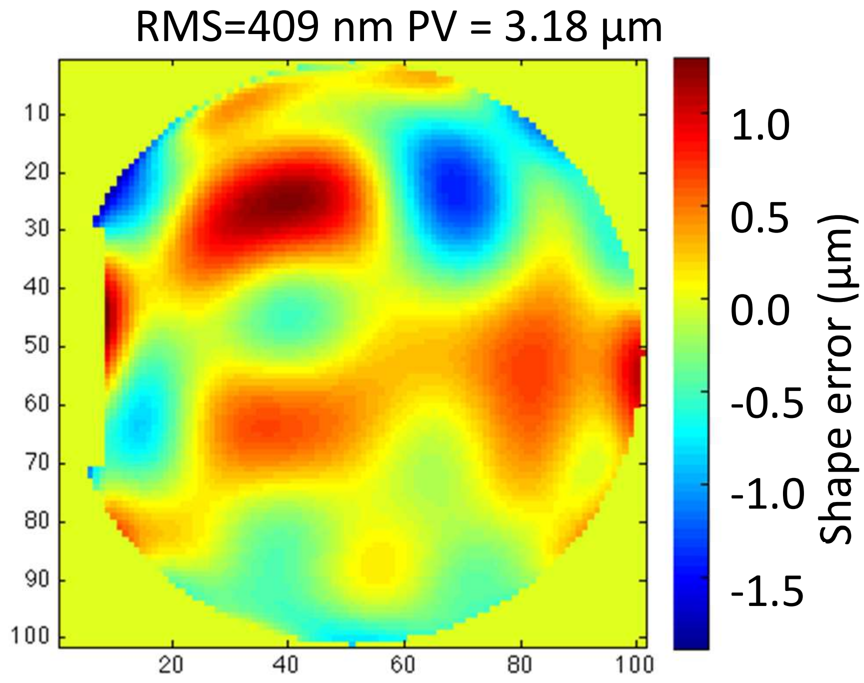
pzt3gs16 – Closed-loop

- Deformable mirror was actuated to a sphere in closed loop
- Residual shape error is shown here for central 80% of mirror
- Spatial extent of errors is similar to the size of the actuators, i.e. we are spatially limited.
  - RMS shape < λ
  - Additional actuation will not improve shape
  - Final shape can be improved by decreasing actuator size or improving initial figure



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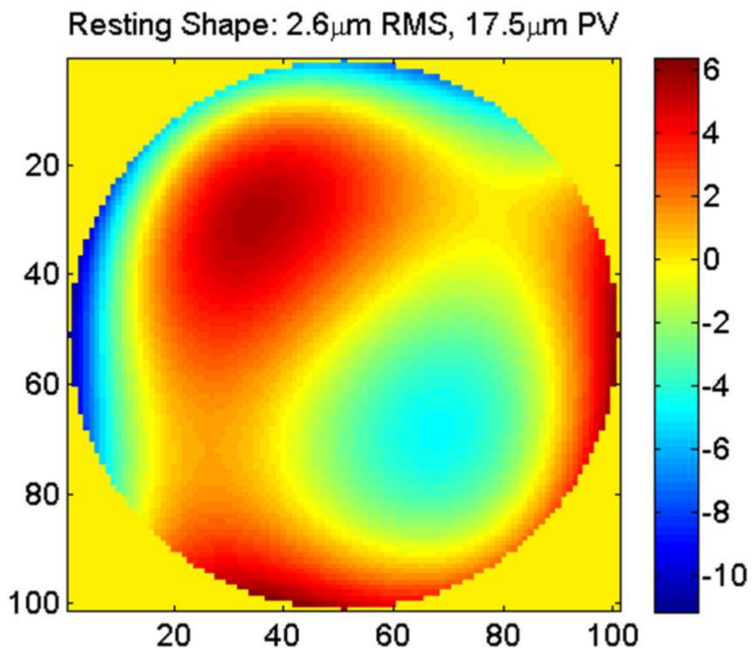
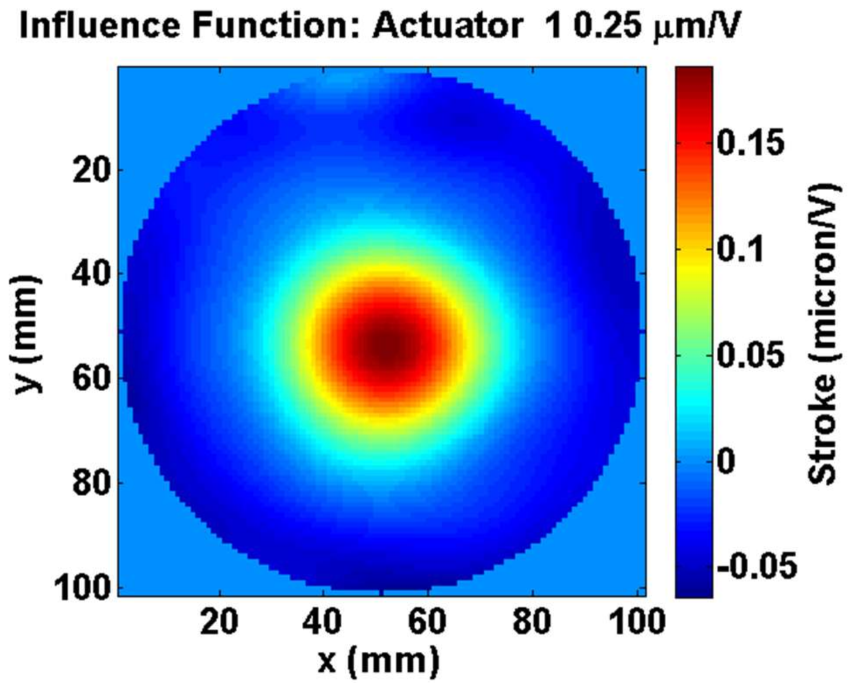
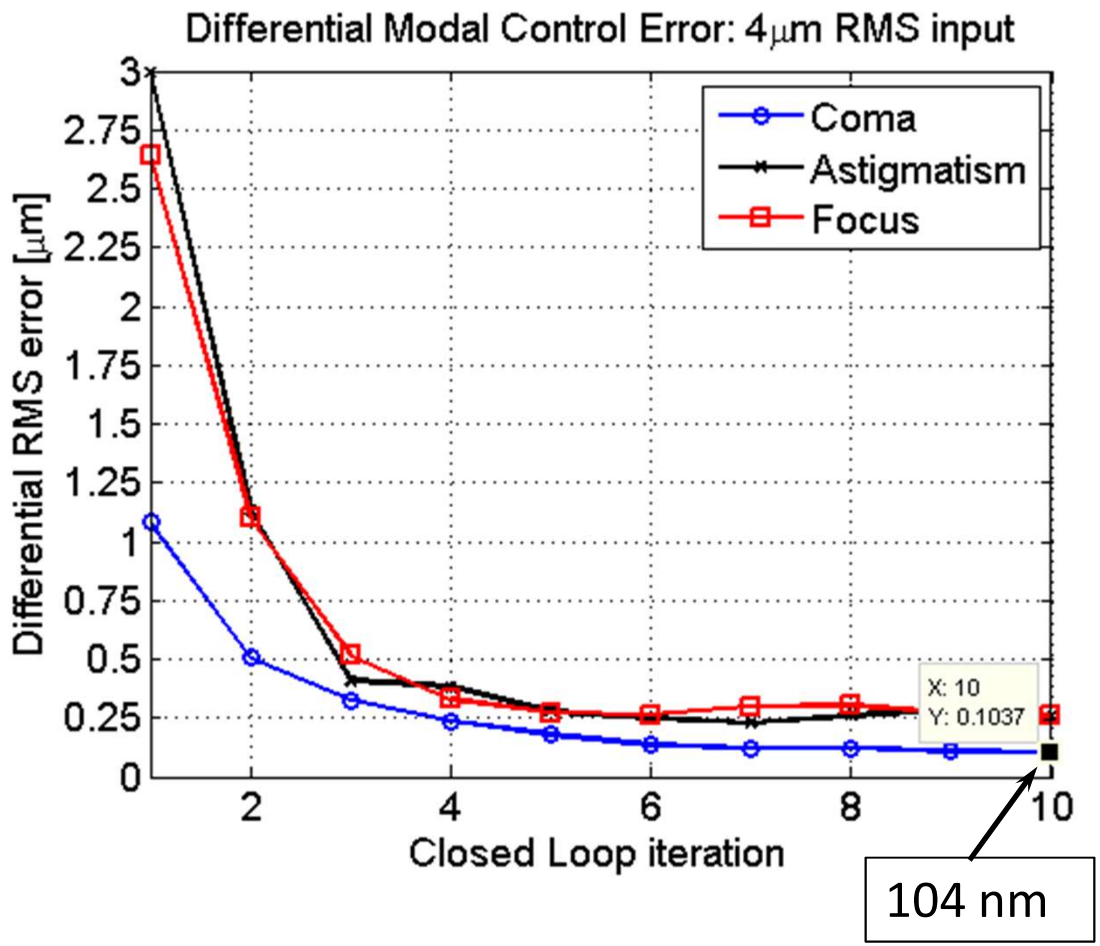
pzt5r1m1 – Shape and

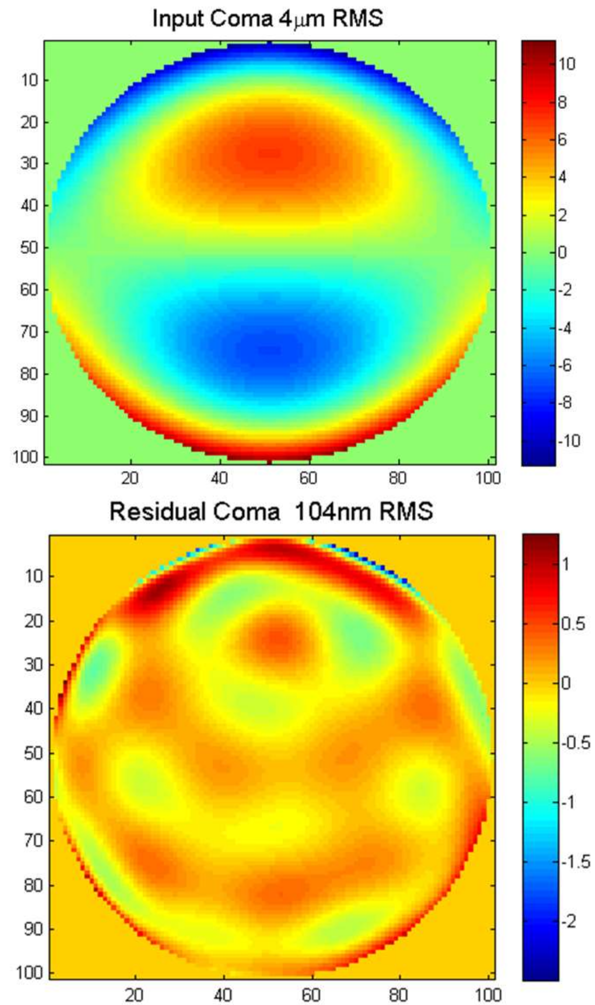




- Rev-Hartmann measurements (above) over central 80% of aperture
- Checked pzt5r1m1 in AAReST SHWS measurement
- Reverse-Hartmann closed loop shape control – ~600 nm RMS shape error
- Edge flattening defect fixed by cutting down slumped glass
- Edge defect introduced during bonding.

Commanding Zernike modes





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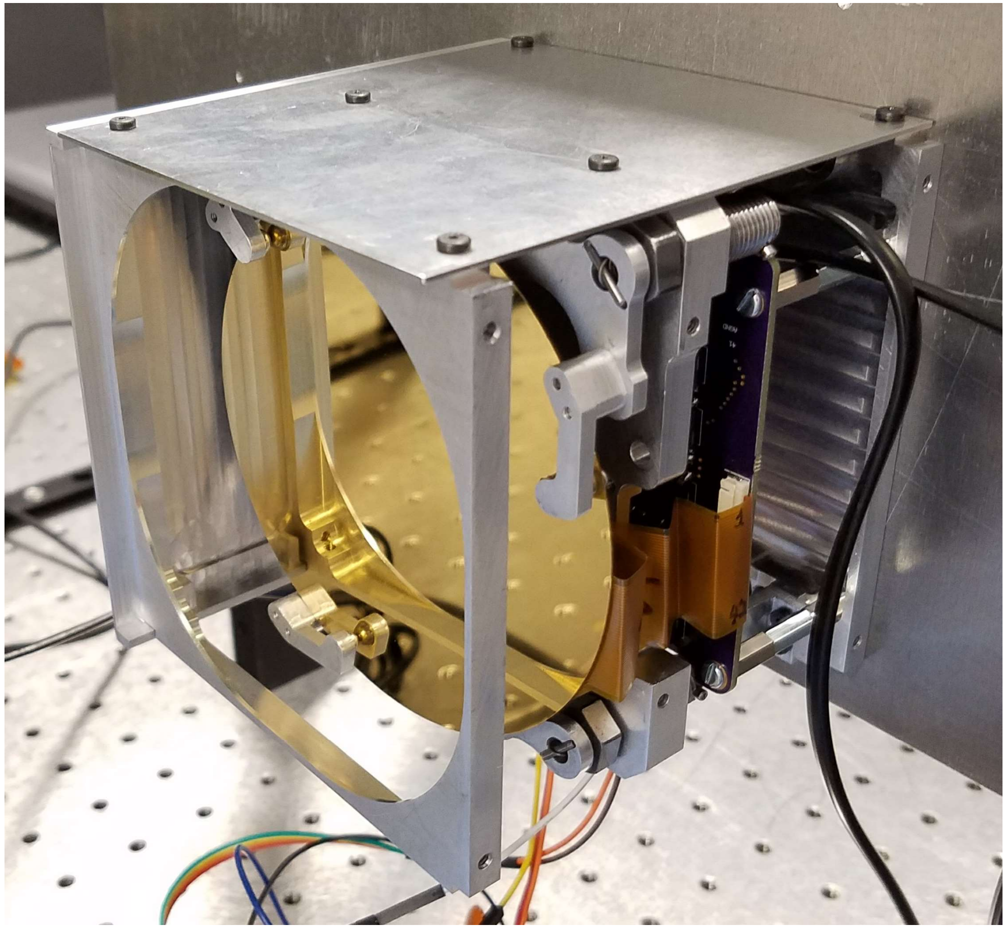
DM integration

- pzt3gs16 integrated in mirrorbox
- Awaiting encircled energy test results



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Flight mirror fabrication timeline

- pzt2gs15 – vibration sample
- pzt3gs16 – integrated in mirrorbox for testing
- pzt4gs17 – vibration sample
- pzt5r1m1 – potential flight mirror
- pzt1r1m2 – 1/16/2017
- pzt6gsf1 – 2/3/2017

Presentation Agenda

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

Camera Instrument

Maria Sakovsky

Subsystem 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 MirrorSat reconfiguration

Constraints:

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

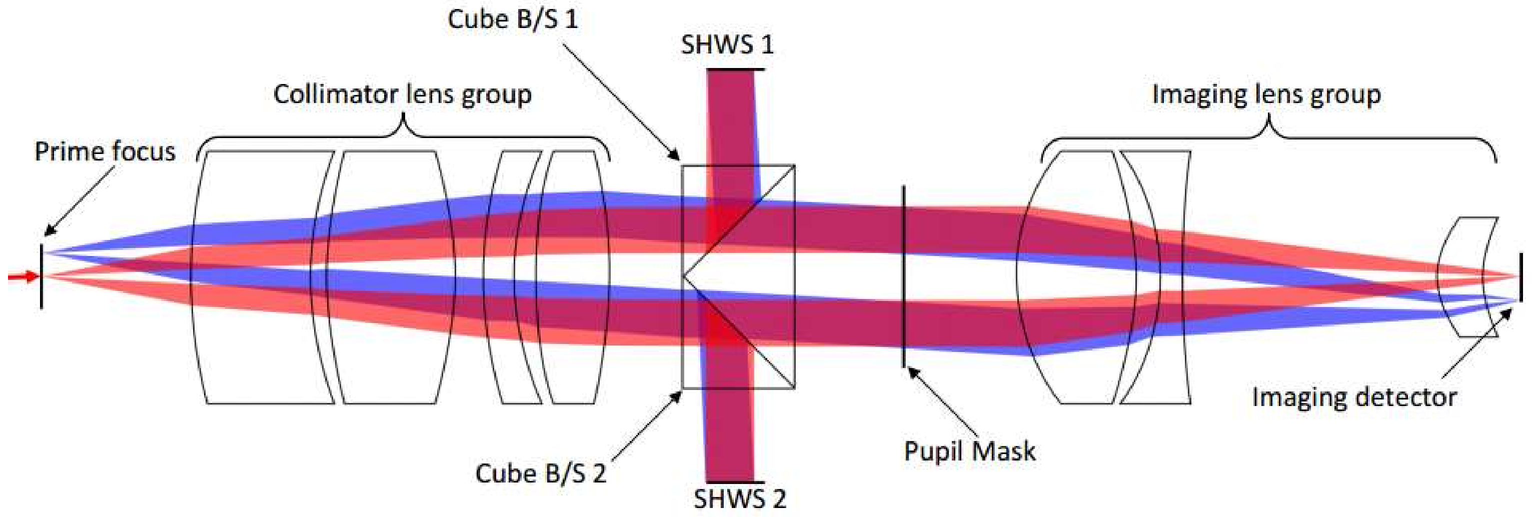
Performance:

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

Environmental:

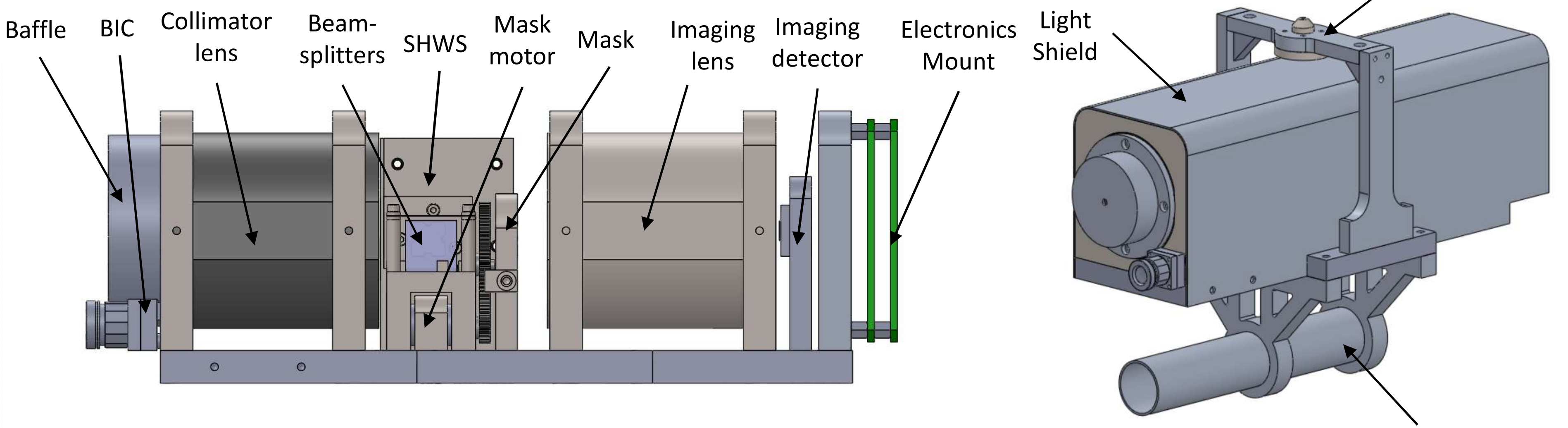
- Survive launch on PSLV with acceptable optical and mechanical performance
- Survive temperatures of -50^{o}C to +50^{o}C
- Function in vacuum environment

Mechanical Overview



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

Mechanical Overview



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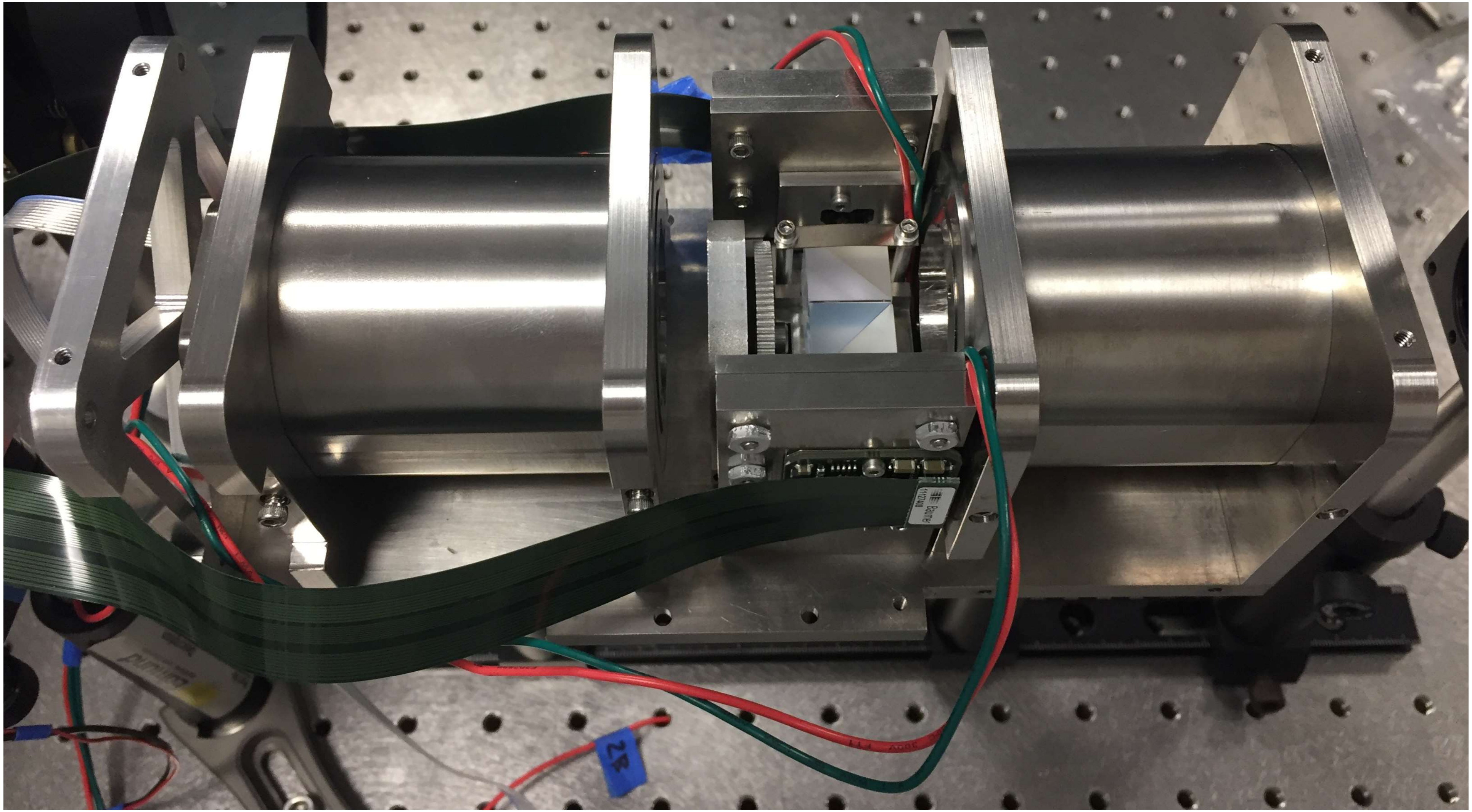

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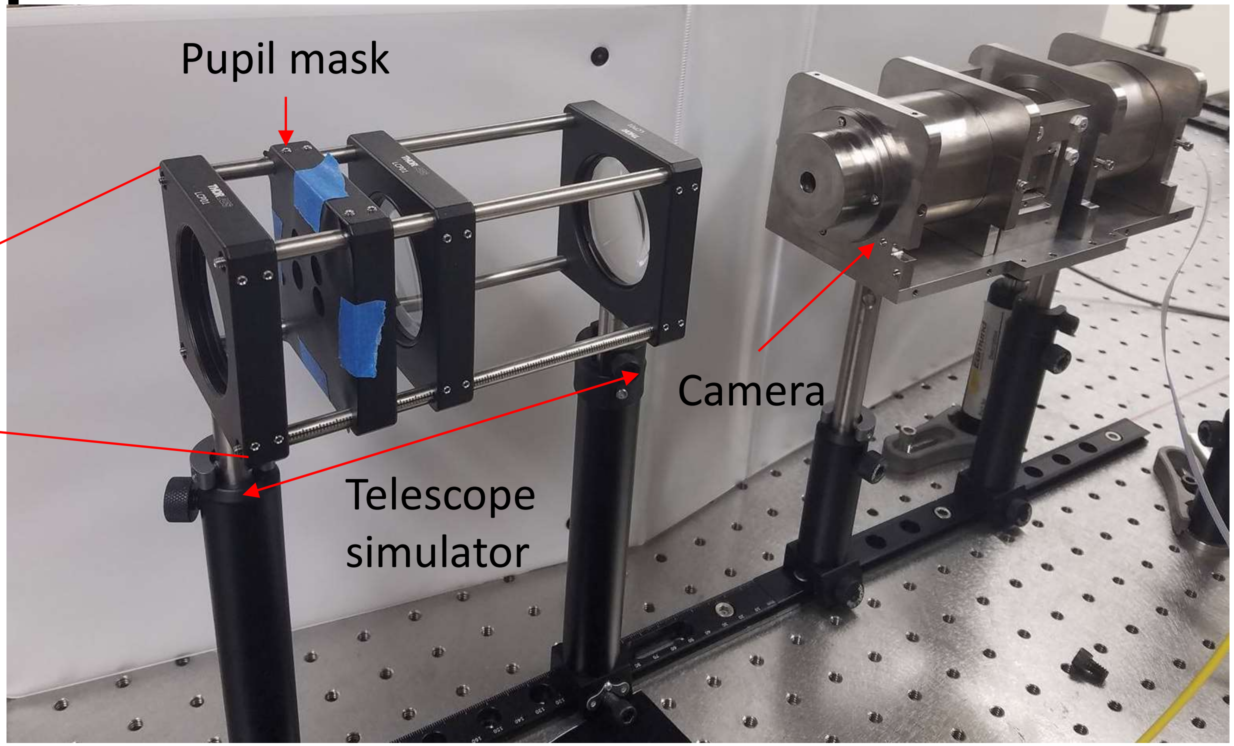
Optical Performance

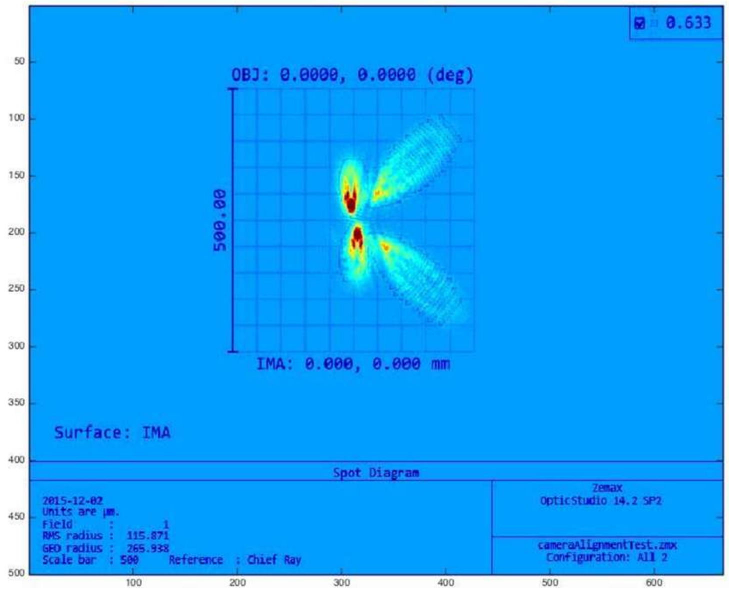


- Performance tested using telescope simulator
  - Matches f/N of AAReST
  - Simulates pupil in wide and narrow configurations
  - Decouples camera testing from mirror alignment

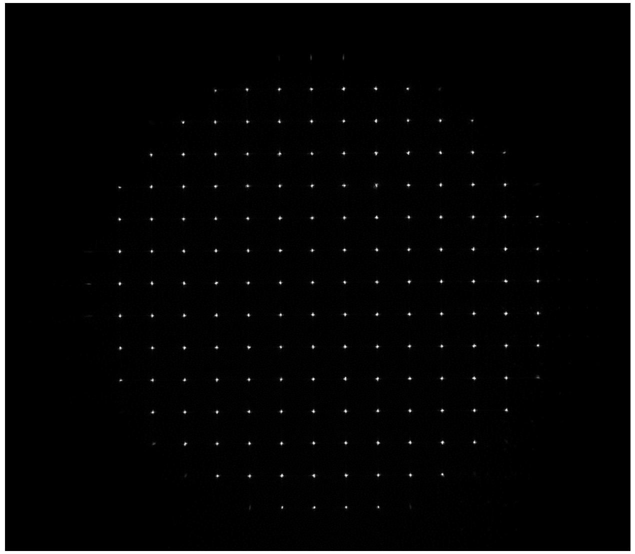
Key Optical Metrics

- Science camera: ~350 px spot (350 px simulated)
- SHWS: 350 spots measured (354 expected); 4.7 px average diameter (4 px expected)
- Science camera SNR:
  - Done in full AAReST testbed with white light source matching flux of star
  - Conservative measurement
  - Measured SNR = 87 (SNR 100 requirement)

Science camera performance



SHWS performance (single mirror)



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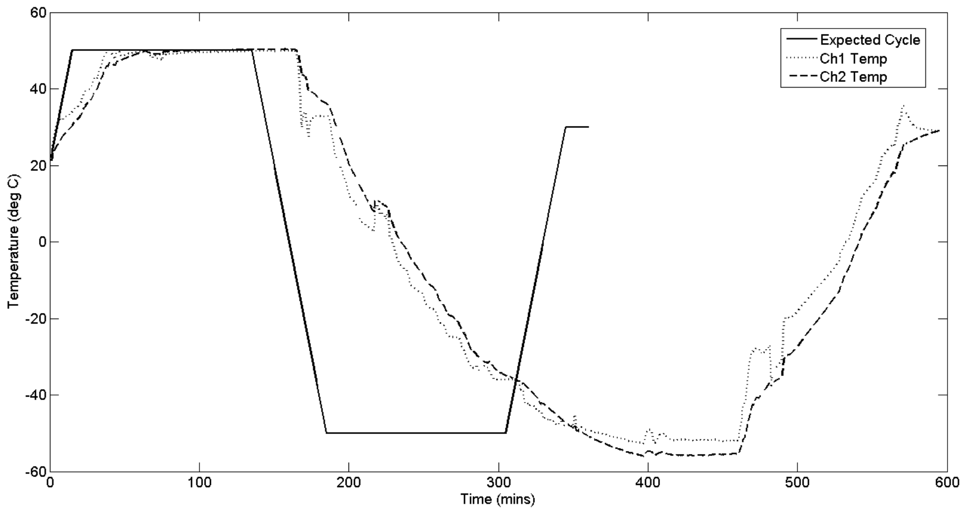
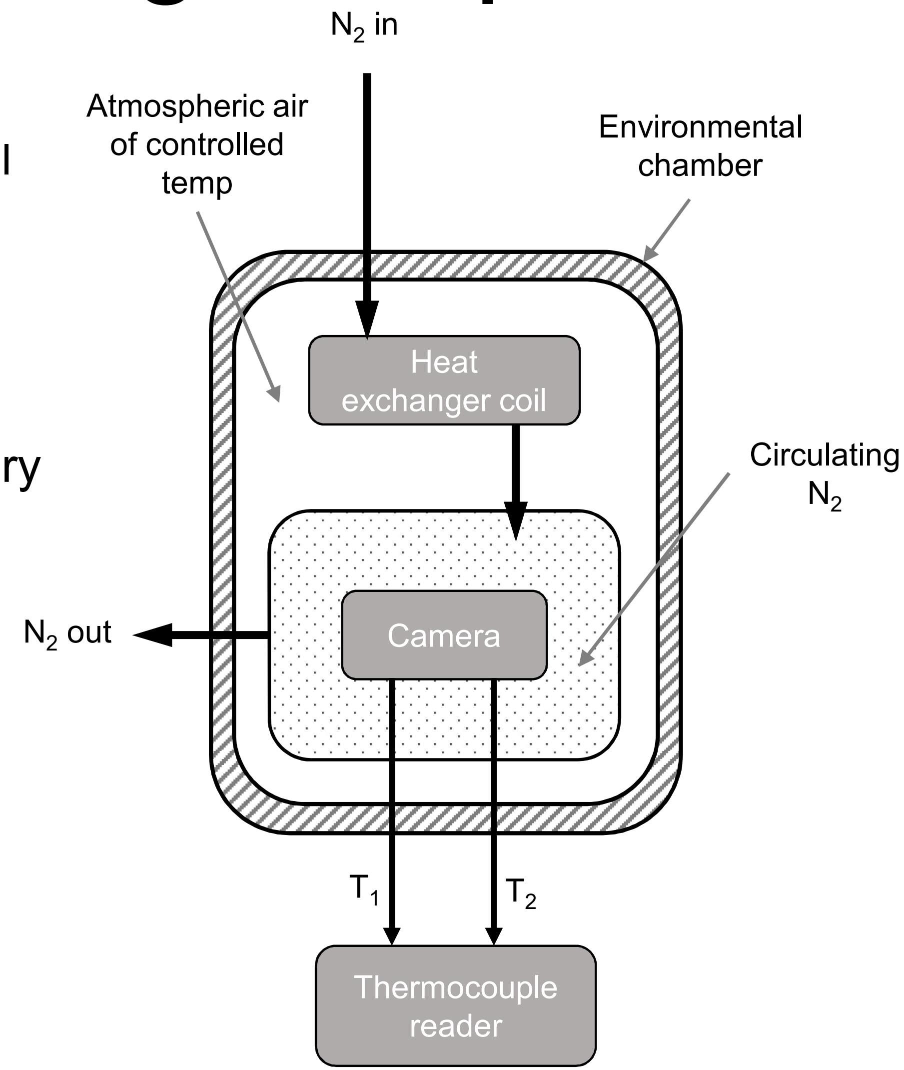
Thermal Testing Setup

- Simulate thermal environment of orbit
  - NASA standard GSFC-STD-7000
  - -50°C to +50°C, 1°C/min rates, 2 hour dwell
  - Low level test (-20°C to +40°C), 3 full level tests
- Environmental chamber at atmospheric pressure
- Camera in bag continuously purged with dry nitrogen to prevent condensation





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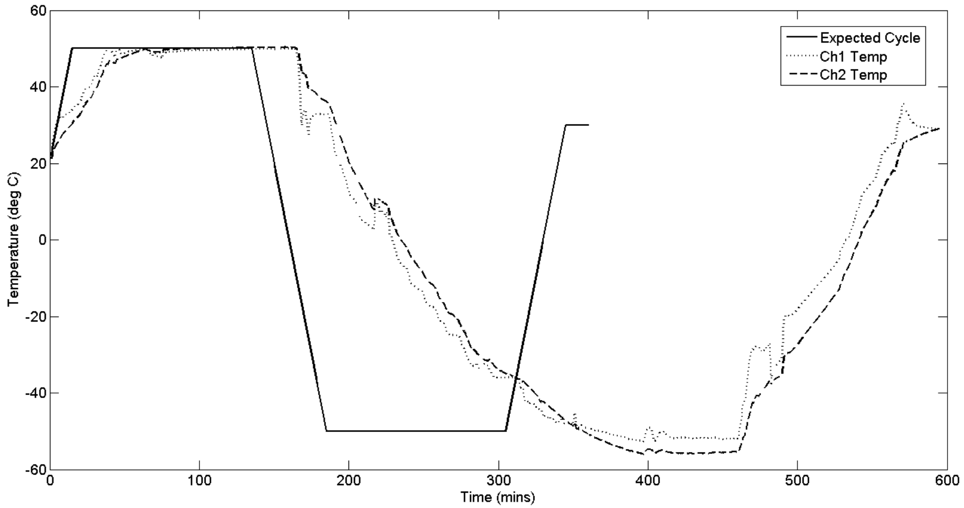

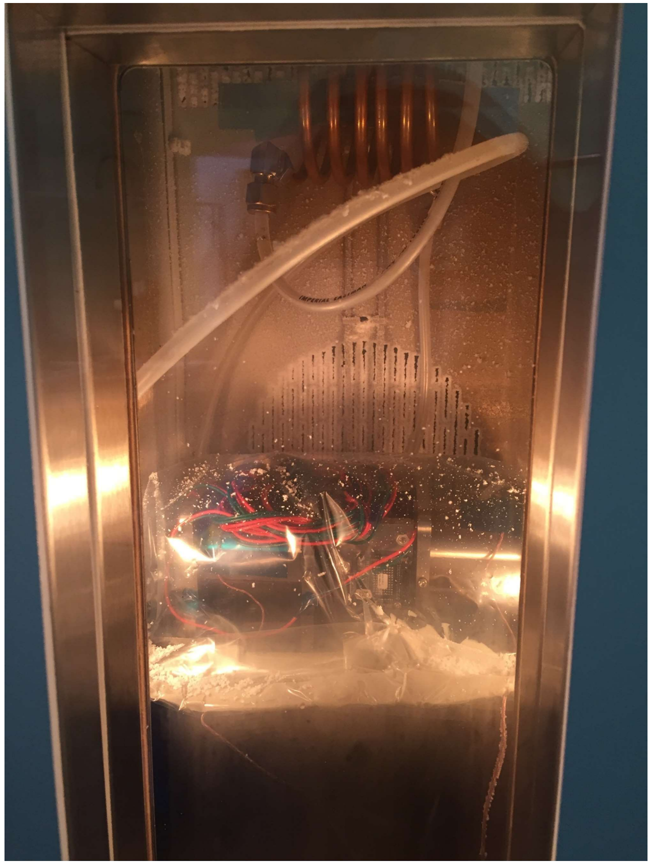

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Thermal Testing Results

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

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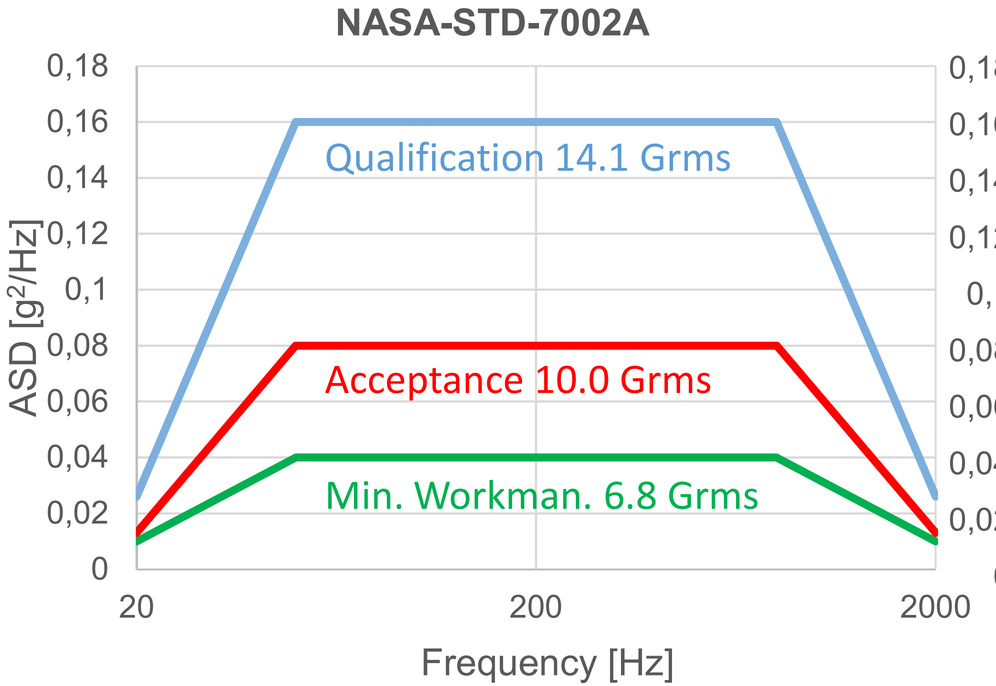
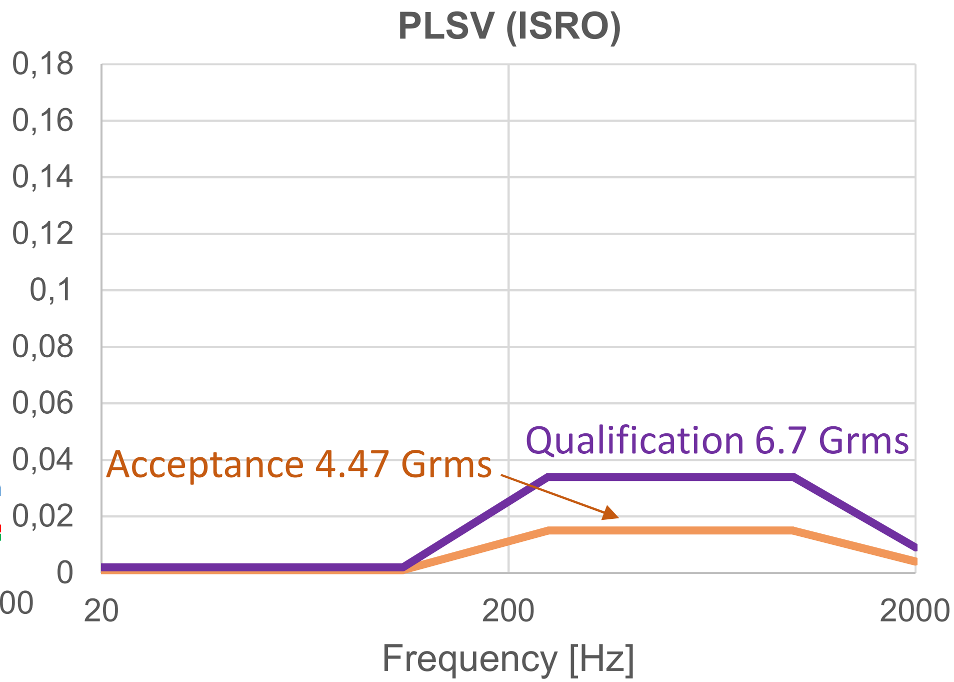
Vibration Testing Overview

White Noise → RV -12dB → White Noise → RV -6 dB (Min.Workman.) → White Noise → RV -3 dB (Acceptance) → White Noise → RV 0dB (Qualification) → White Noise

- White Noise vibe to detect changes in natural frequencies
  - 1 Grms
  - 10% allowable max shift
- For each subsystem identified PASS/FAIL criteria (mechanical, optical)

Vibration Testing Overview





- NASA Standards used for kinematic mount and mirror boxes
  - 0.5 min duration for Acceptance and Min. Workmanship
  - 1 min duration for Qualification
- PLSV profile used for camera
  - 1 min duration for Acceptance
  - 2 min duration for Qualification

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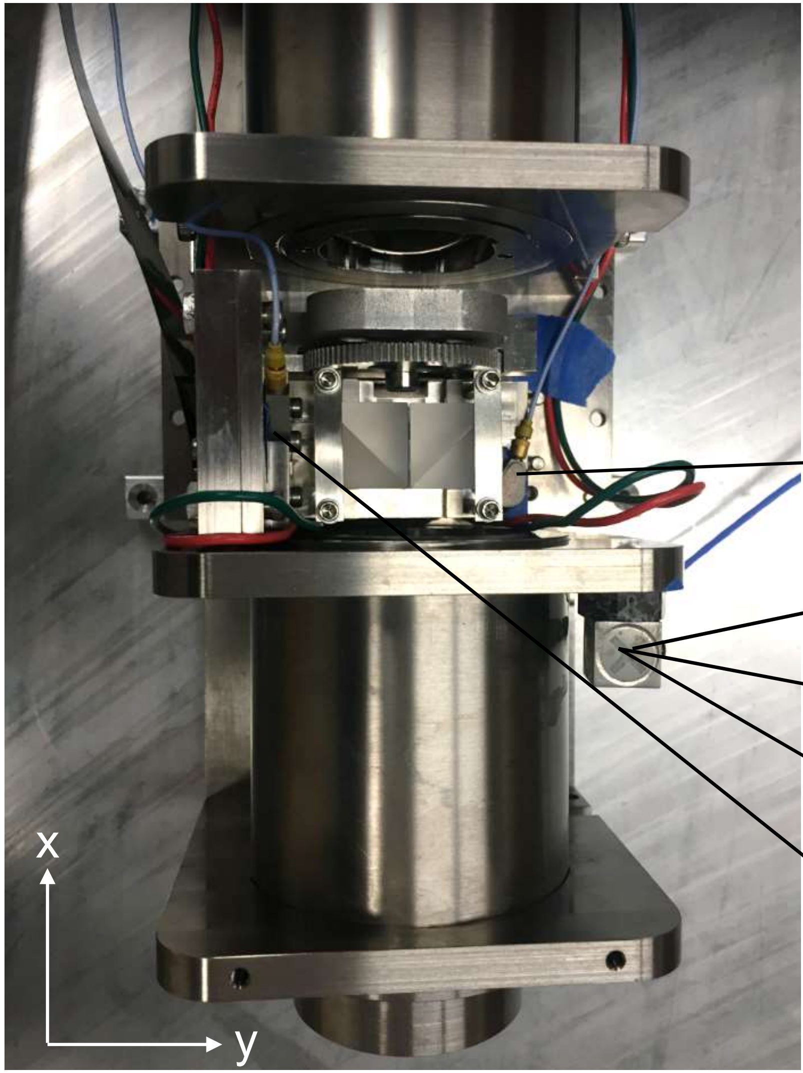
Vibration Testing Setup



1. Control, y
2. Control, x
3. Control, z (input)

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4. B/S, z
5. Collimator assembly, z
6. Collimator assembly, y
7. Collimator assembly, x
8. SHWS, y

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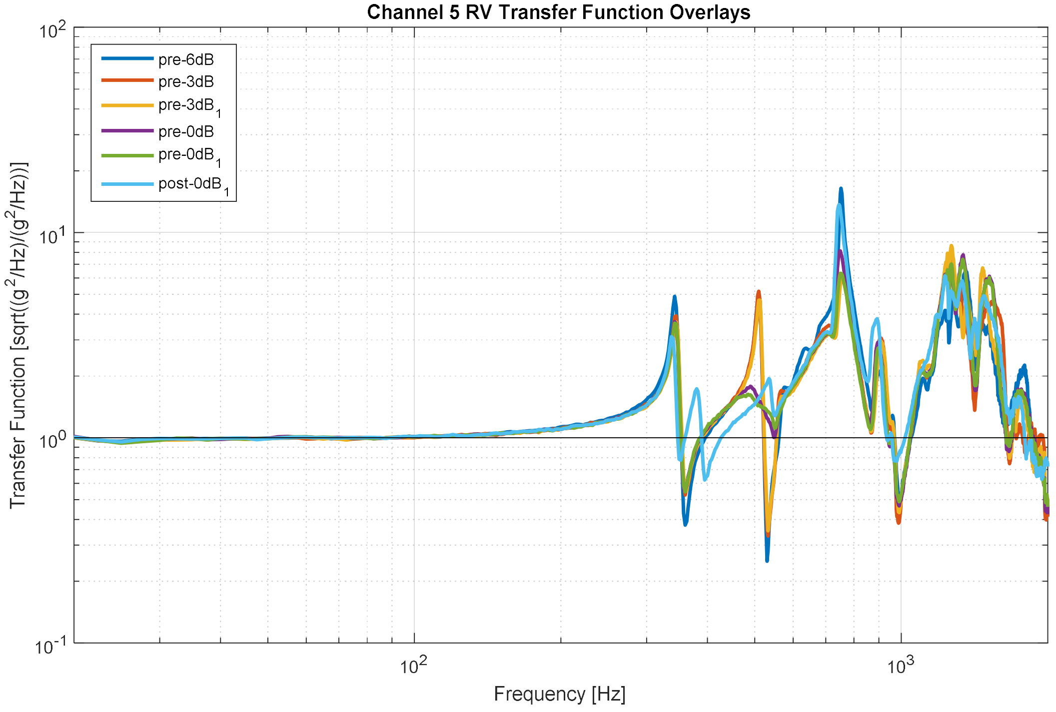
Vibration Testing Results

- Significant cross-coupling in input excitation. For qualification:
  - Input axis: 6.85 grms
  - Cross-coupling of input: 4.36 and 4.18 grms
- No significant frequency shifts seen until final qualification round
  - 500 Hz original frequency split into two
  - Possibly vibration absorber formed due to settling of structure
  - No damage seen



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Vibration Testing Results

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

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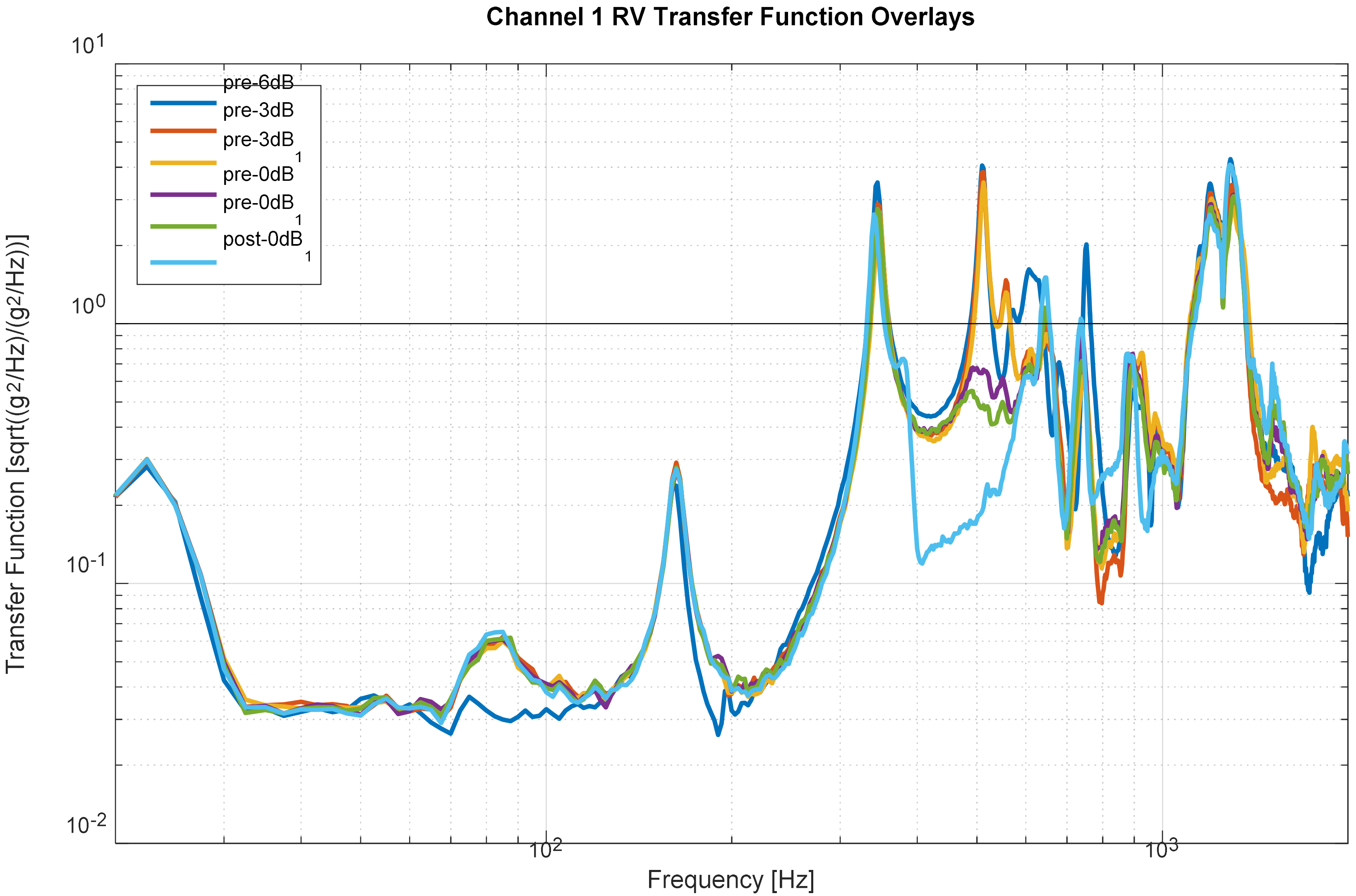
Conclusion and Remaining Tests

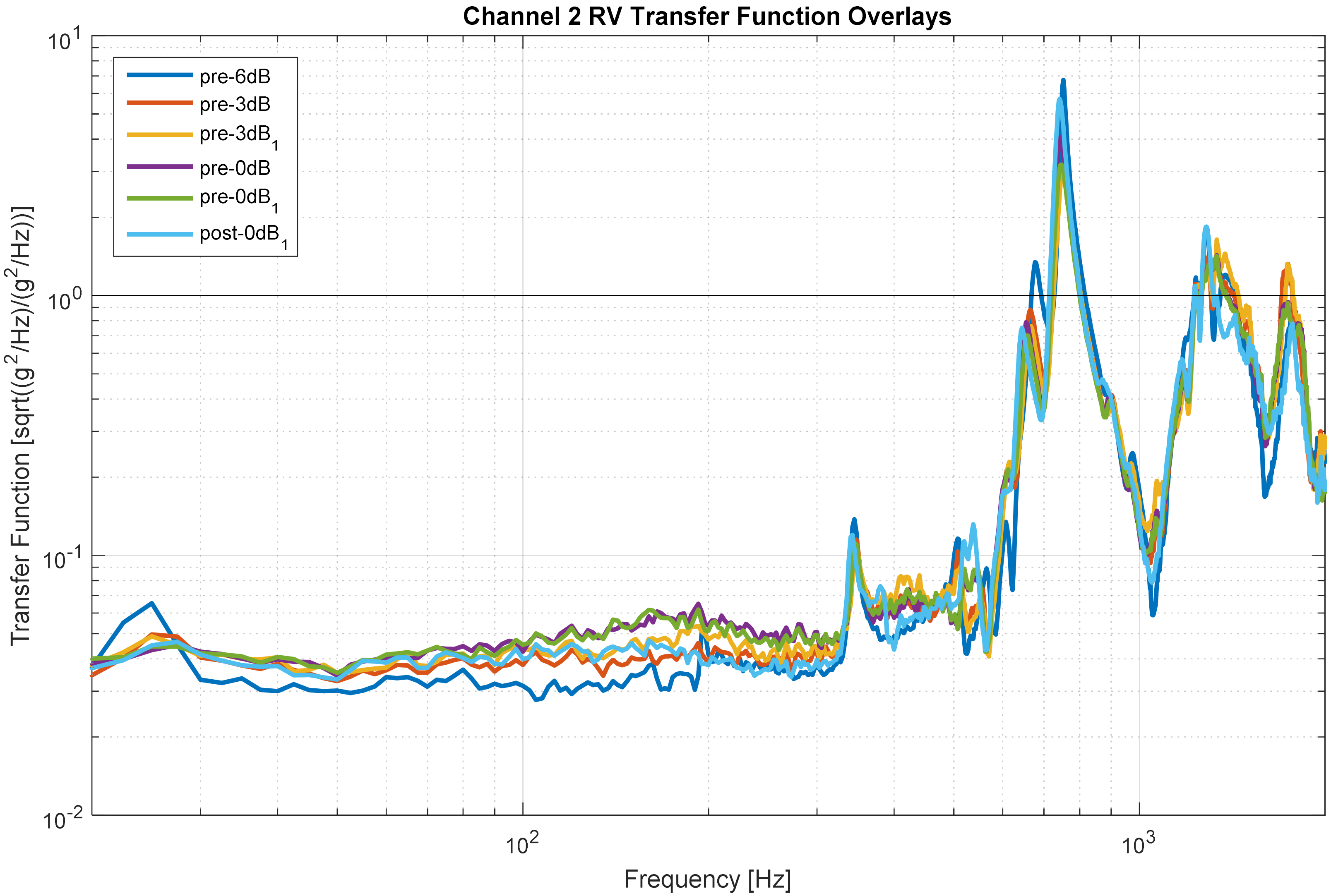
- Camera meets all requirements
  - Mechanical, functional requirements met
  - Optical performance as expected
  - Environmental testing done to show survivability and functionality
- Remaining work:
  - Swap out B/S and lenses for flight optics
  - Vibration testing to check electronics survivability
  - Fabrication of external interfaces
  - Verification of power requirement (currently met by operating in various modes)

Backup

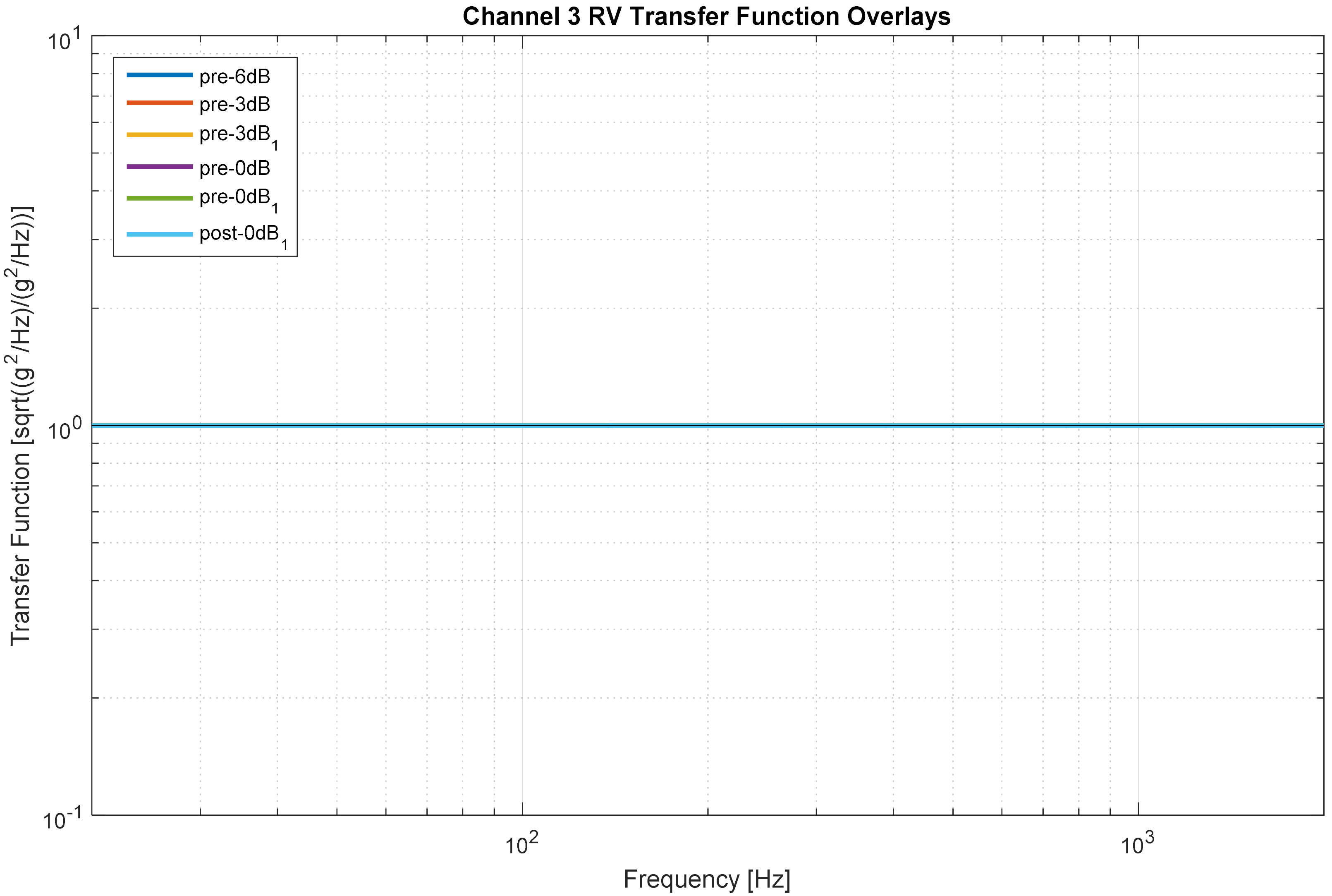
Ch 1 RV Transfer Function



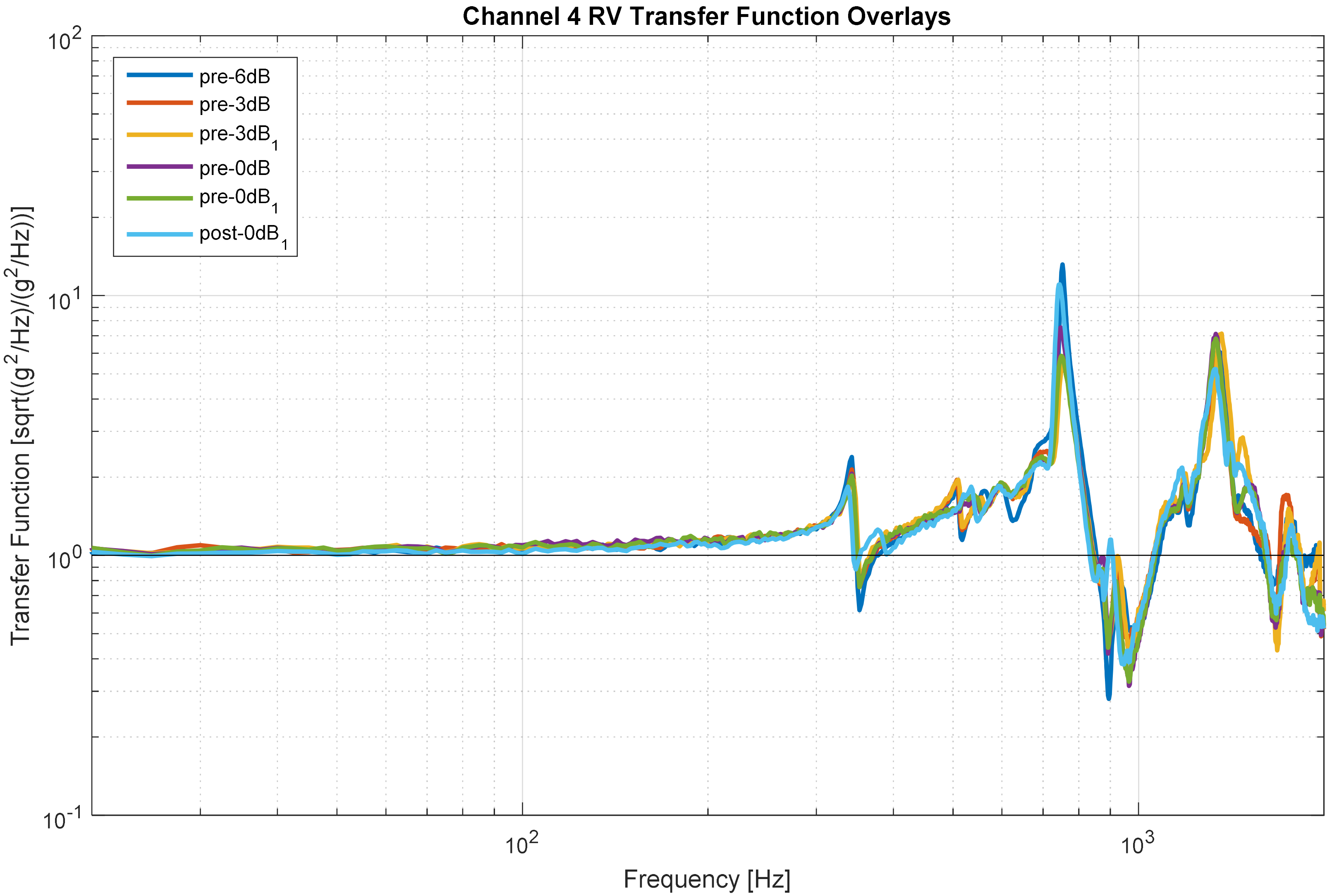
Ch 2 RV Transfer Function



Ch 3 RV Transfer Function



Ch 4 RV Transfer Function



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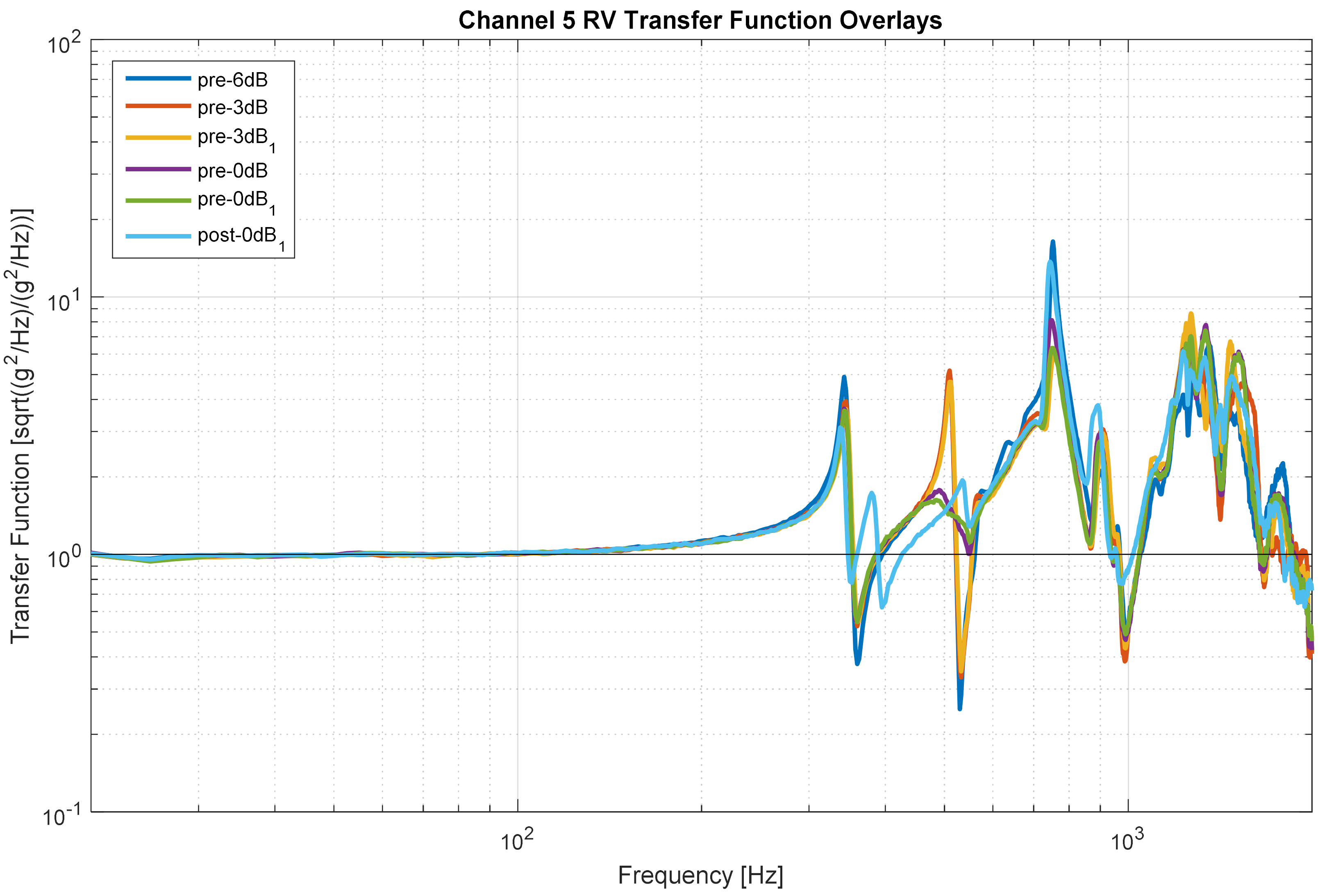
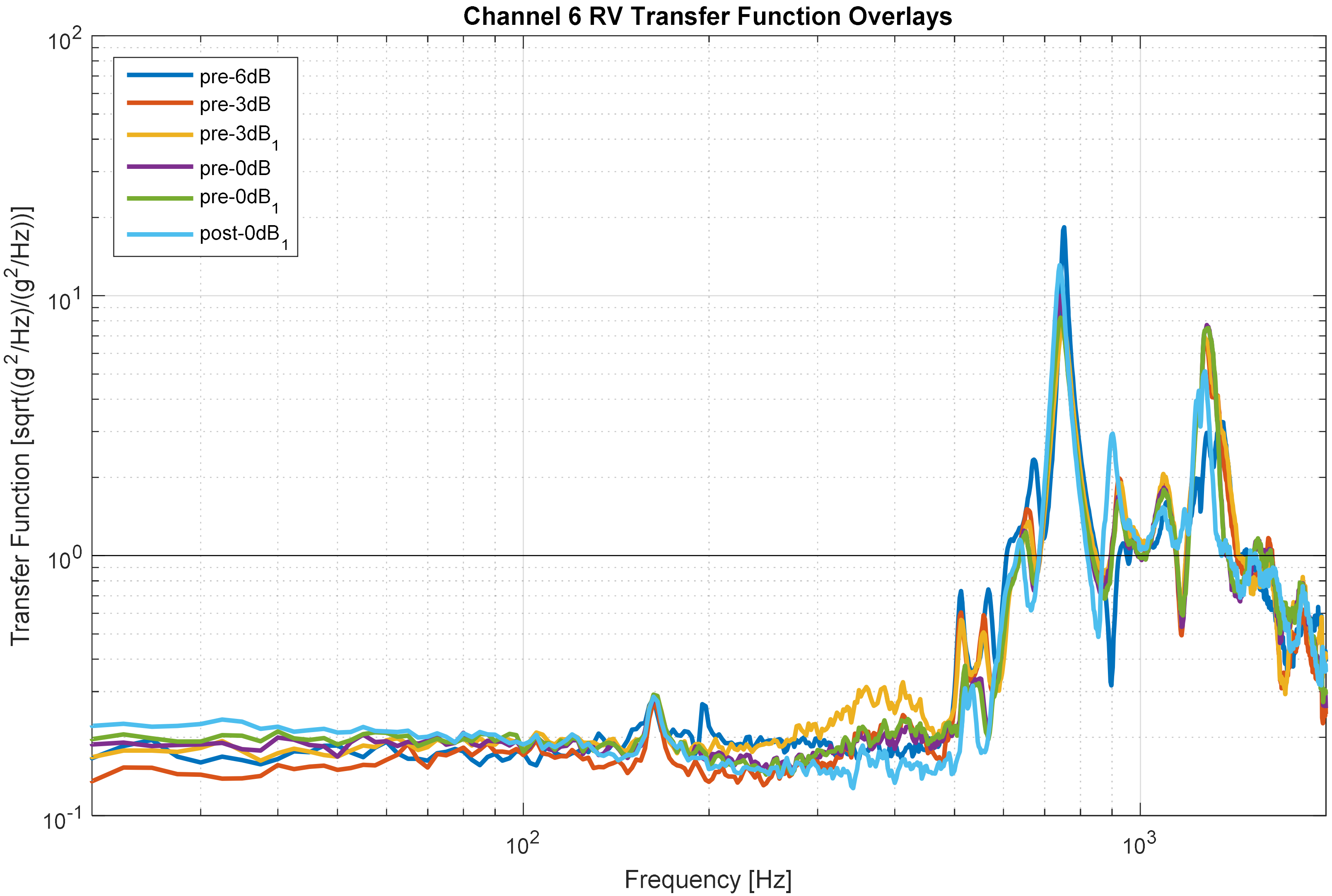
Ch 5 RV Transfer Function



Ch 6 RV Transfer Function



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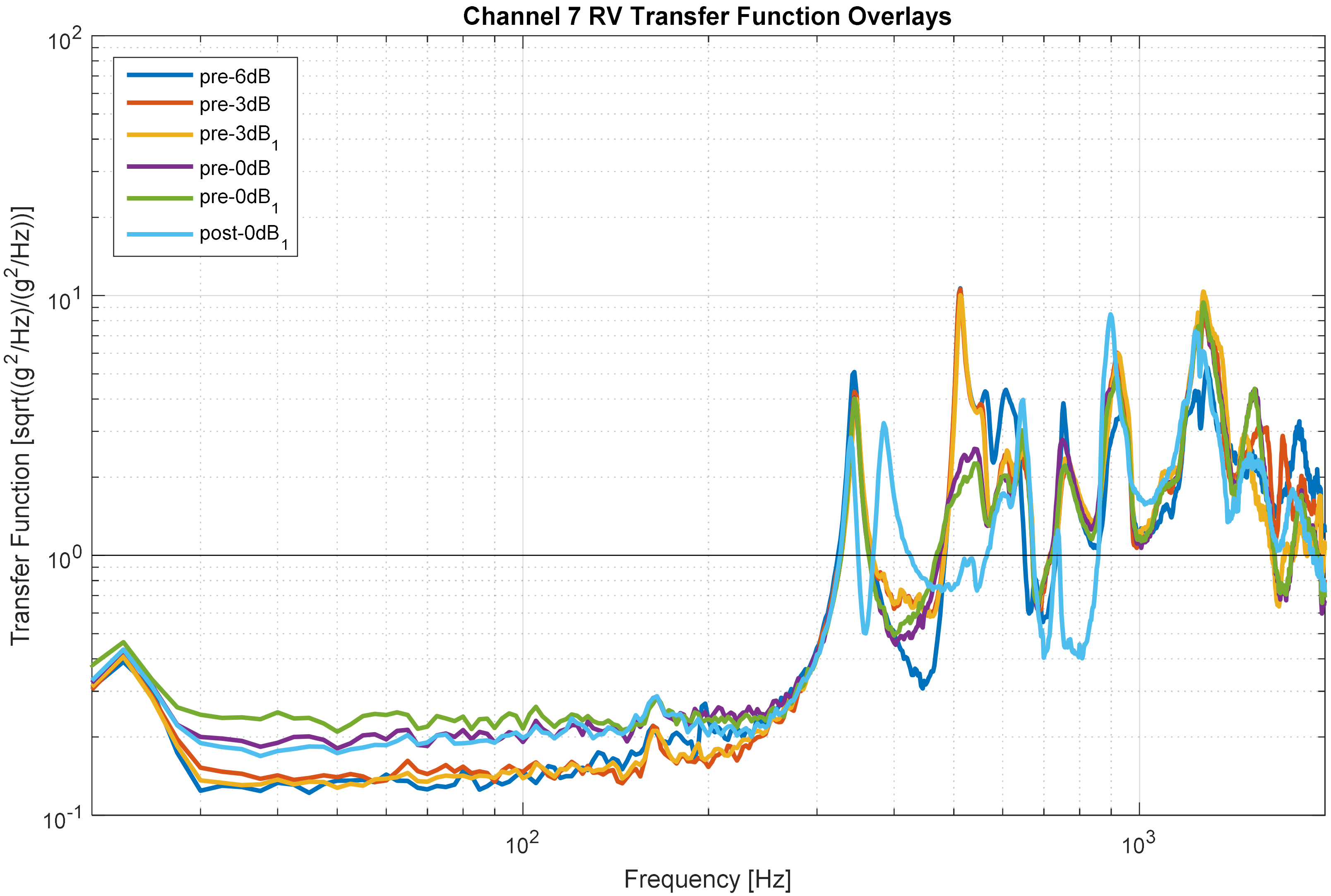
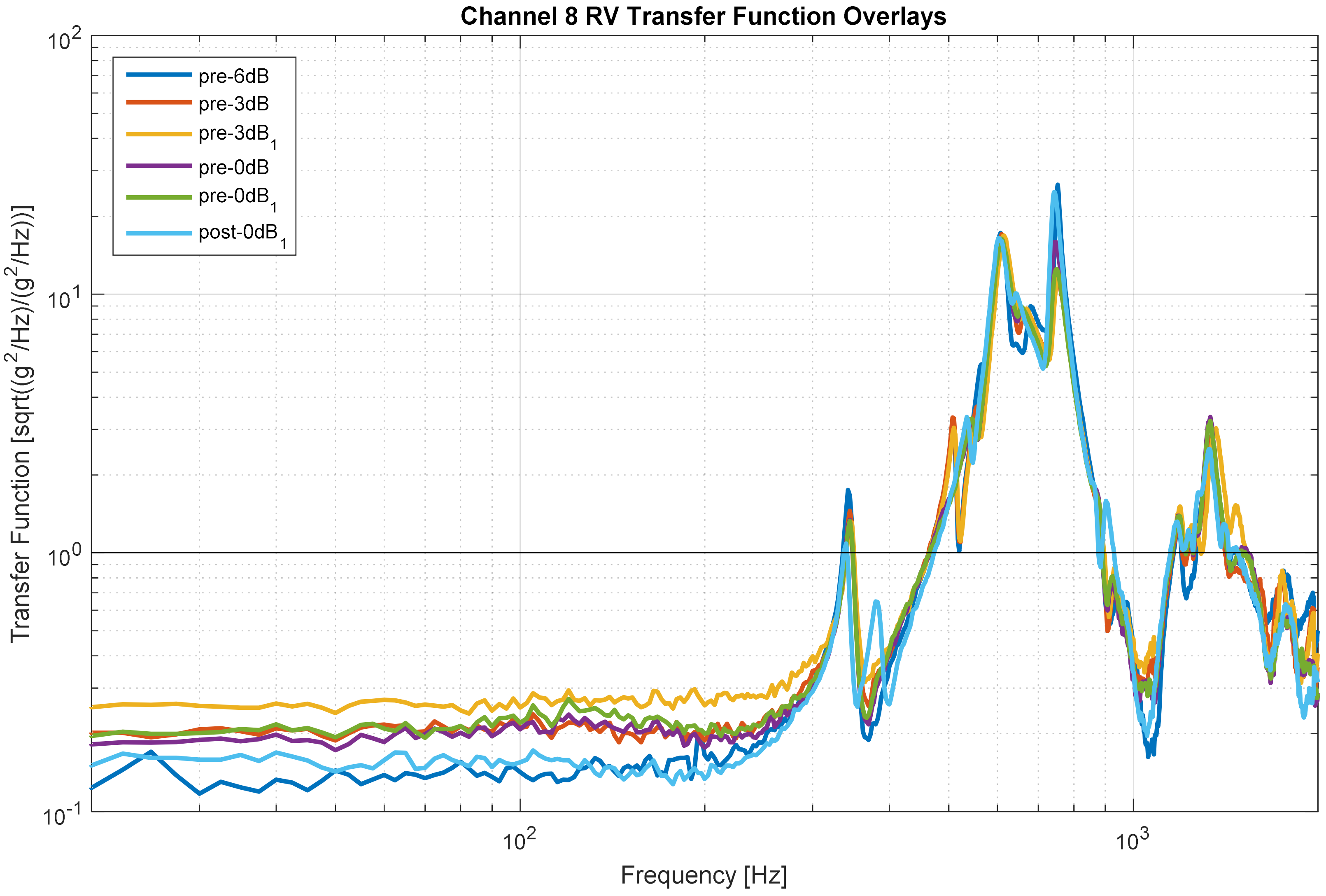
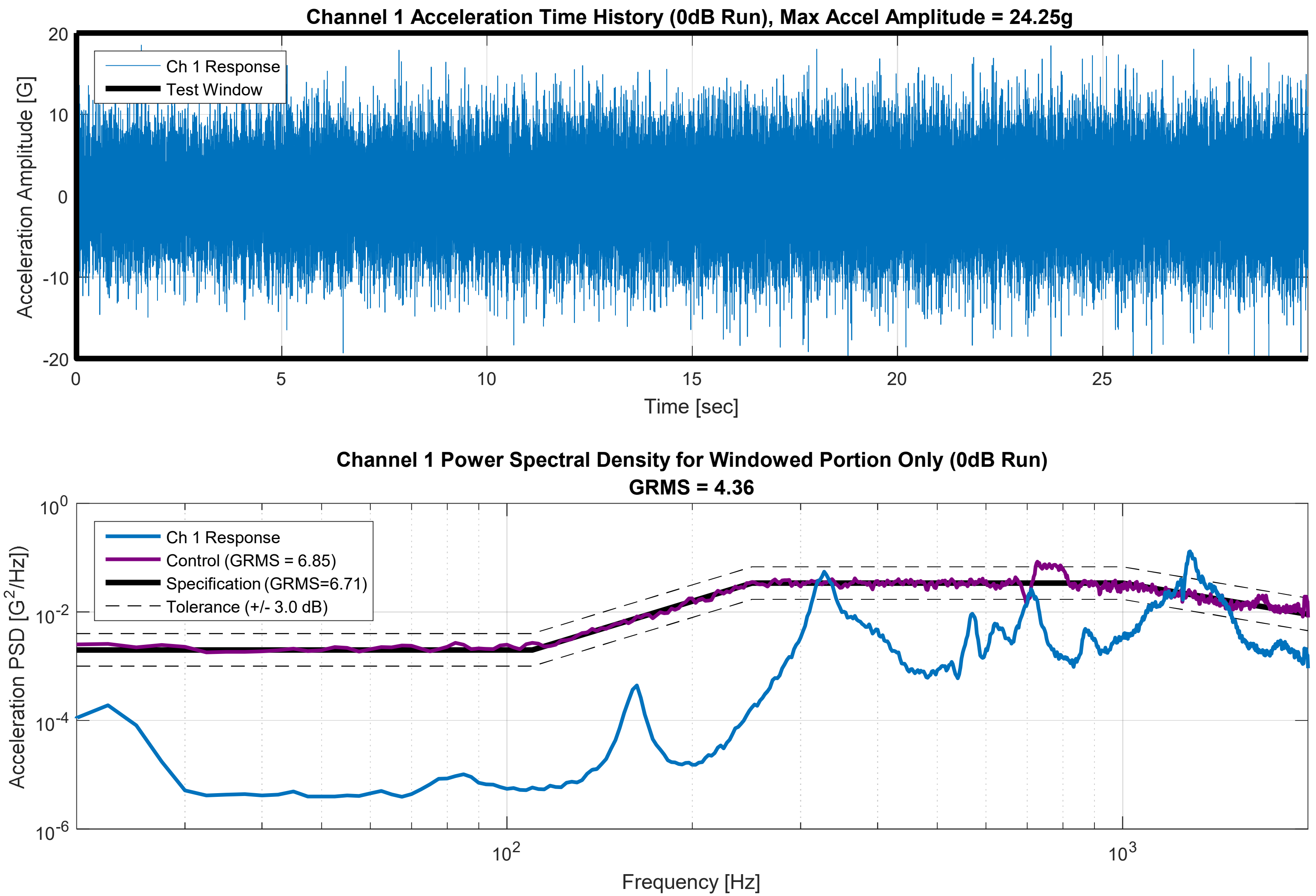
Ch 7 RV Transfer Function



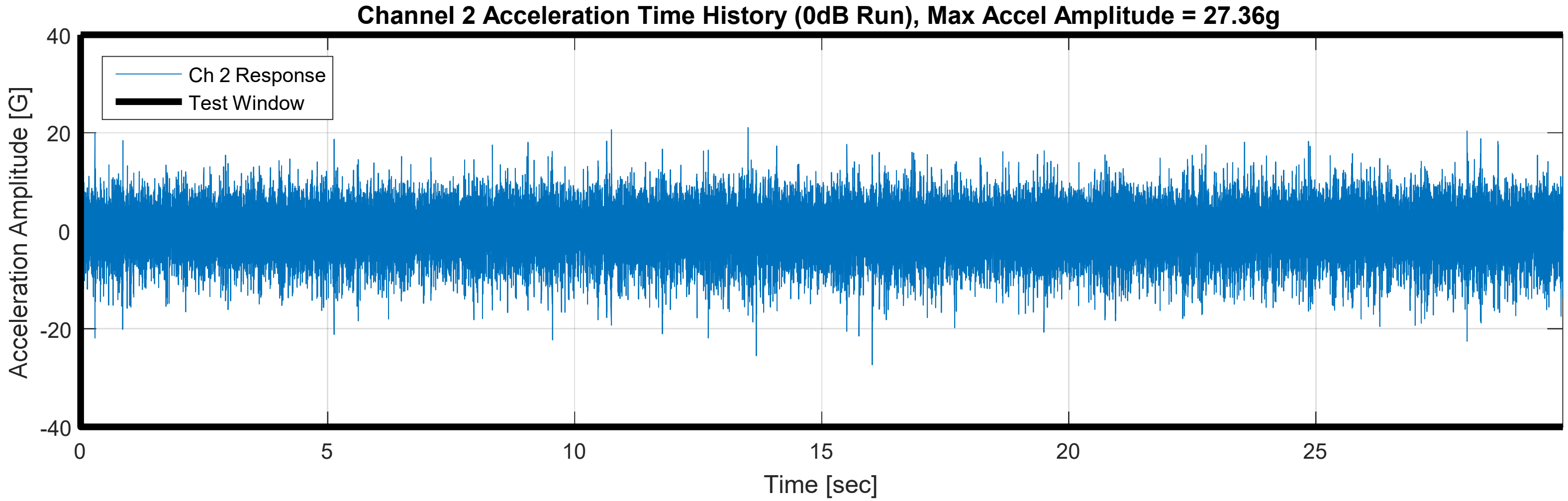
Ch 8 RV Transfer Function

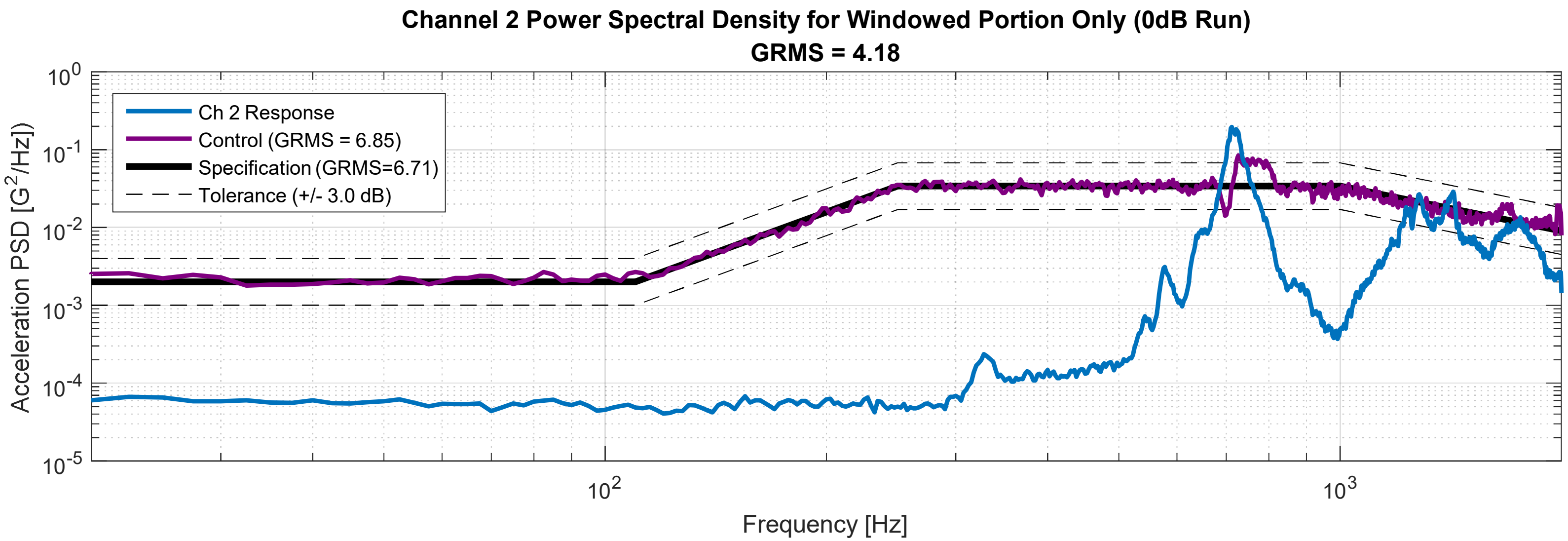


Ch 1 RV Test Results (0dB Run)

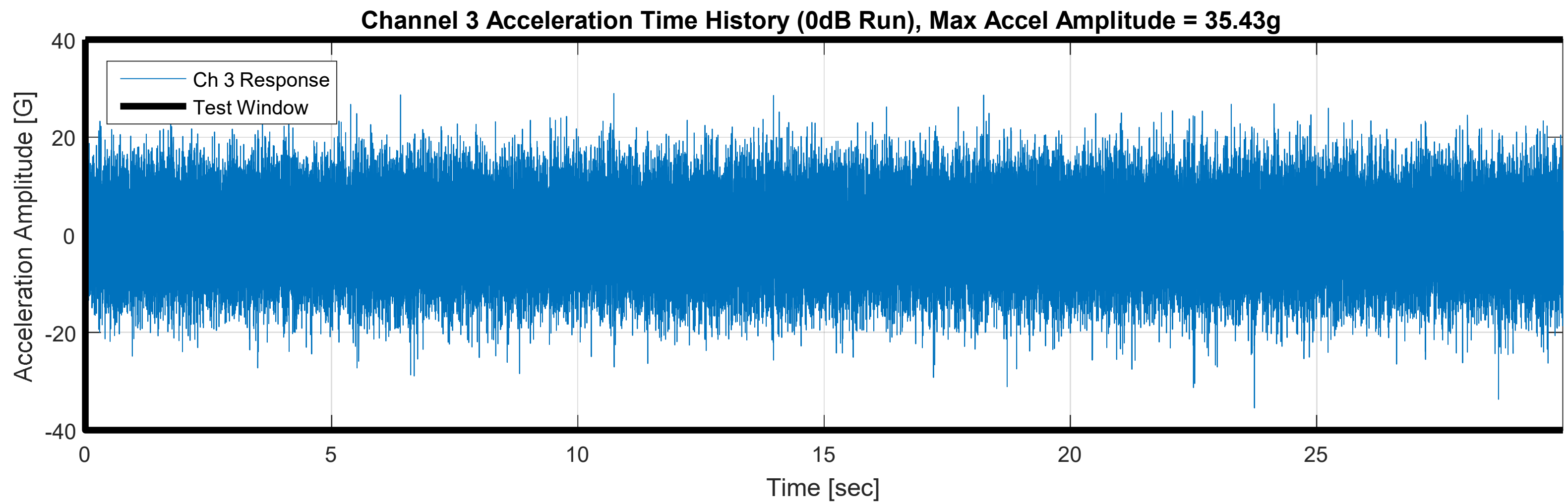


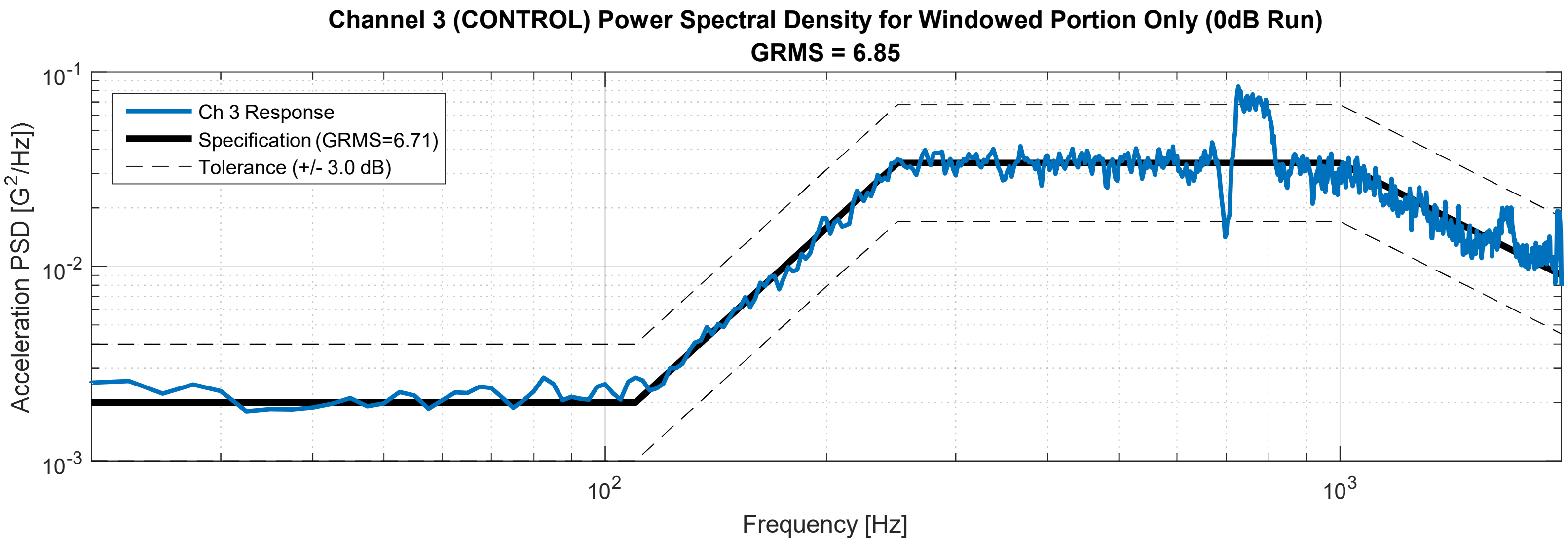
Ch 2 RV Test Results (0dB Run)



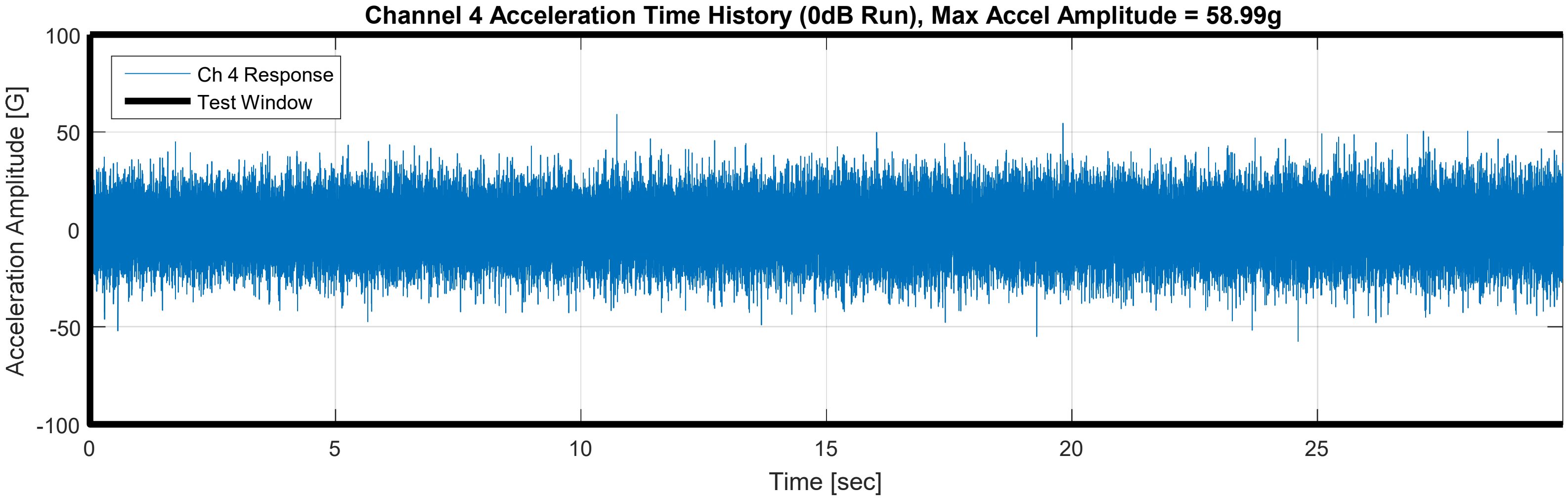


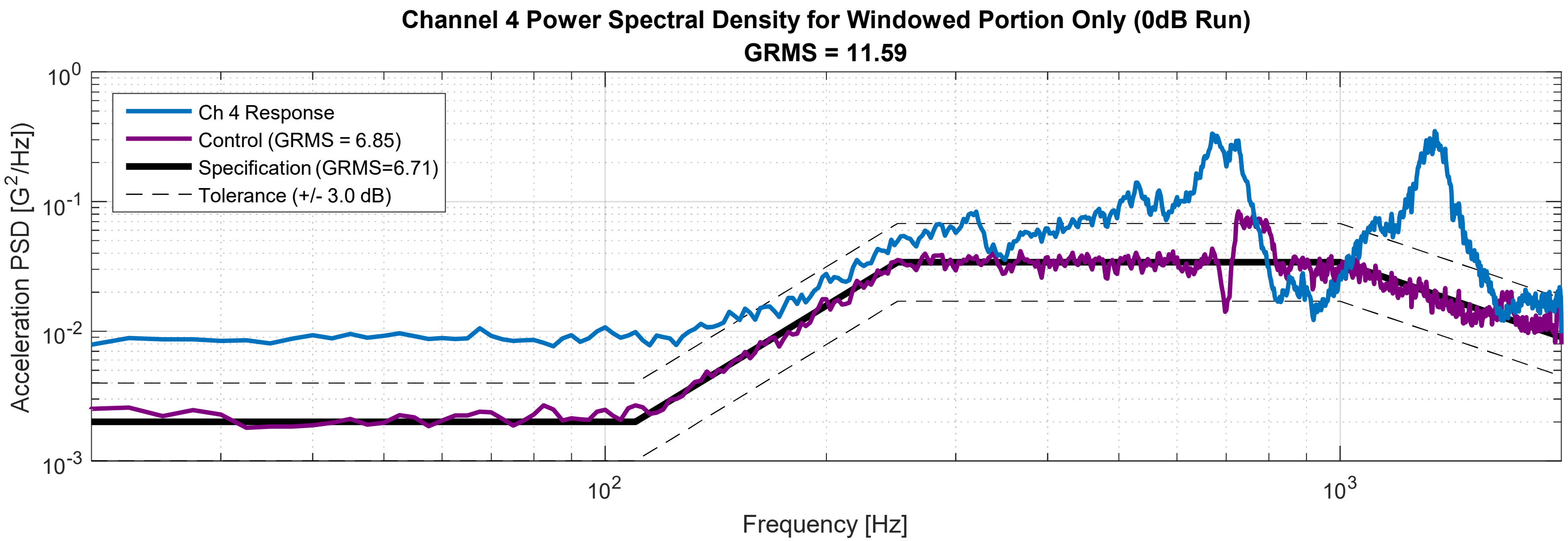
Ch 3 RV Test Results (0dB Run)



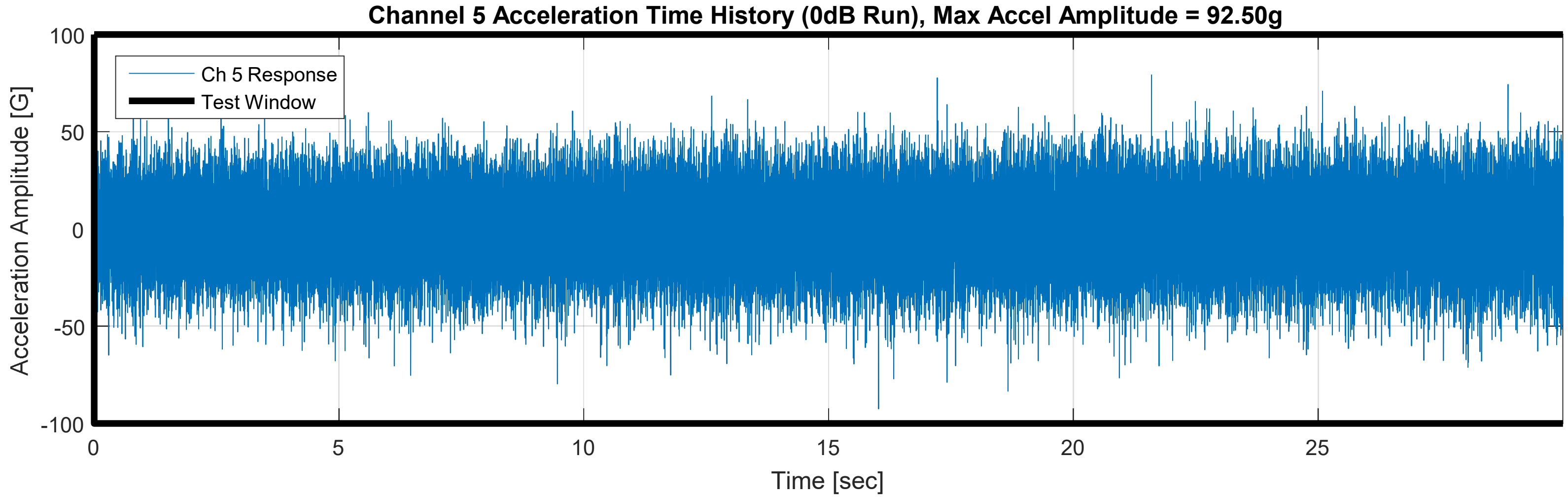


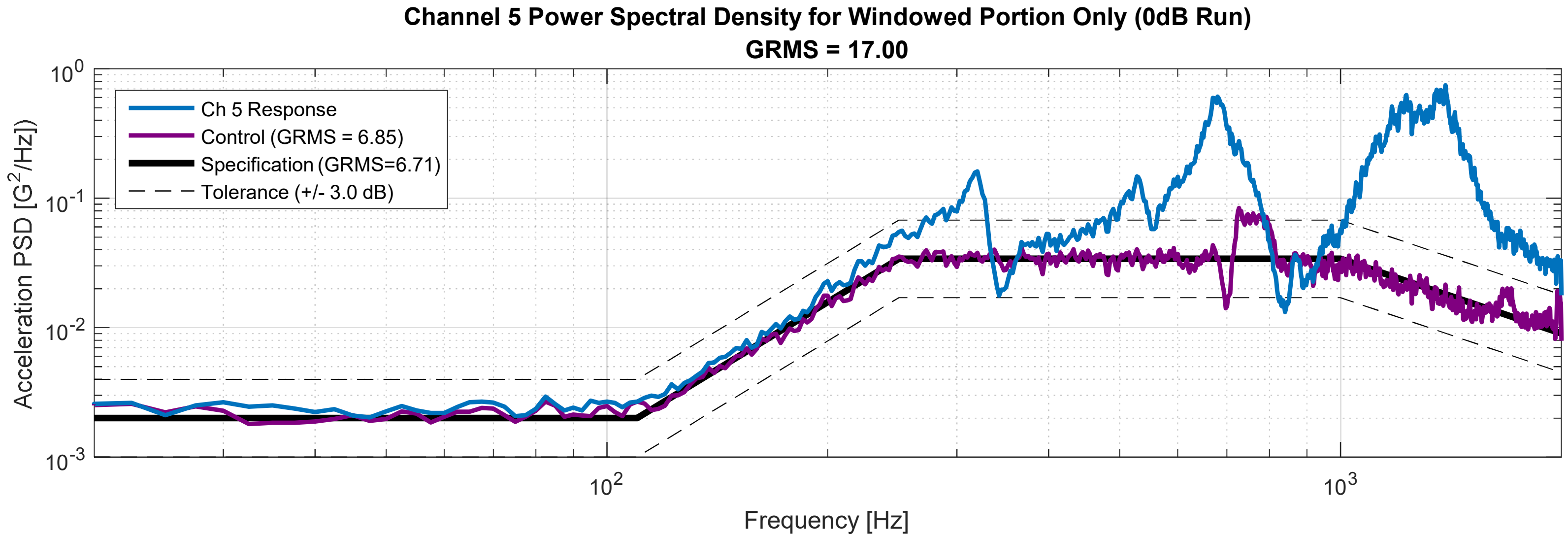
Ch 4 RV Test Results (0dB Run)



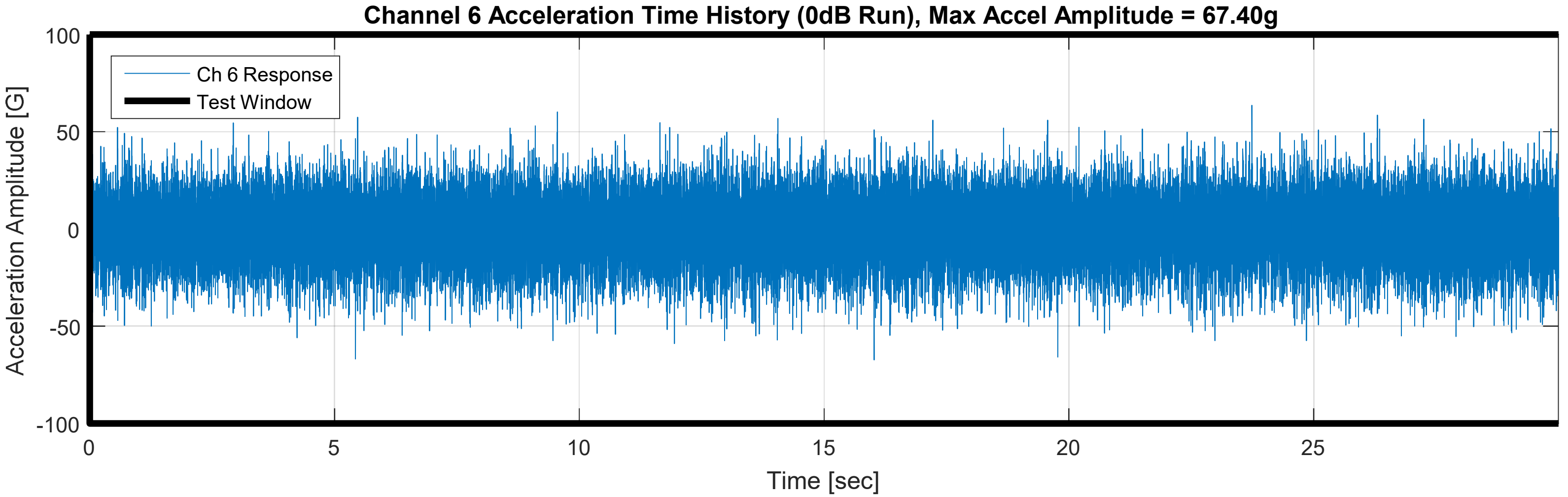


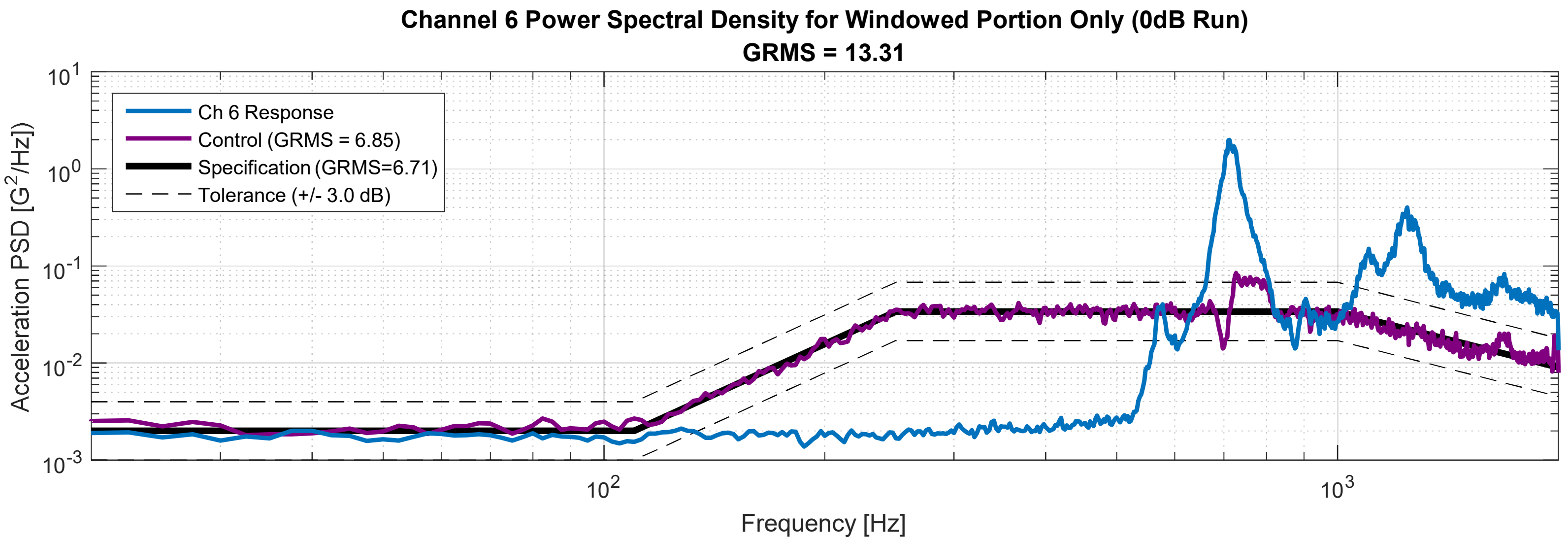
Ch 5 RV Test Results (0dB Run)



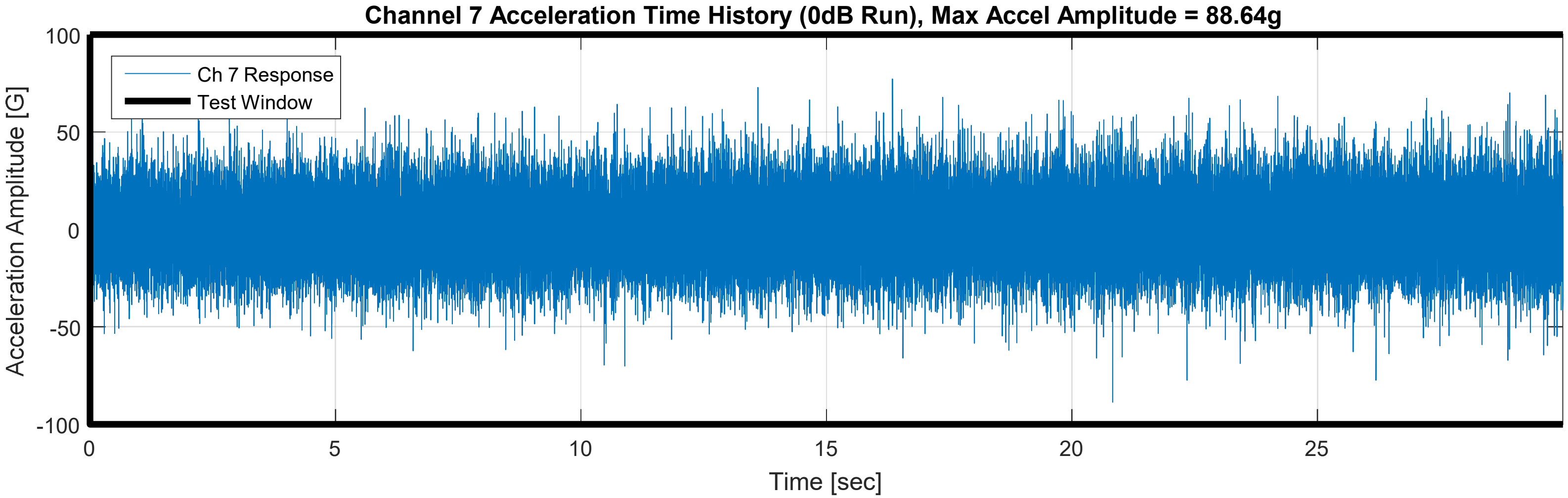


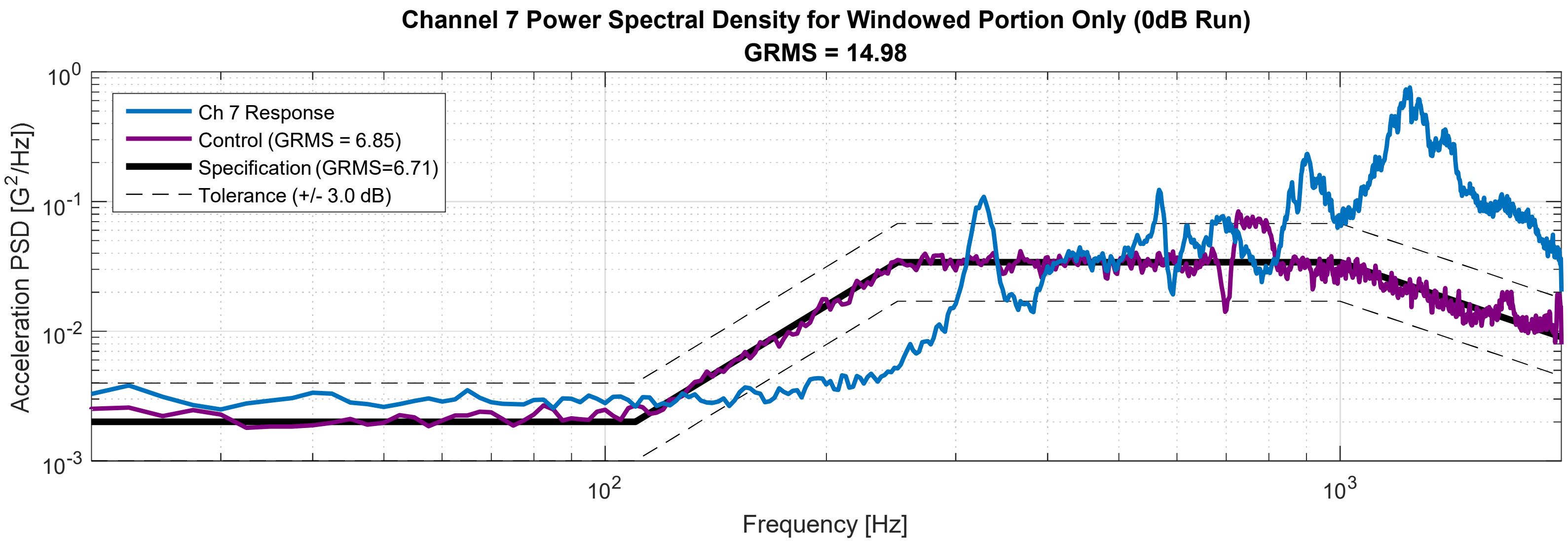
Ch 6 RV Test Results (0dB Run)



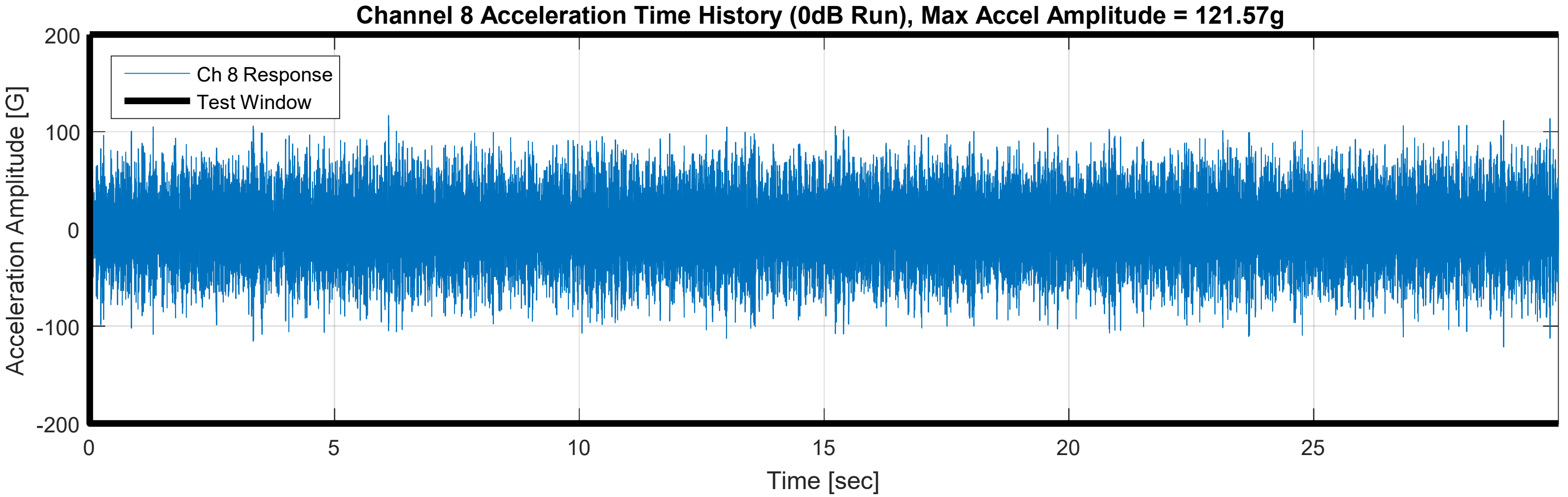


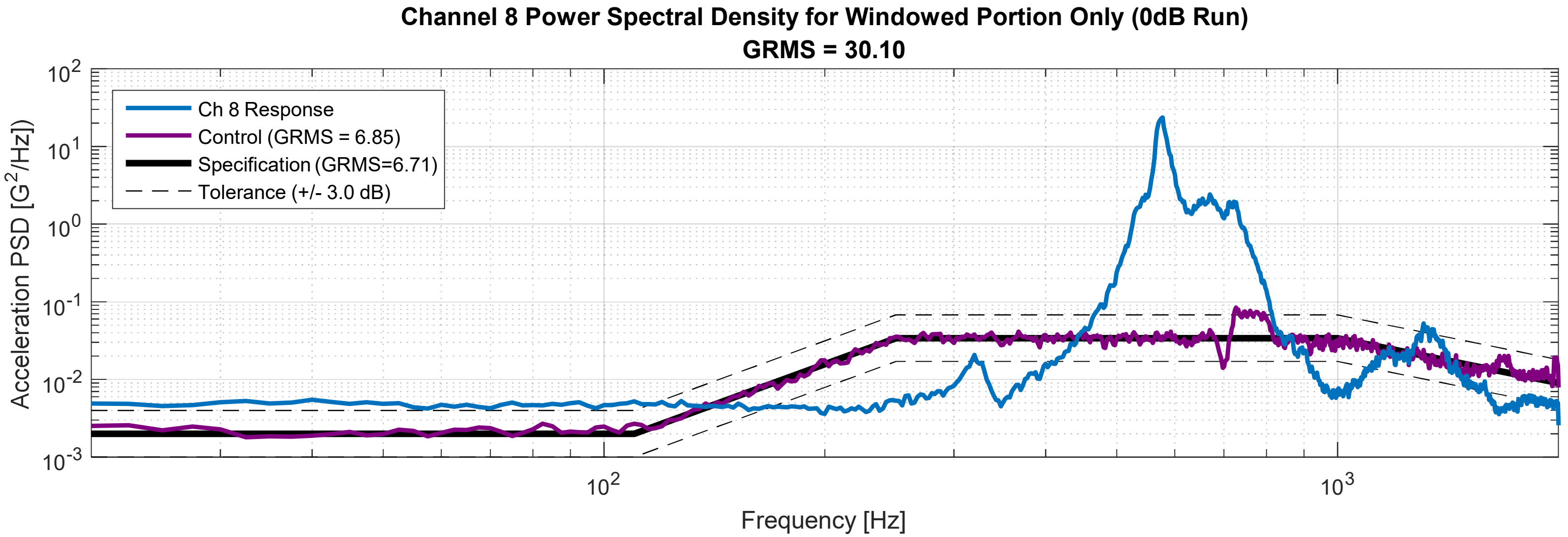
Ch 7 RV Test Results (0dB Run)





Ch 8 RV Test Results (0dB Run)





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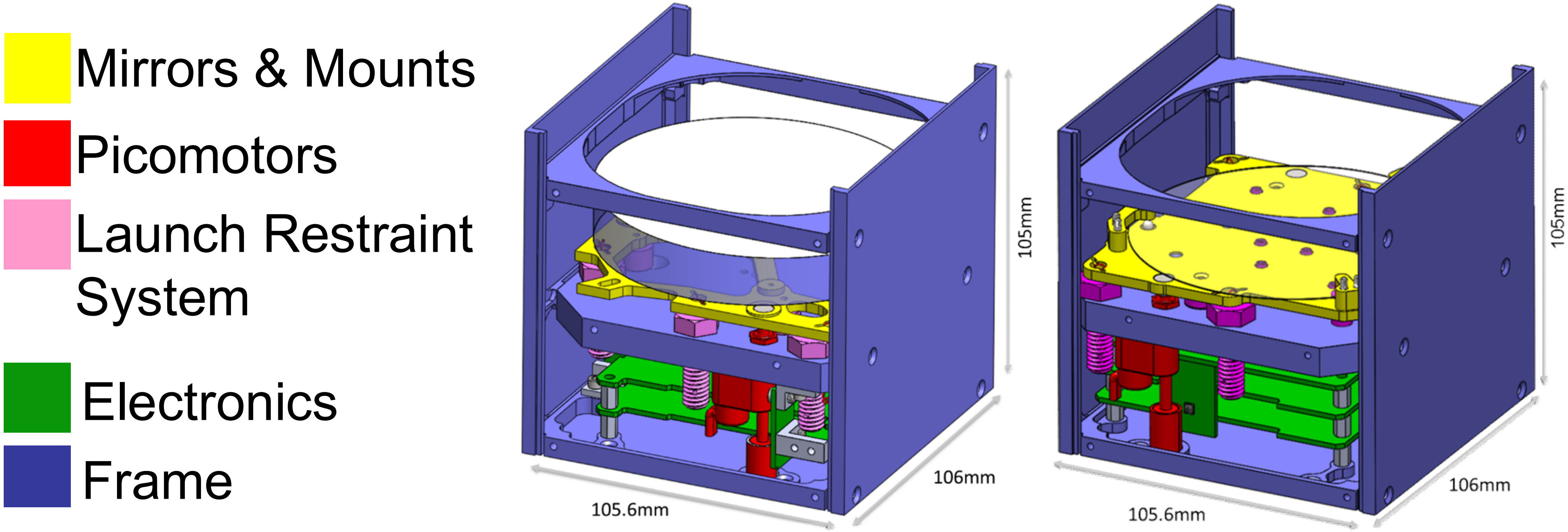
Mirror Boxes Overview

Requirements Overview

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



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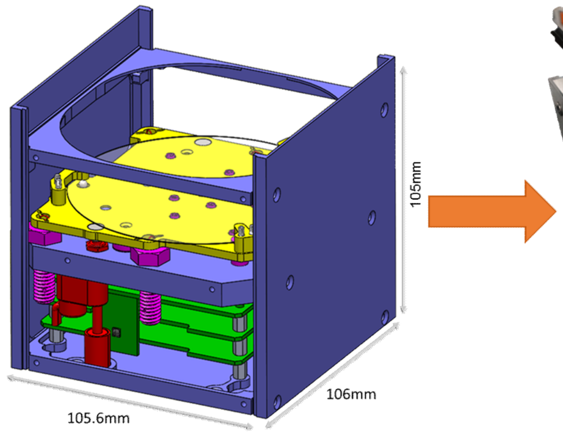
Outline

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

Accomplishments

Assembly

- Fully assembled mirror boxes from CAD models
- Assembly procedures



Testing

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

Integration

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

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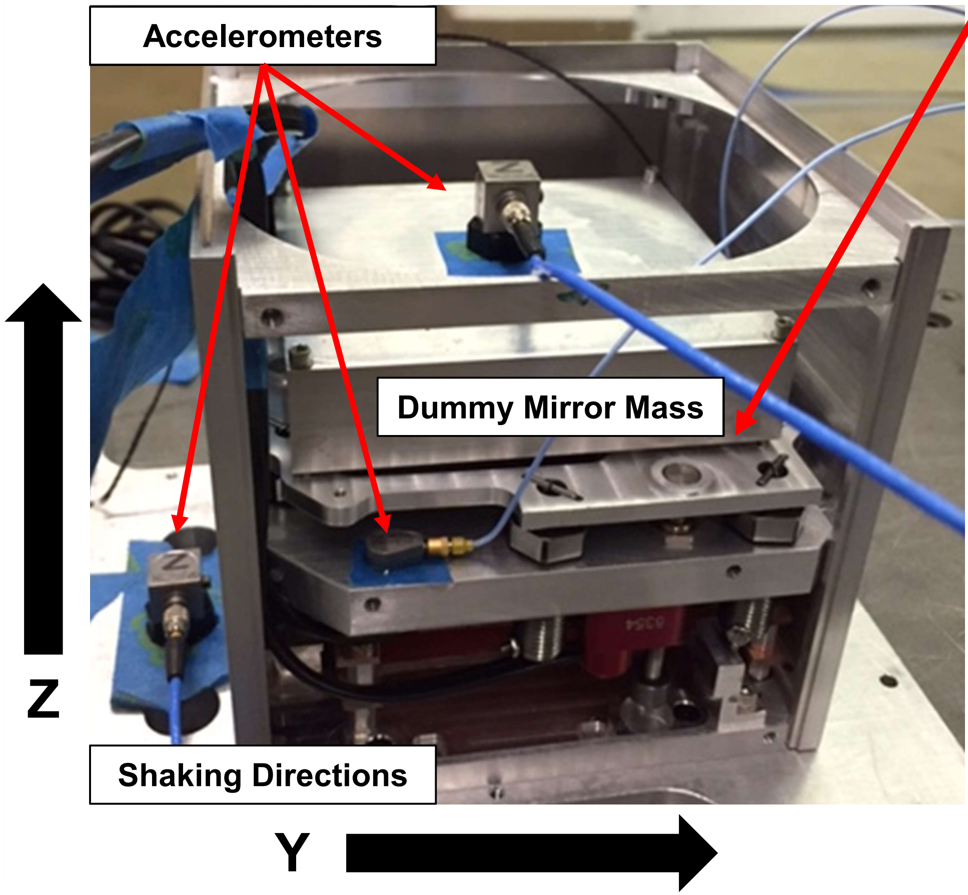
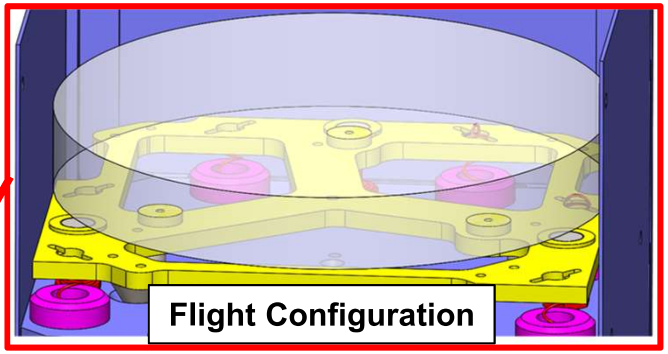
Rigid Mirror Box Vibration Tests

Test Setup

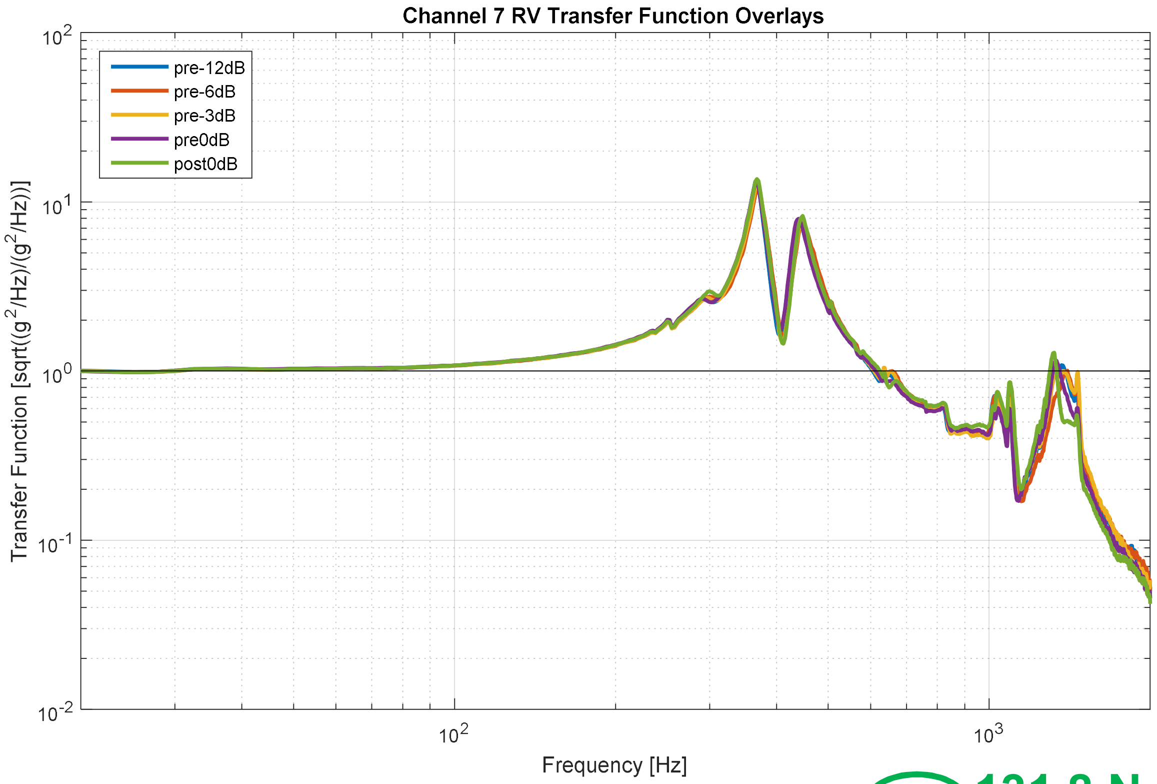


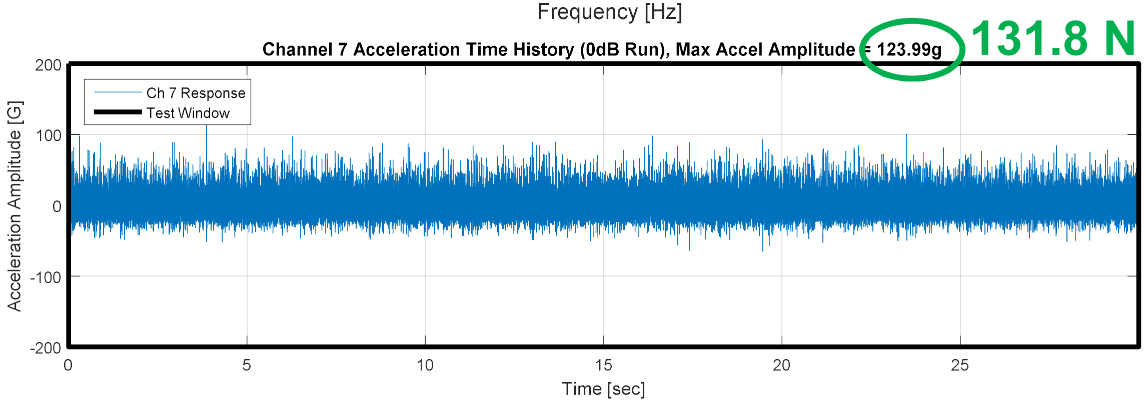


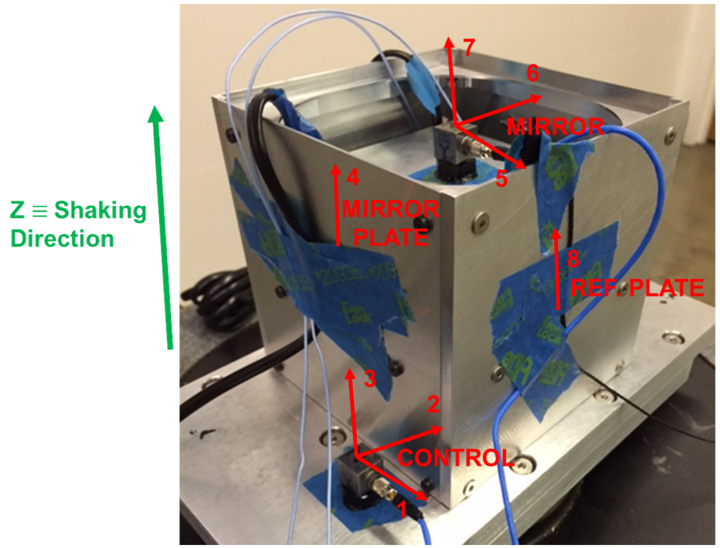
Test Pass/Fail Evaluation Criteria

Criterion	Pass	Fail
Frequencies peaks shift	<5%	>5%
Springs location	not-shifted	Shifted
Picomotors	operational	not-operational
Screws	tight	Loose
Vectran cable	not-shifted	shifted

Rigid Mirror Box Vibration Tests







Results

- No noticeable frequencies shift
- General visual check passed (springs, vectran cable)
- Picomotors functioning

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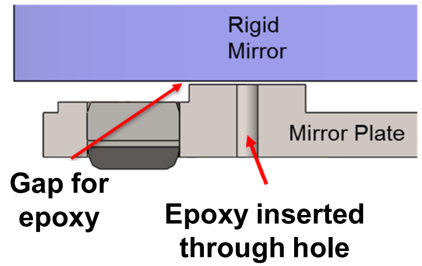
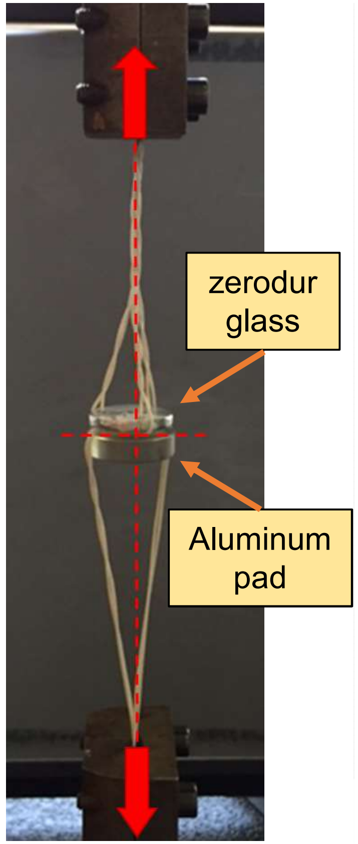
Bond Strength Tests

Highest Peak Measured from Vibe Tests: 131.8 N per pad

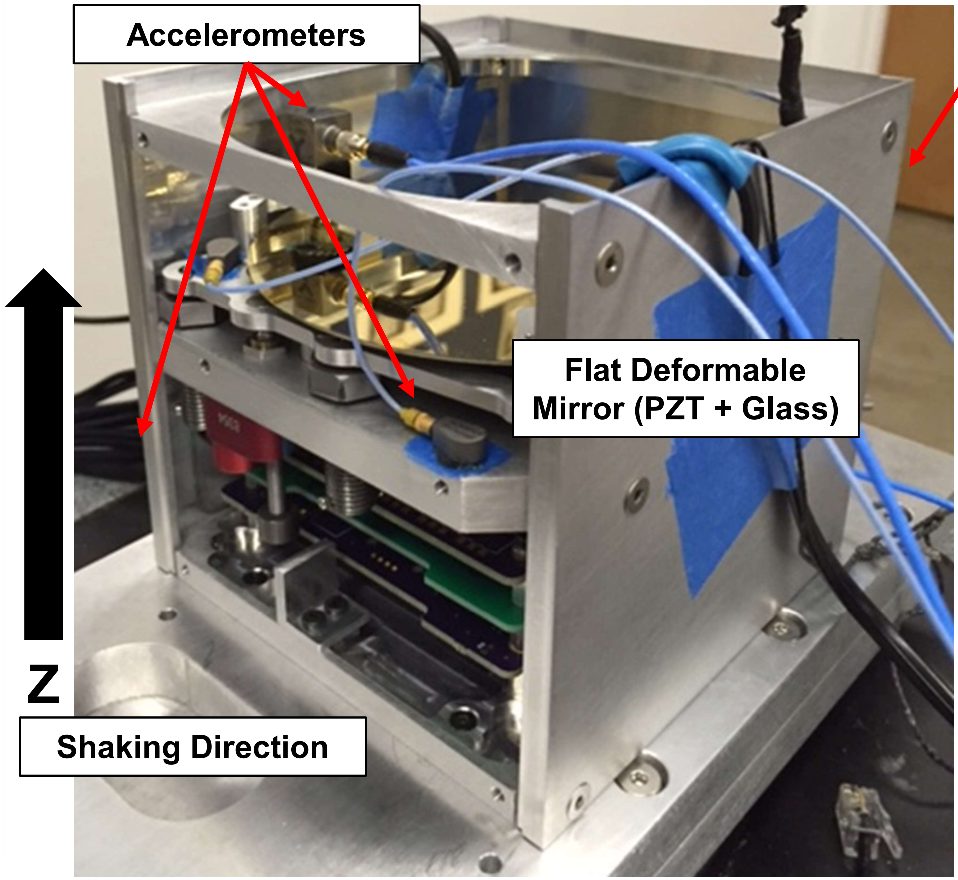
Bond Strength Performance - LOCTITE EA 9394 AERO		
Documented Technical Data Sheet	**Tensile Lap Shear Strength**	**Tensile Bond Strength**
	28.9 Mpa - 1452.7 N (per pad)	N/A
	Test Setup	**Tensile Failure Load**
Test #1	– no primer – no surface grinding – no wait after surface cleaning – application through hole (0.254mm thickness) – room temperature cure	88.8 N
Test #2	– no primer – 180 grit surface grinding – 20 min wait after surface cleaning – application by hand (thicker) – 1 hour at 66 °C cure	486.6 N
Test #3		721.1 N
Test # 4	– primer EA 9203 – 240 grit surface grinding – 20 min wait after surface cleaning – application by hand (thicker) – 1 hour at 66 °C cure	329.2 N
Test #5	– primer EA 9203 – 240 grit surface grinding – 20 min wait after surface cleaning – application through hole (0.5mm thickness) – 1 hour at 66 °C cure	511.3 N
Test #6		589.6 N
Test #7		518.1 N
Test #8		649.3 N





Deformable Mirror Box Vibe Tests

Test Setup



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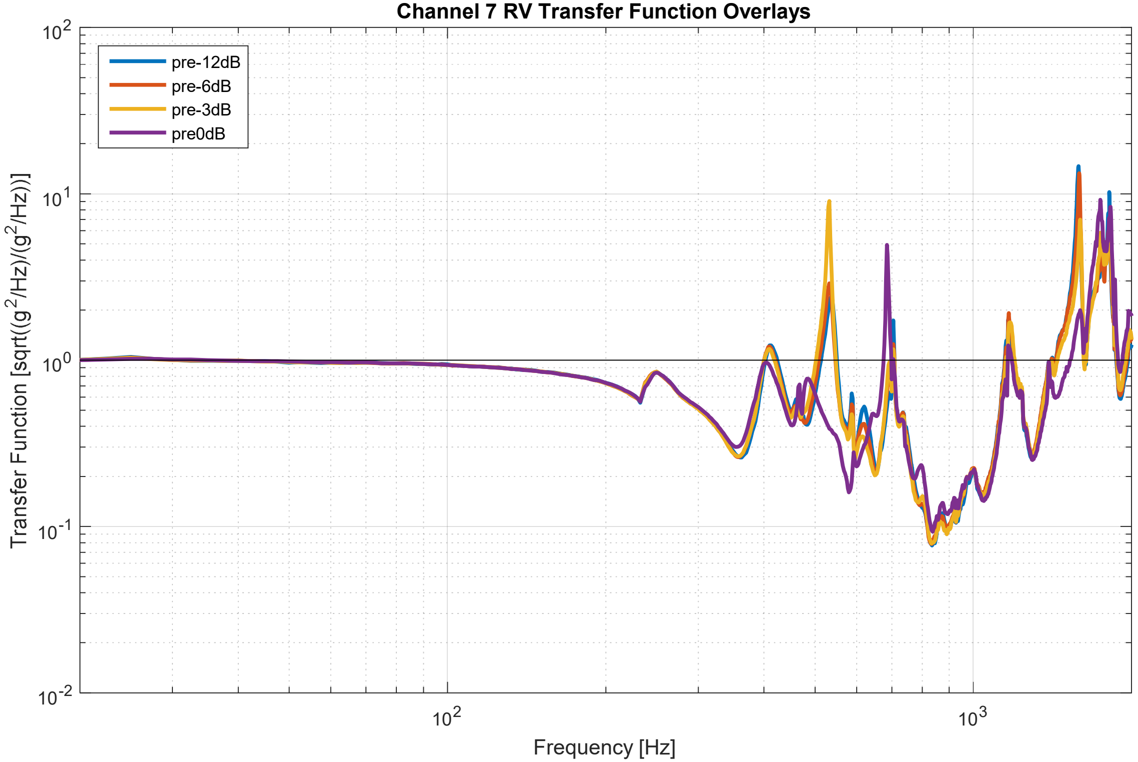
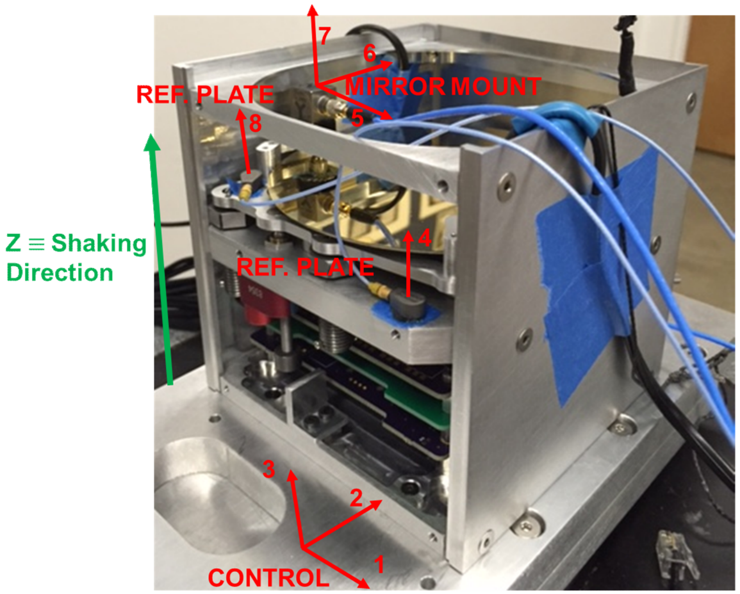
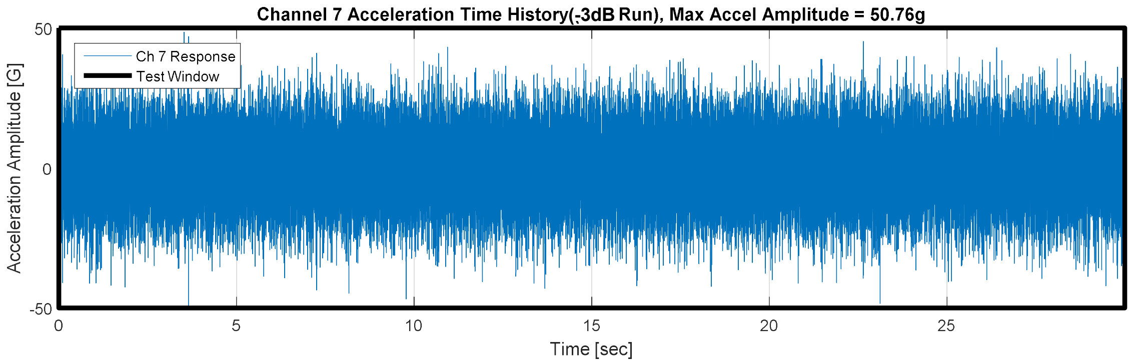
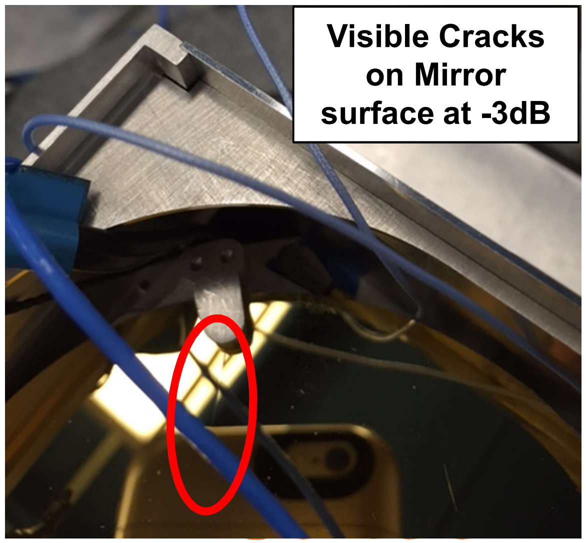
Springs location	not-shifted	shifted
Picomotors	operational	not-operational
Screws	tight	loose
Vectran cable	not-shifted	shifted
Deformable Mirror	not-broken	broken

Deformable Mirror Box Vibe Tests

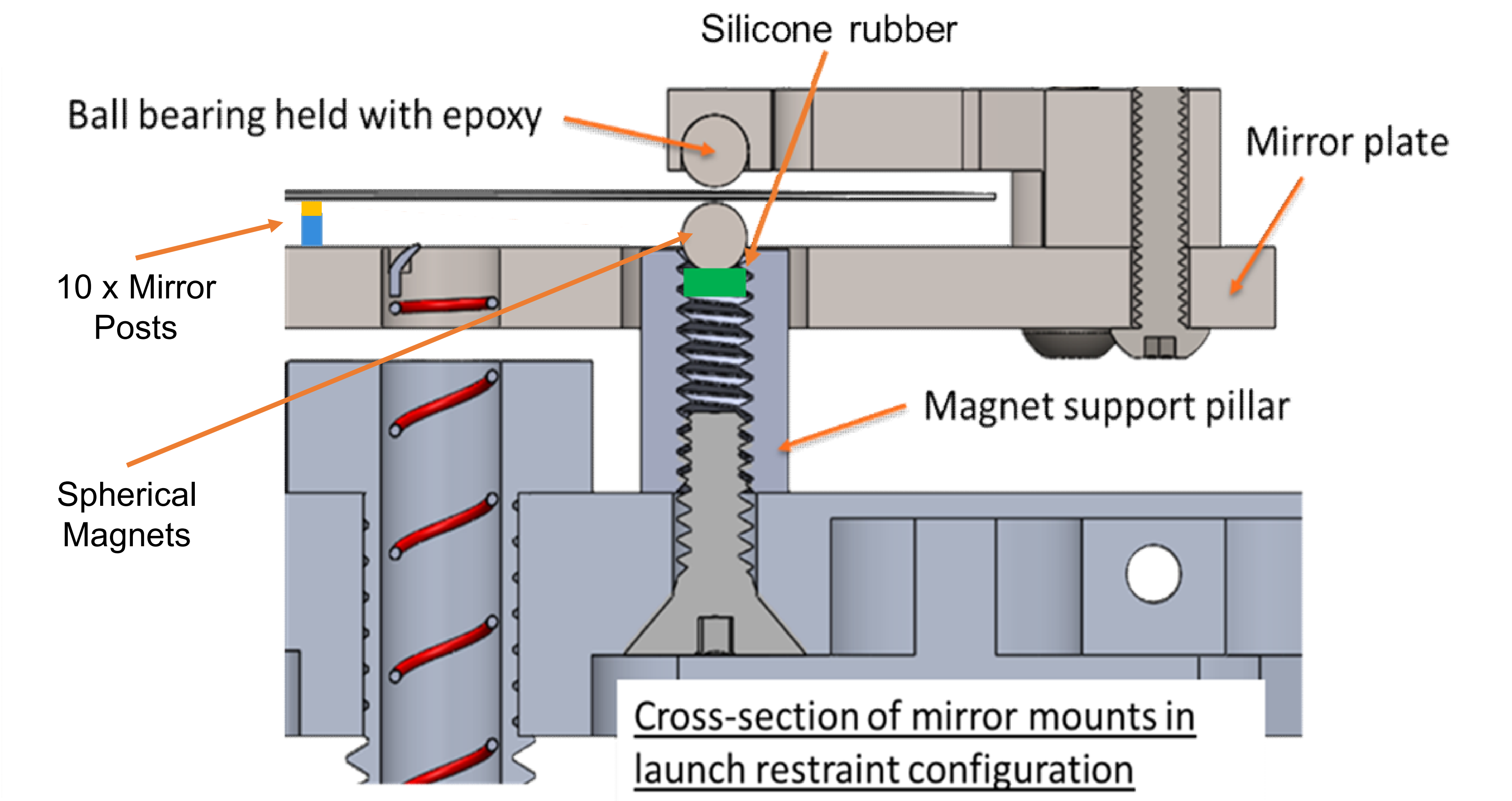








Deformable Mirror Mounts



Cross-section of mirror mounts in launch restraint configuration

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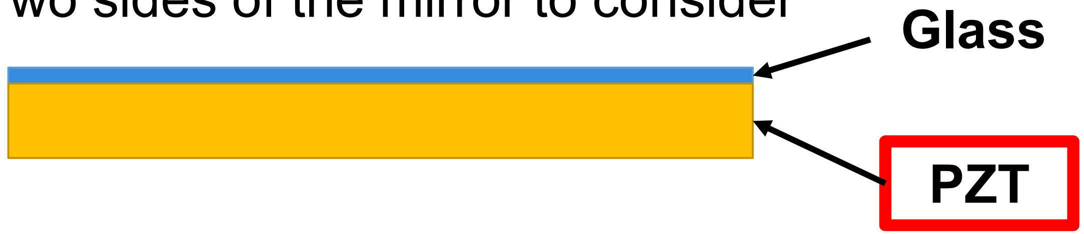
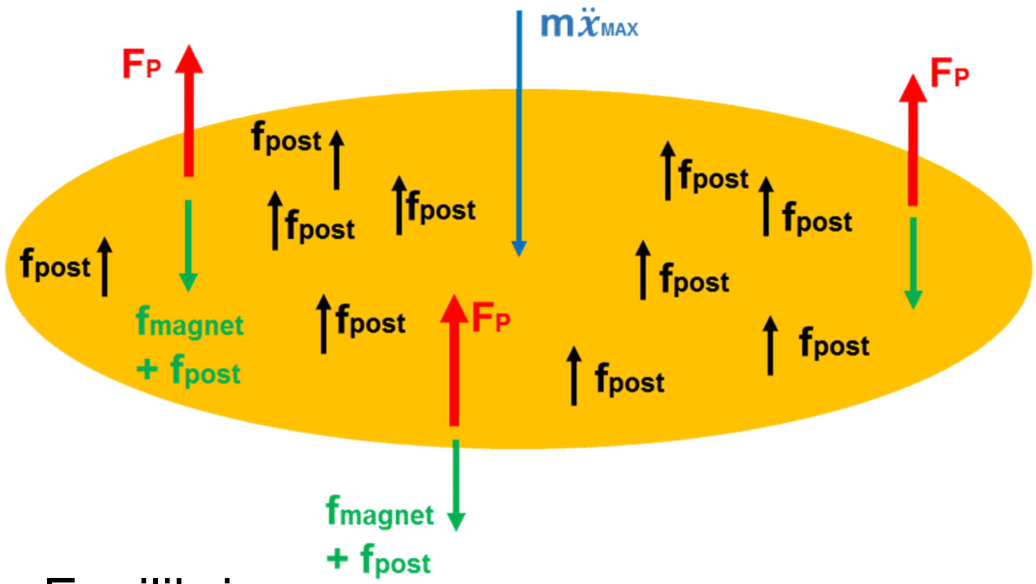
Mirror Failure Analysis

Two sides of the mirror to consider



PZT free body diagram



- F_P = contact force magnets (assume equal at each mount)
- f_{post} = force from mirror posts (10)
- mx_{max} = vibrating mirror
- f_{magnet} = magnet pull force

Equilibrium

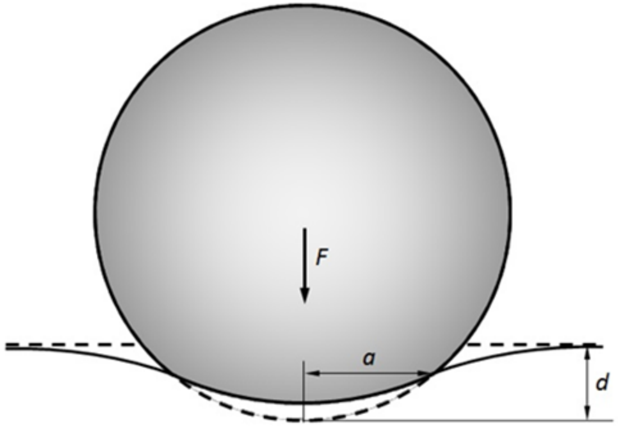
$$F_p = \frac{-10\, f_{post} + m\ddot{x}_{\max} + 3(f_{magnet} + f_{post})}{3} = 12.401N$$

PZT Failure Analysis

Hertzian contact stress theory

- Contact between a sphere and a half-space

$$p_0 = \frac{3F}{2\pi a^2} = \frac{1}{\pi}\left(\frac{6FE^{*2}}{R^2}\right)^{1/3}$$



$\nu_{sphere} = 0.24$ (Neodymium)
$E_{sphere} = 100\ GPa$
$\nu_{PZT} = 0.31\ (Yuchen's\ data\ PZT - 5A)$
$E_{PZT} = 62.66\ GPa$

$E^* = 49.72\ GPa$
$\mathbf{p_0 = 1.0152\ GPa}$

PZT Compressive Strength
$\sigma_{u_{PZT}} = \mathbf{0.81458\ GPa}$

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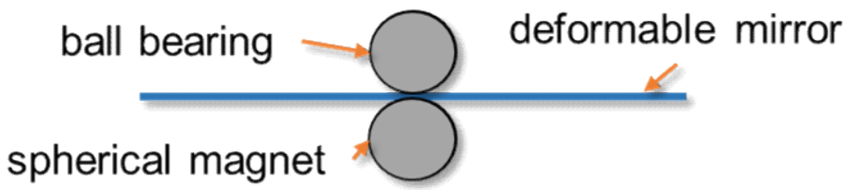
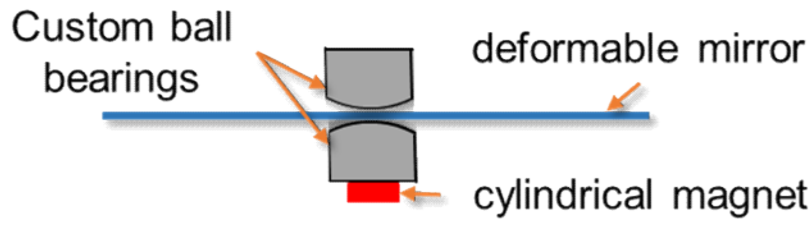
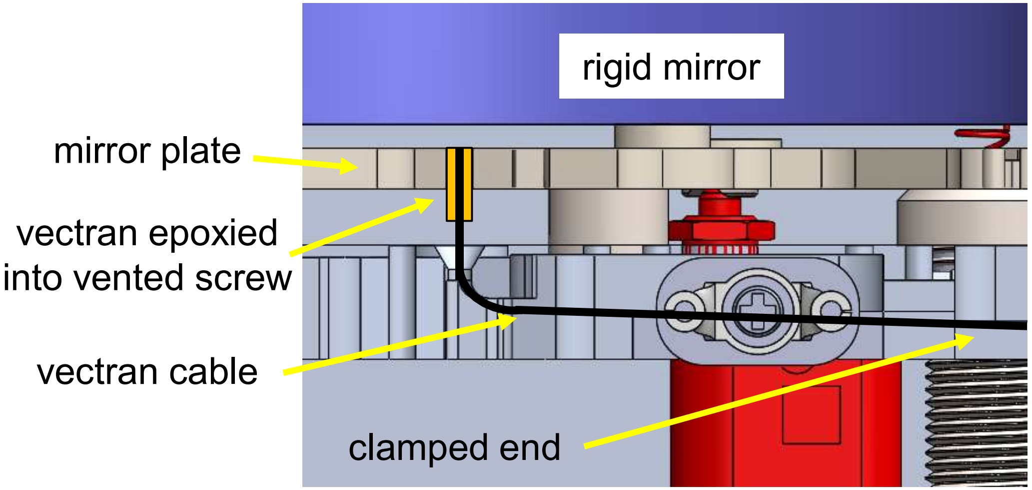
New Mirror Mounts Design

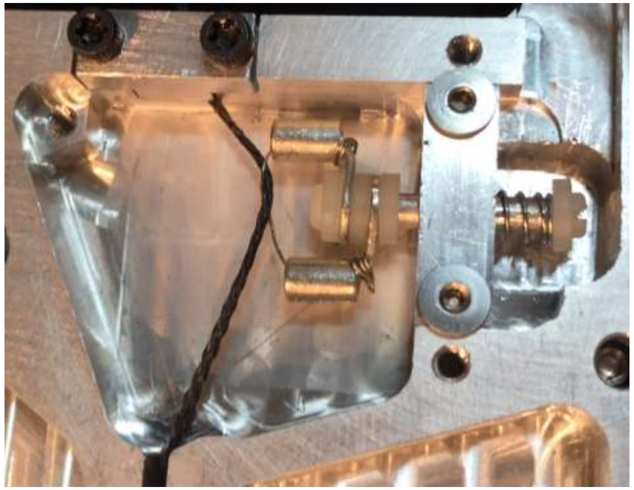
Old Design	New Design
	
Spheres radius: **R_{sphere} = 2.38mm**	Semi-spheres radius: **R_{new} = 7.65mm**
	Bearings thickness: **t_{total} = 2mm**
Magnet pull force (including mirror thickness): **f_{magnet} = 3.11 N**	Magnet pull force (including bearing and mirror thickness): **f_{new} = 4.67 N**
Contact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

Separation Device Tests

Side view



Bottom view



Current [A]	Cutting Time [s]
< 2.16	No Cut
2.20	27.9
2.25	25.0
2.35	10.4
2.40	10.0
2.45	8.5
2.50	8.0
2.60	6.0
2.70	4.0

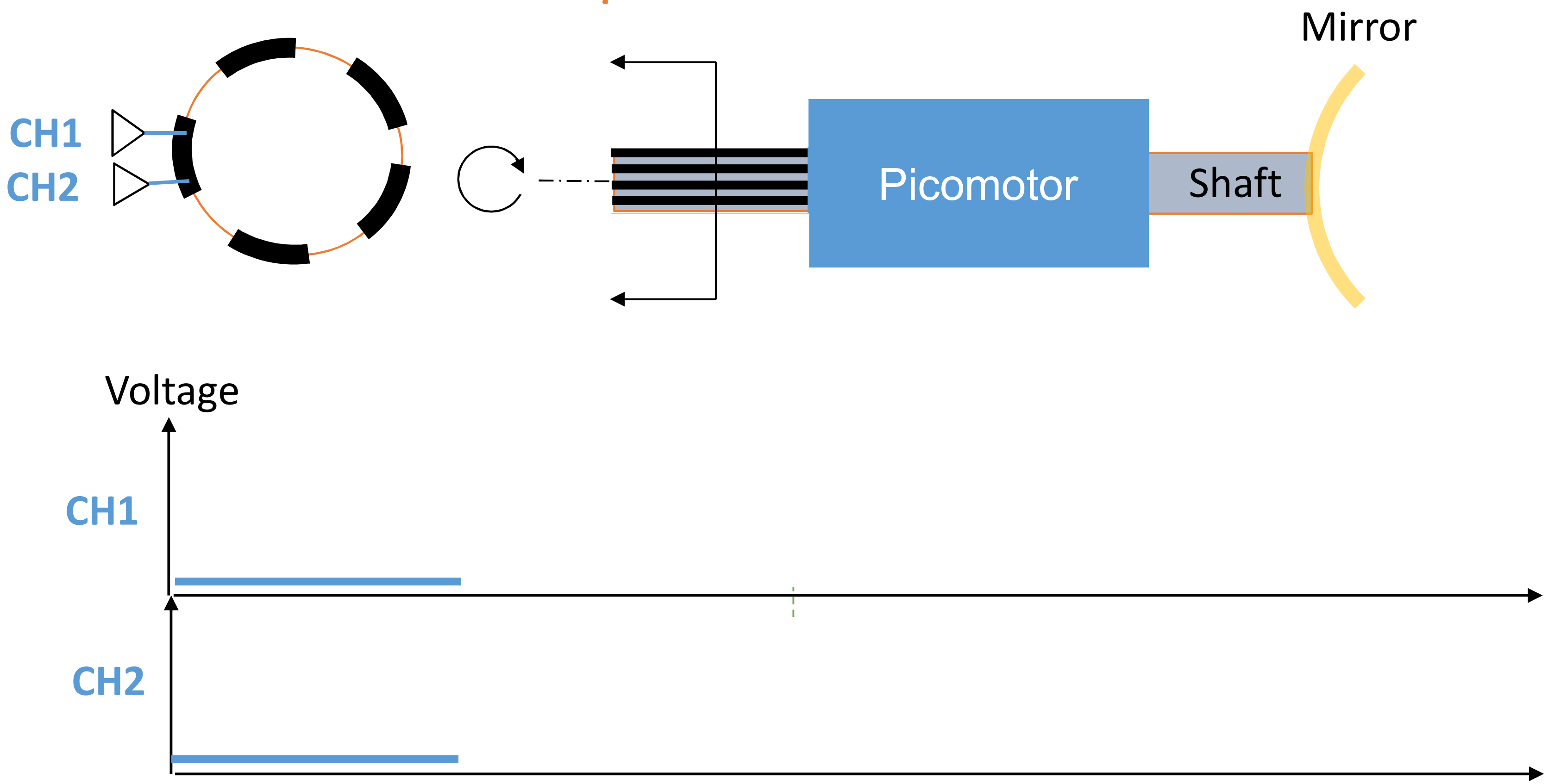
Tests

- Purpose is to set current requirement for electronics
- Tests conducted using external power supply (current controlled) attached to each arm
- Current level chosen is 2.5 A
- Tests performed in air

Picomotors Position Control

Encoders help estimate mirror position within an interval

Encoder interval: $41\mu m$



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Encoder Shaft

- Established manufacture procedure to create dimension-stable encoder shafts
  - Thermally deform and bond encoder to cylindrical shaft
  - Variation of shaft outer diameter within $25\mu m$
  - Encoder strip interval $41\mu m \pm 0.5\mu m$(post bonding)
  - Thermally loaded to $-50°C$
- Created statistical calibration – actuation algorithm for picomotor position control
  - Picomotor axial precision within $221nm$
- Tested open loop position control with algorithm

Encoder shaft with strip

Encoder strip interval after bonding

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Systems Readiness Level

Rigid Mirror Box

Completed

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

Future Work

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

Deformable Mirror Box

Completed

- Assembly procedure
- Preliminary vibration tests (successful up to -6dB NASA standard)
- New mirror mounts design

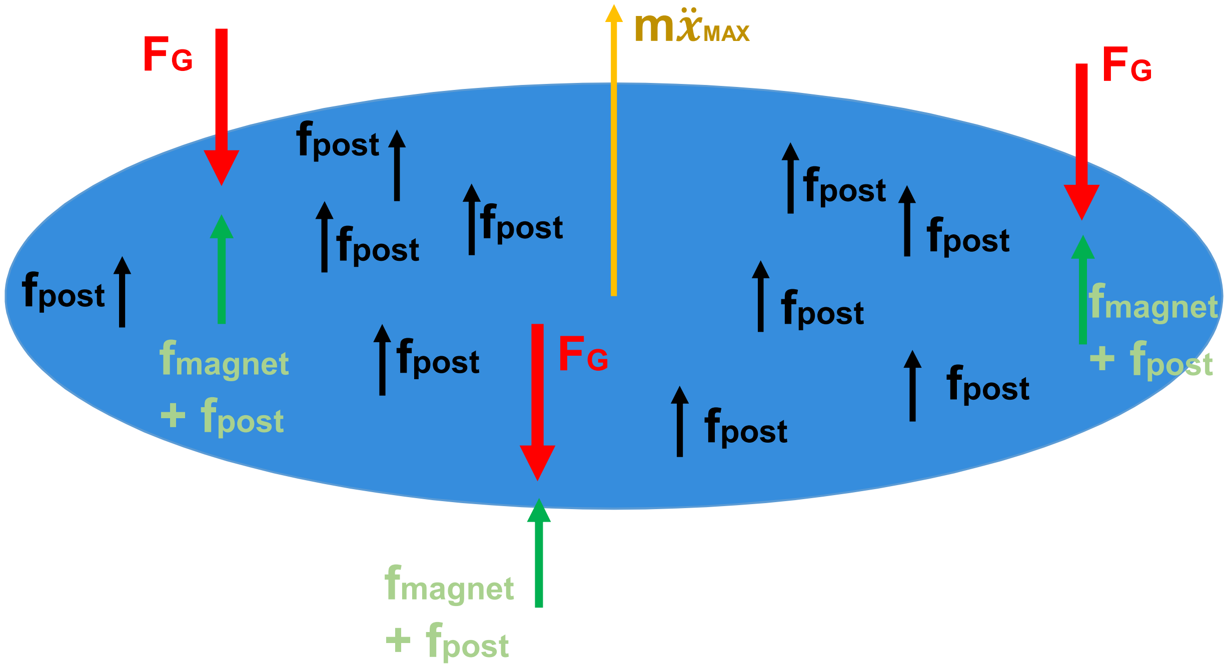
Future Work

- Vibration tests with new mounts, spherical DM, and flight electronics (using PSLV standard)
- Integration on optical testbed
- Separation device tests with flight electronics, in vacuum

Mirror Boxes Backup Slides

Mirror Failure Analysis

GLASS free body diagram



- F_G = contact force ball-bearing (assume equal at each mount)
- f_{post} = force from mirror posts (10)
- mx_{max} = vibrating mirror
- f_{magnet} = magnet pull force

Equilibrium of Forces

$$3F_G = 10f_{post} + m\ddot{x}_{MAX} + 3(f_{magnet} + f_{post})$$

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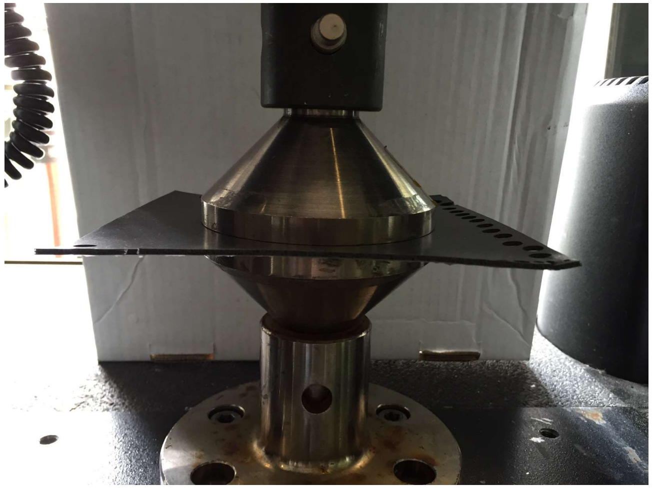
Glass Failure Analysis



$\mathbf{f_{post}} = \frac{85N}{A_{instron}} A_{post} = \mathbf{0.306N}$

- Foam compressed 50% of its thickness (0.8mm)

$\mathbf{mx_{max}} = 45g * 61.54g's = \mathbf{27.2N}$

- Peak acceleration on mirror plate

$\mathbf{f_{magnet}}$ = from datasheet **4.048N**

- Highest measurement

Equilibrium of Forces

$$\boldsymbol{F_G} = \frac{10f_{post} + m\ddot{x}_{MAX} + 3(f_{magnet} + f_{post})}{3} = \mathbf{14.441N}$$

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Glass Failure Analysis

Hertzian contact stress

- Contact between a sphere and a half-space

Contact between a sphere and a half-space [edit]

An elastic sphere of radius R indents an elastic half-space to depth d, and thus creates a contact area of radius

$$a = \sqrt{Rd}$$

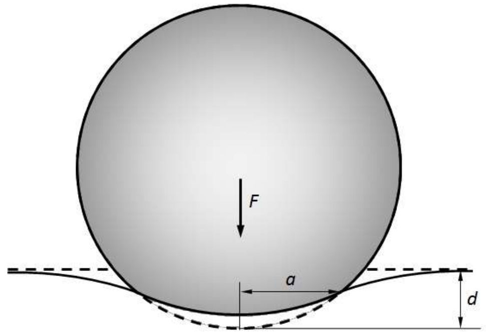
The applied force F is related to the displacement d by[16]

$$F = \frac{4}{3} E^* R^{1/2} d^{3/2}$$

where

$$\boxed{\frac{1}{E^*} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}}$$

and E_1, E_2 are the elastic moduli and ν_1, ν_2 the Poisson's ratios associated with each body.



The distribution of normal pressure in the contact area as a function of distance from the center of the circle is[1]

$$p(r) = p_0 \left(1 - \frac{r^2}{a^2}\right)^{1/2}$$

where p_0 is the maximum contact pressure given by

$$\boxed{p_0 = \frac{3F}{2\pi a^2} = \frac{1}{\pi}\left(\frac{6F{E^*}^2}{R^2}\right)^{1/3}}$$

Glass Failure Analysis

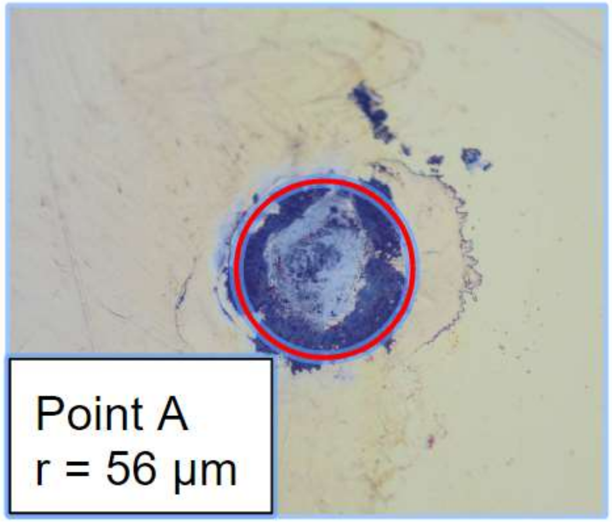
Hertzian contact stress

- Contact between a sphere and a half-space

$$p_0 = \frac{3F}{2\pi a^2} = \frac{1}{\pi}\left(\frac{6FE^{*2}}{R^2}\right)^{1/3}$$

$$\nu_{sphere} = 0.3\ (steel)$$
$$E_{sphere} = 160\ GPa$$
$$\nu_{glass} = 0.21\ (borosilicate)$$
$$E_{glass} = 68\ GPa$$

$$E^* = 50.65\ GPa$$
$$\mathbf{p_0 = 1.0813\ GPa}$$



$$\mathbf{p_0 = 2.758\ GPa}$$

Borosilicate Glass
Compressive Strength = 2GPa

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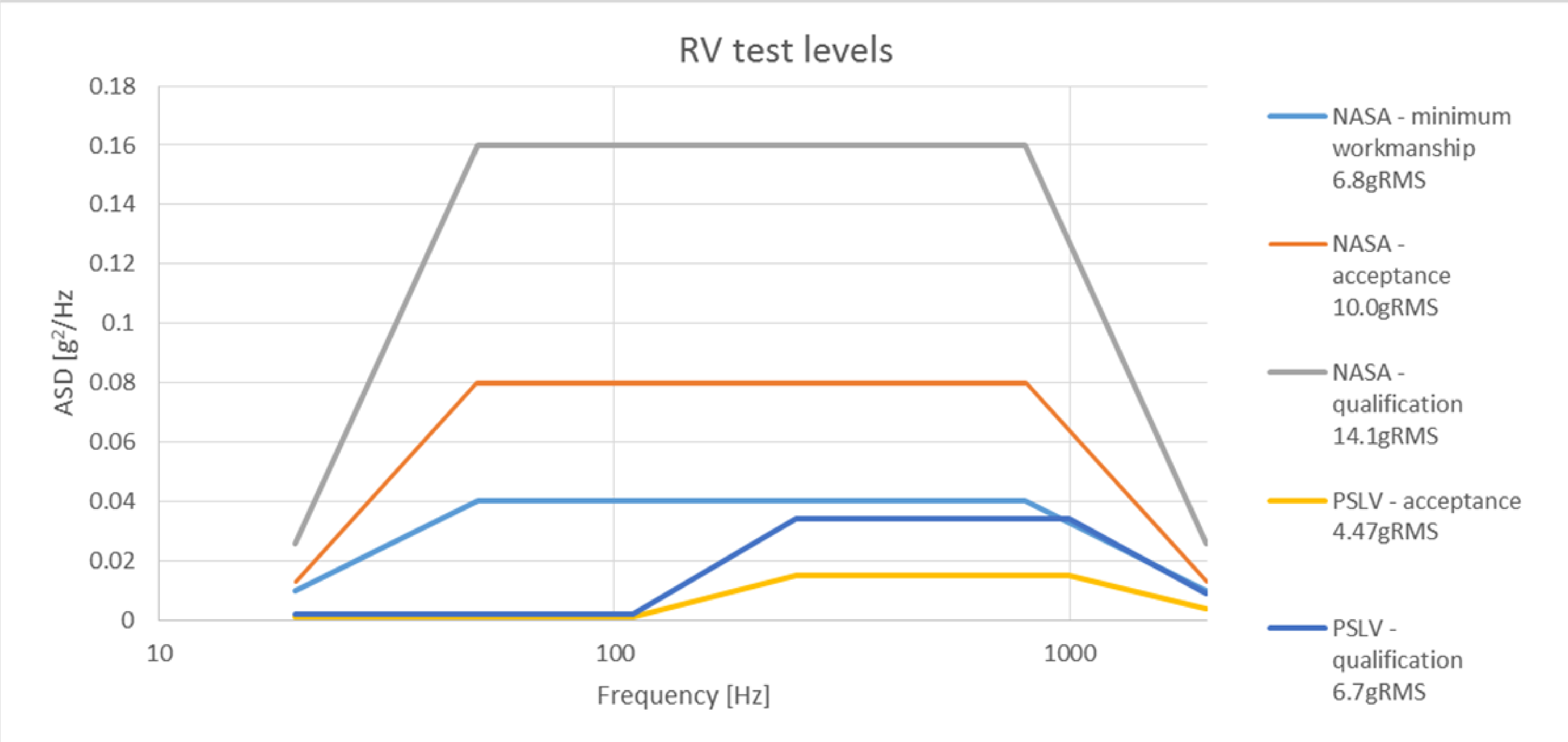
Vibration Loads



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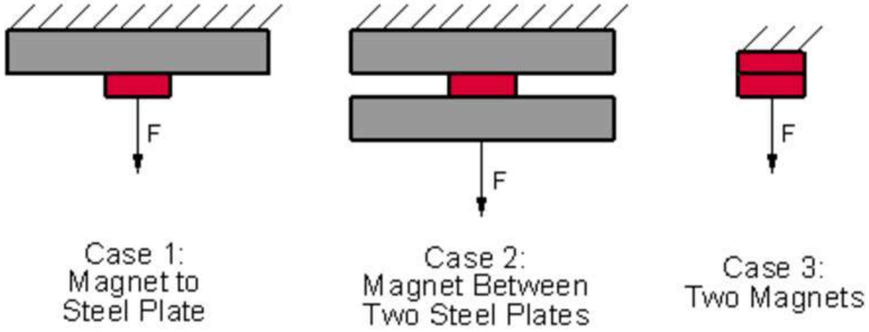
Magnets Pull Force Measurements

11. How is the pull force of each magnet determined?

All of the pull force values we specify have been tested in our laboratory. We test these magnets in two different configurations. Case 1 is the maximum pull force generated between a single magnet and a thick, ground, flat steel plate. Case 2 is the maximum pull force generated with a single magnet sandwiched between two thick, ground, flat steel plates. Case 3 is the maximum pull force generated on a magnet attracted to another magnet of the same type.

The values are an average value for five samples of each magnet. A digital force gauge records the tensile force on the magnet. The plates are pulled apart until the magnet disconnects from one of the plates. The peak value is recorded as the "pull force". If using steel that is thinner, coated, or has an uneven or rusty surface, the effective pull force may be different than recorded in our lab.



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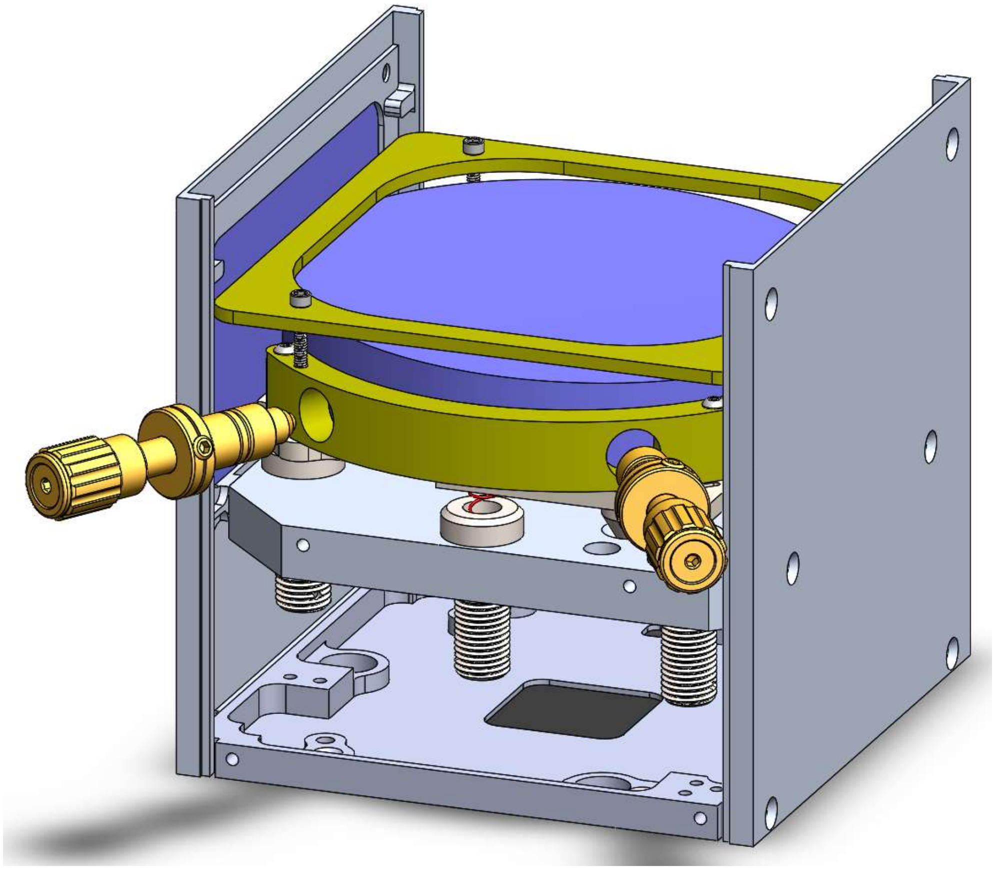
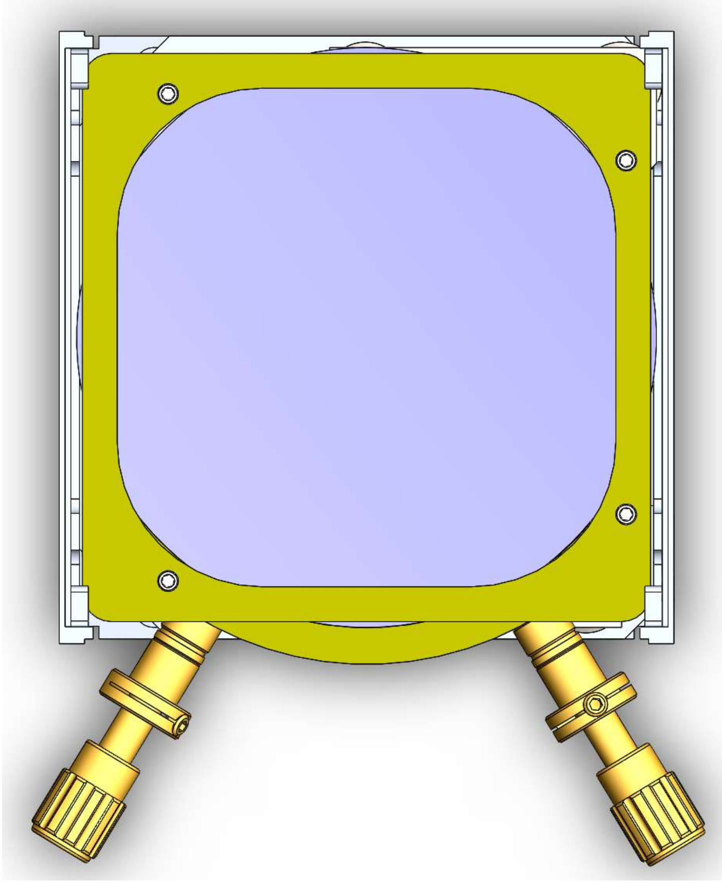
Optical Alignment Fixture

Needs

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





AAReST Telescope Electronics Review

Ashish Goel

January 4th, 2017

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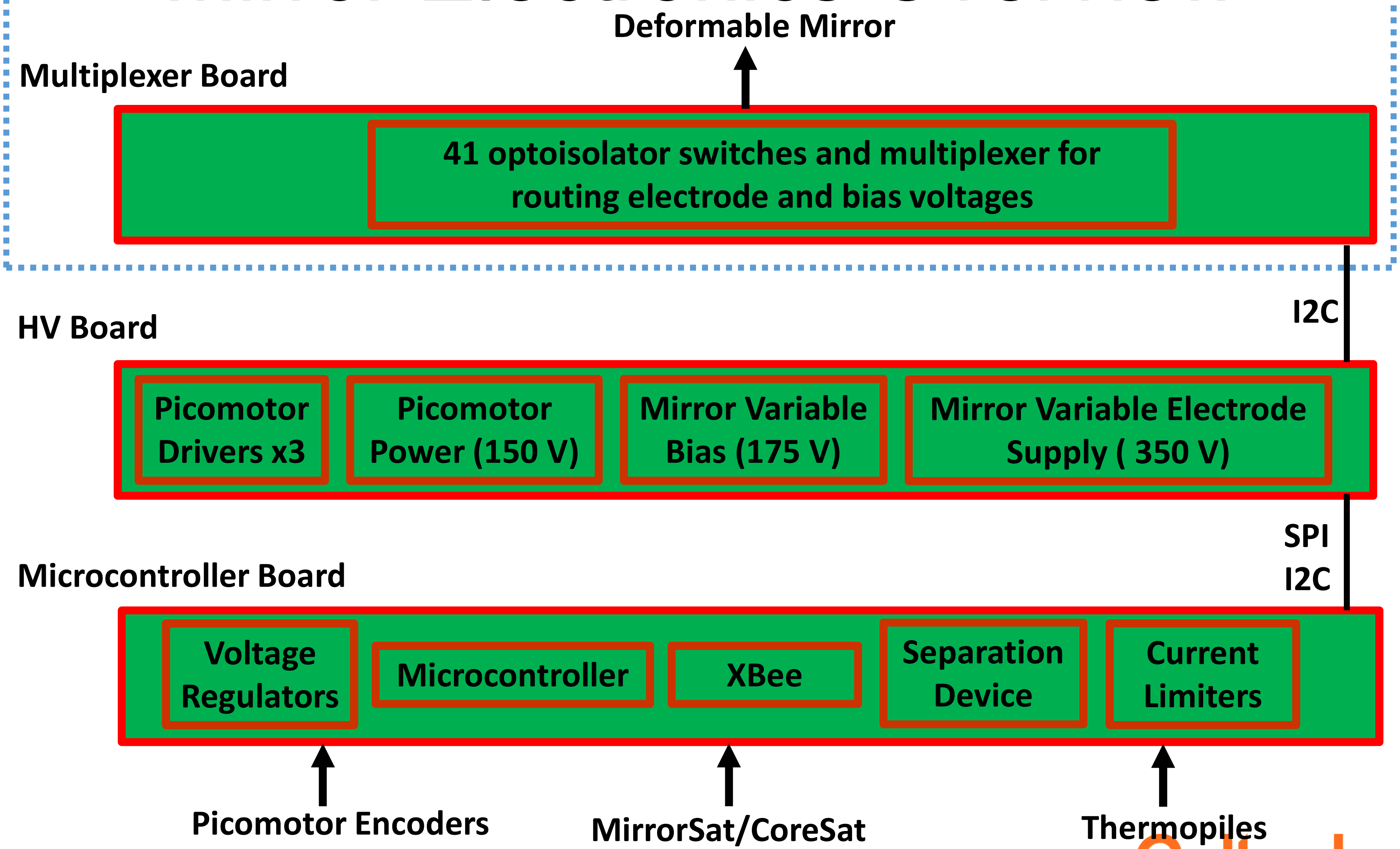
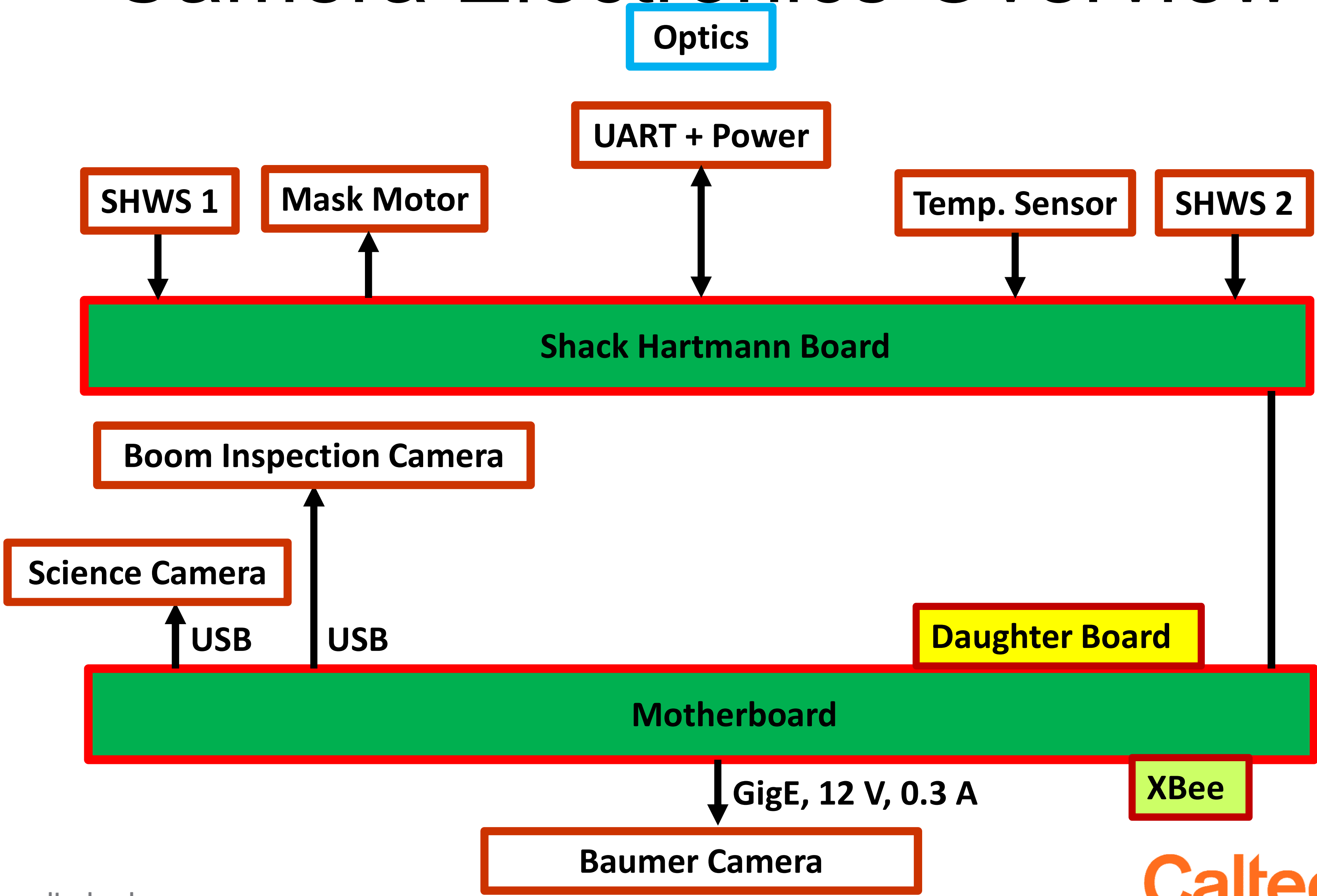
Overview

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

Mirror Electronics Overview



Camera Electronics Overview



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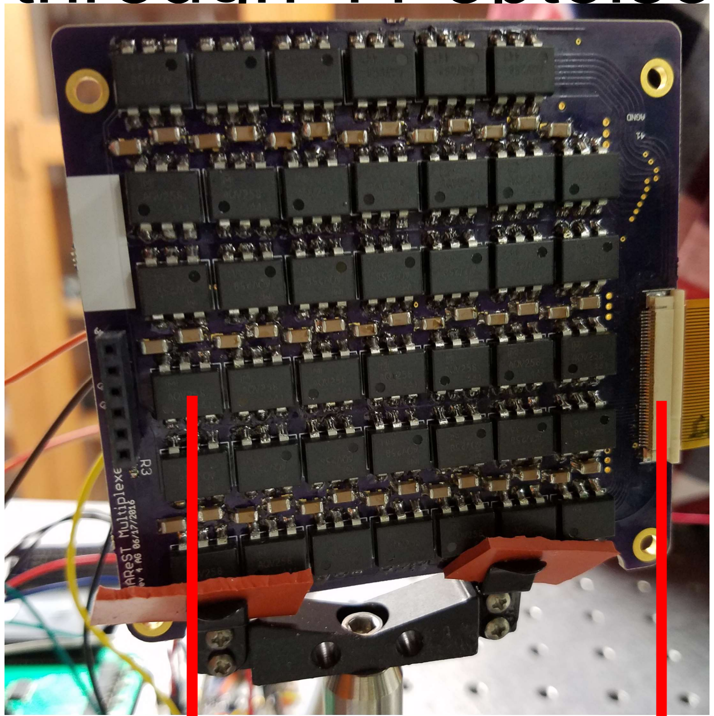
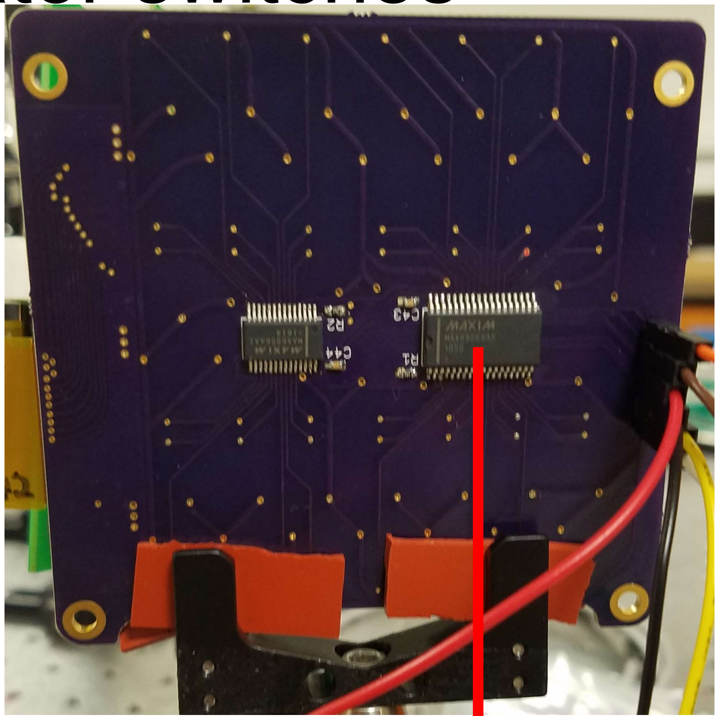
Current Status

Board	Status
Mirror Electronics	
Multiplexer board	Flight boards ready and tested
HV board	V1.0 functional, V2.0 currently under testing
Microcontroller board	V1.0 functional, V2.0 currently under testing
Camera Electronics	
Motherboard	Debugging issues in V1.0
Shack-Hartmann board	Yet to be fabricated

Multiplexer Board

Distributes HV to mirror electrodes through 41 optoisolator switches





Optoisolator switch

FFC connector for electrode routing layer on the mirror

Multiplexer

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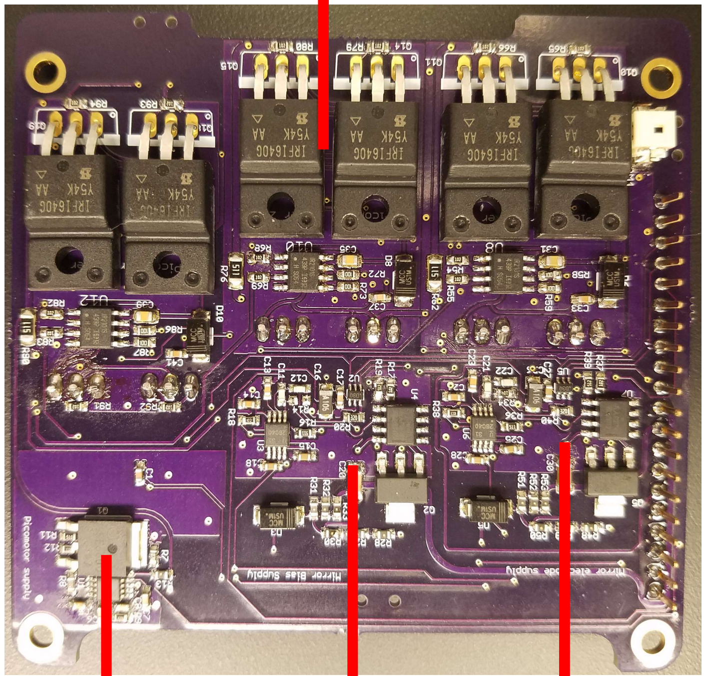
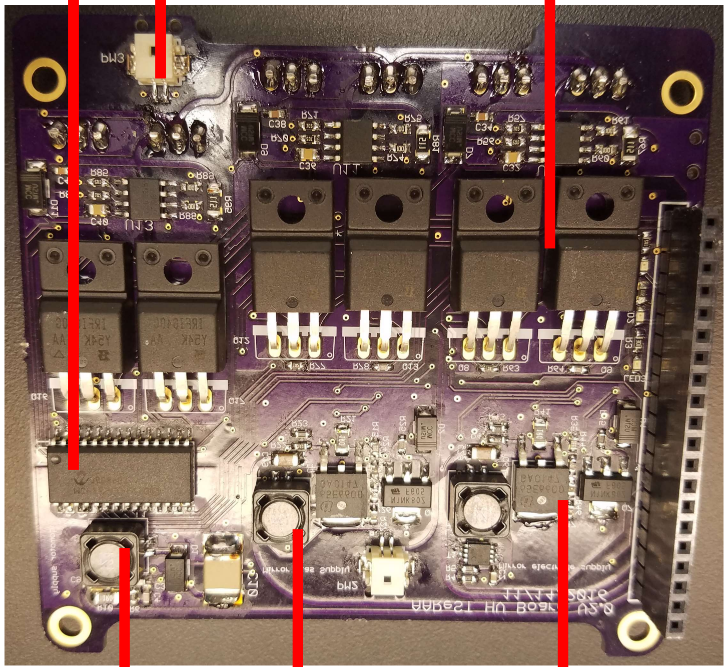
HV Board



Picomotor driver x3
Picomotor power
Mirror bias supply
Electrode HV supply

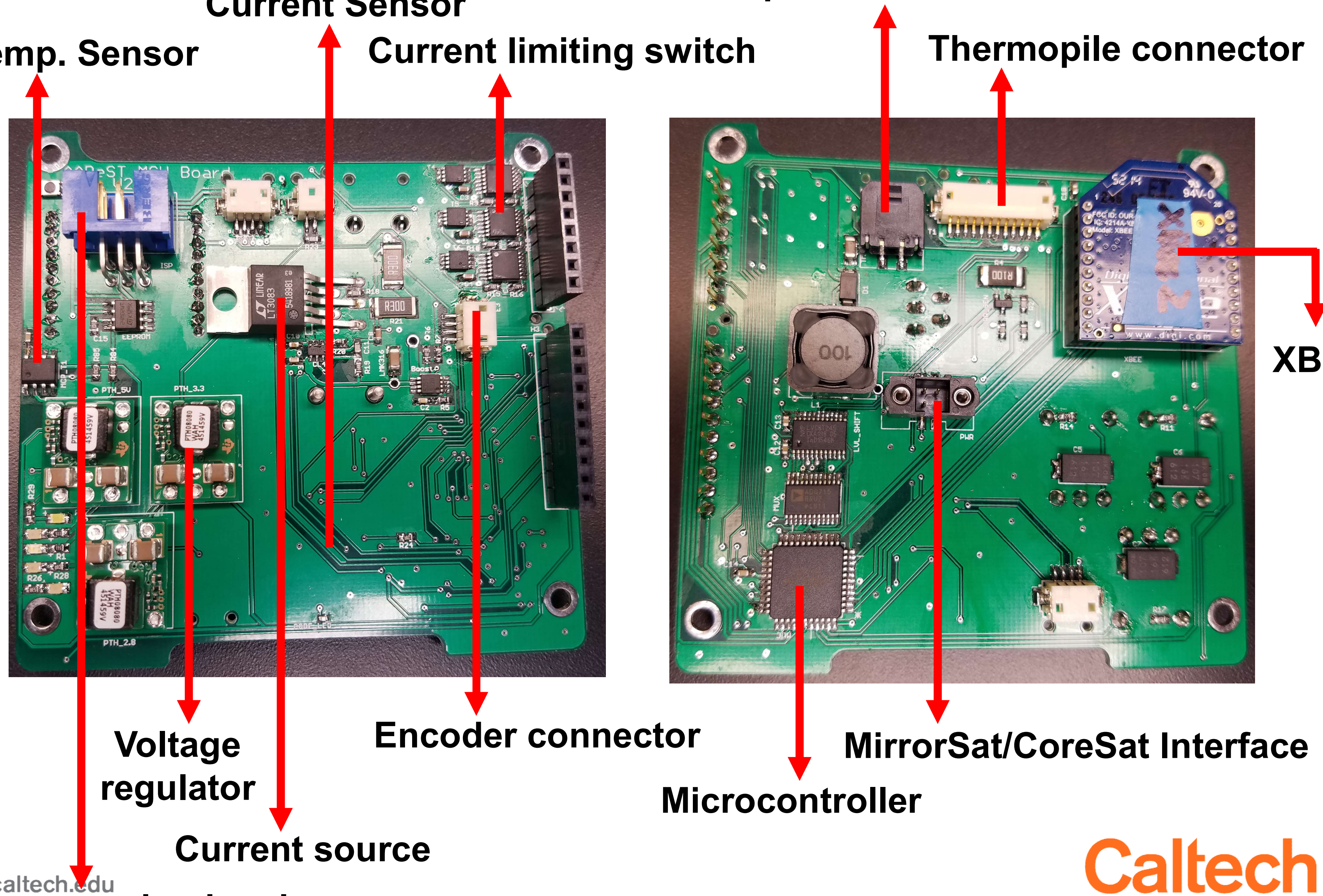


Picomotor connector
I/O Expander
Picomotor driver x3
Picomotor power
Mirror bias supply
Electrode HV supply

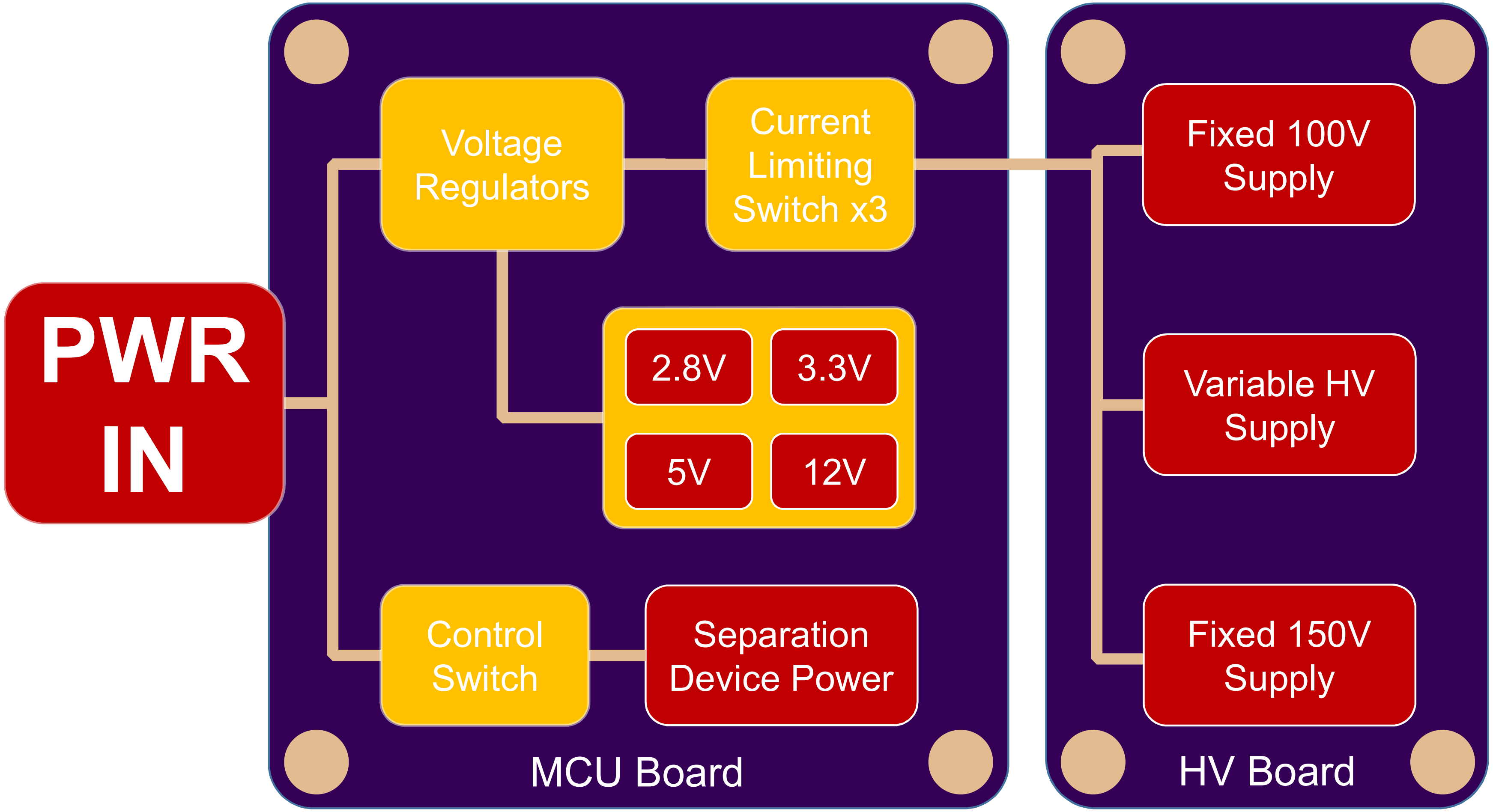
Microcontroller Board

- DC-DC converters to produce regulated
  - 12 V for HV electronics
  - 5 V for DAC for HV electronics
  - 3.3 V for microcontroller and all digital electronics
  - 2.8 V for encoder sensors
- Atmega 1284P microcontroller
- External EEPROM for storing flight software
- XBEE for communicating with camera
- Current source for separation device
- Current and Voltage monitoring at power supply input
- Current limiting switches for HV supply
- Temperature sensor

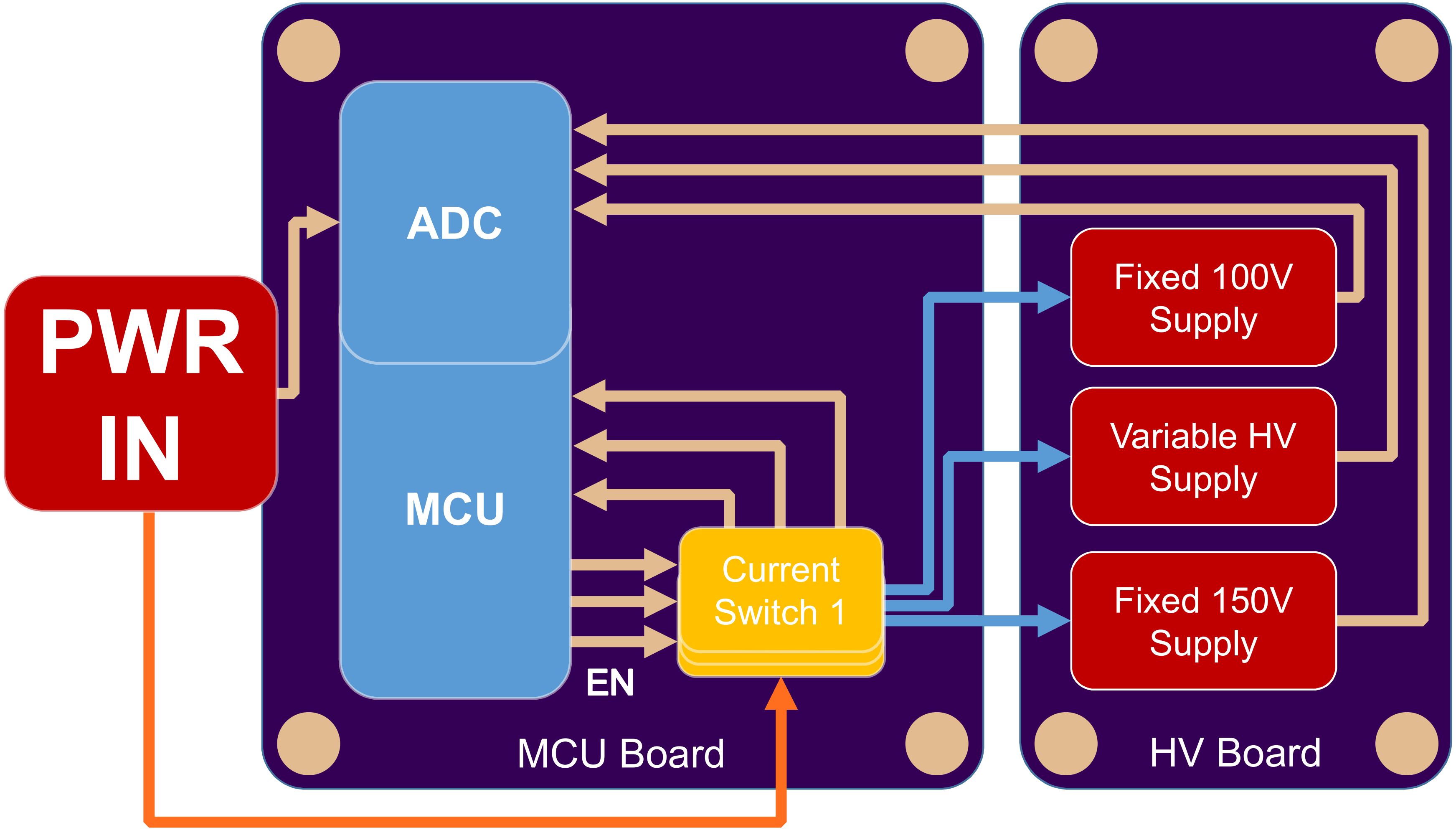
Microcontroller Board



Power Distribution



Power Control & Monitoring



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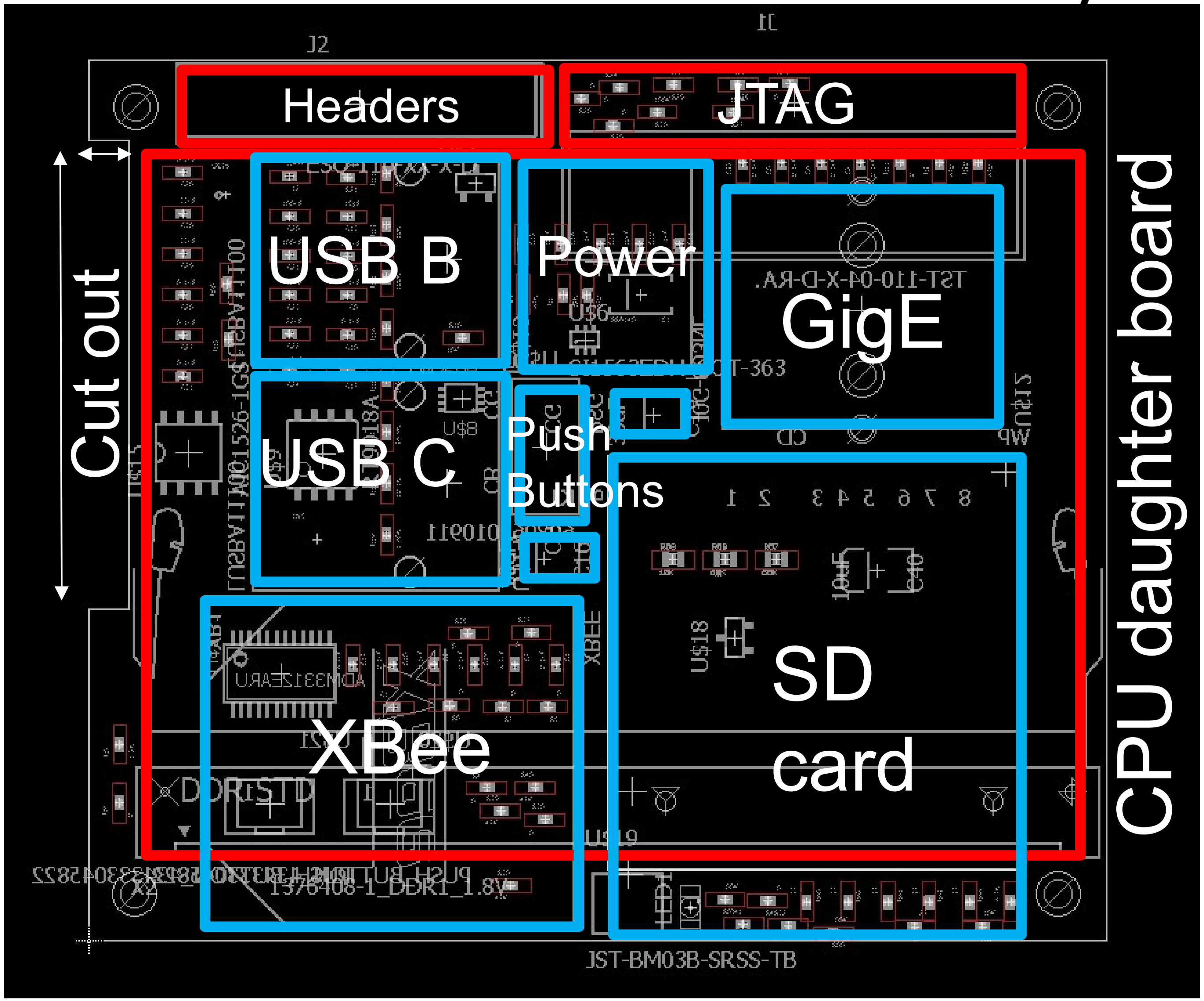
Connectors and Cabling -

End 1 Connection	End 2 Connection	End 1 Connector	End 2 connector	# Wires	Qty	Image
HV board	Picomotor	DF13	Patch cable	2	3	
µC board	Separation device	JST rectangular	Soldering or Brazing	2	1	
µC board	Encoder sensor	DF13	Direct solder	4	3	
µC board	Thermopile	DF13	Direct solder	4	3	
µC board	Mirrorsat	Harwin M80	TBD	4	1	
µC board	Limit Switch	DF13	Direct Solder	2	1	
µC board	Desktop computer	3 x 2 header	N/A	6	1	

Custom cabling using PTFE wires through DigiKey

Motherboard - Layout



Components:

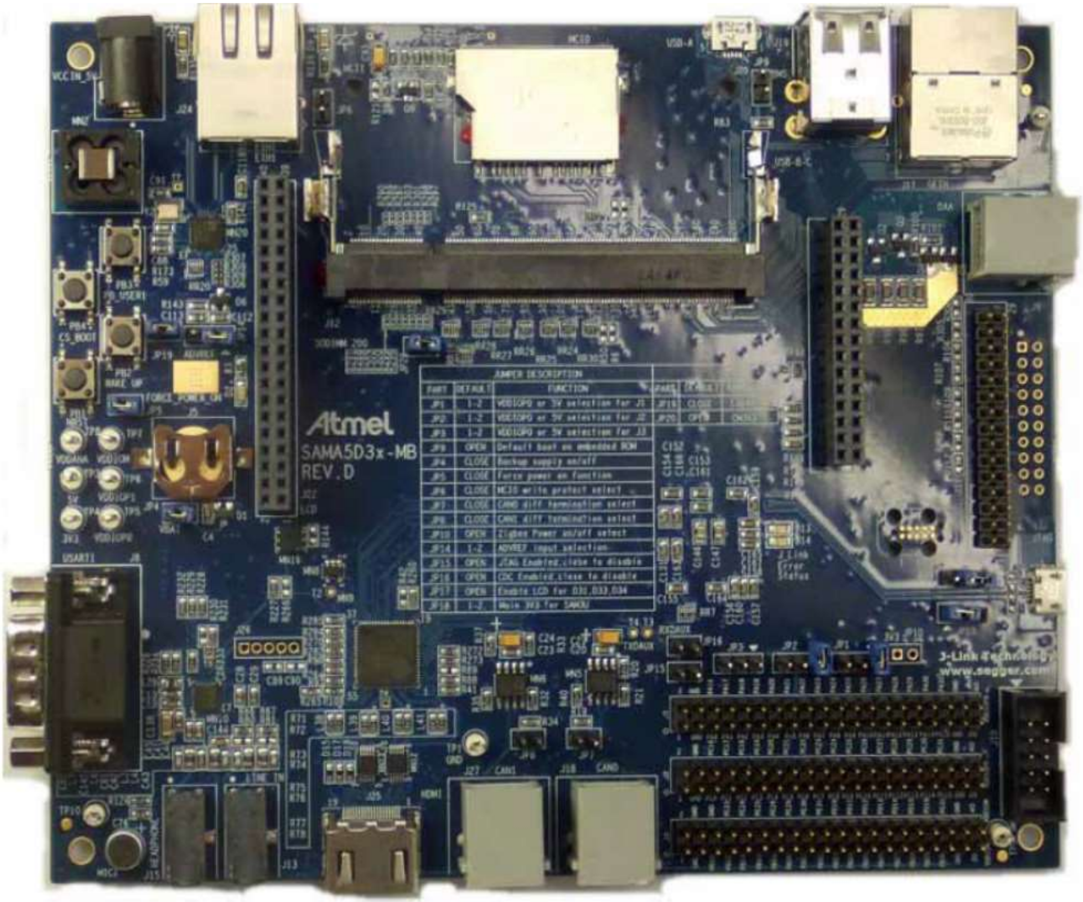
- USB B & USB C to communicate with imaging & boom inspection cameras
- Power management circuit
- GigE for Baumer camera
- SD card
- XBee module
- CPU daughter board

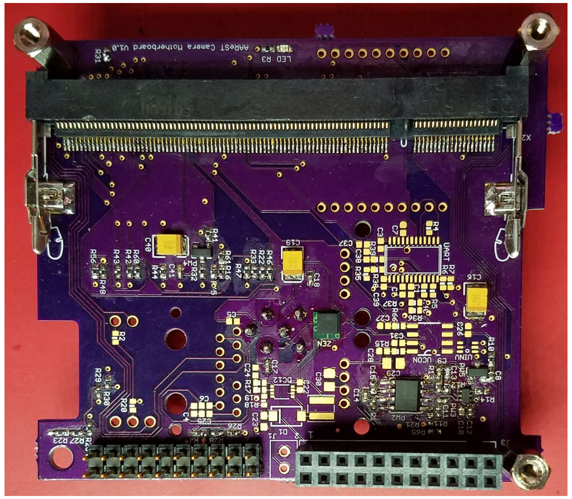
Top side

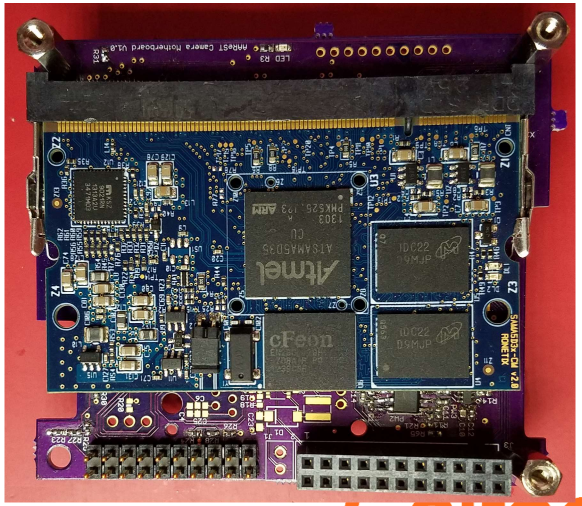
Bottom side

Camera Motherboard

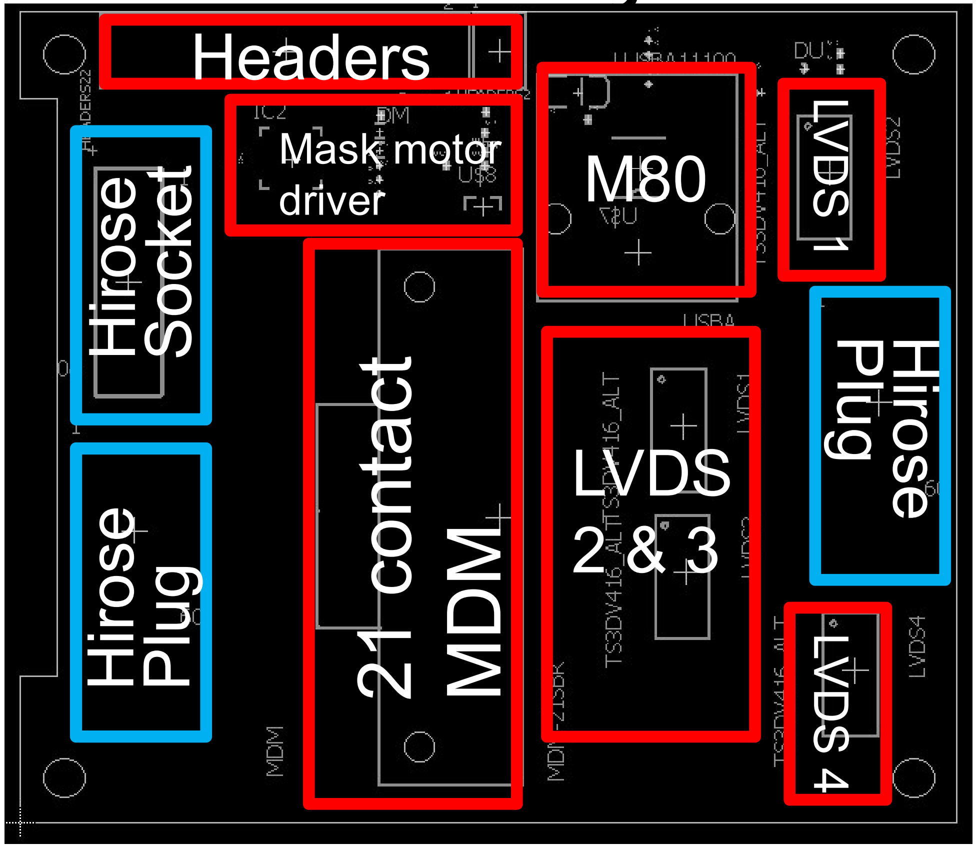
Based on Atmel Cortex A5 ARM processor development board







SHWS – Layout of Components

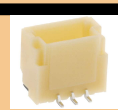
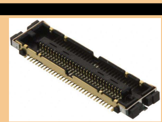
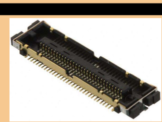


Components:

- M80 to communicate with CoreSat
- 2 Hirose Plugs to receive SHWS signals
- 1 Hirose Receptacle for Baumer camera
- 21 pin MDM connector for mask motor, contact detectors, 3 temperature sensors
- 4 LVDS switches
- Mask motor driver circuit

Top side
Bottom side

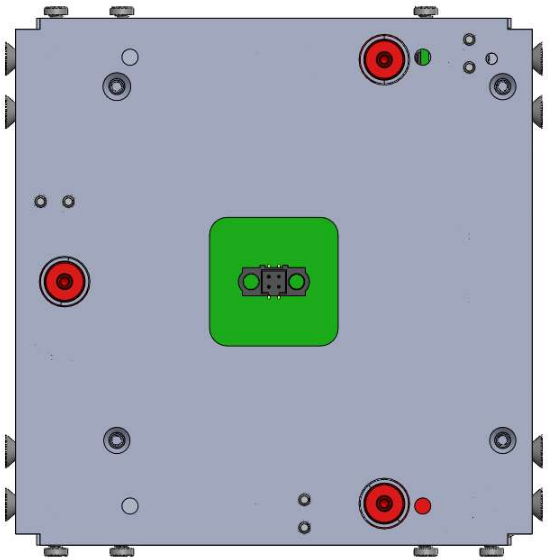
Connectors and Cabling - Camera

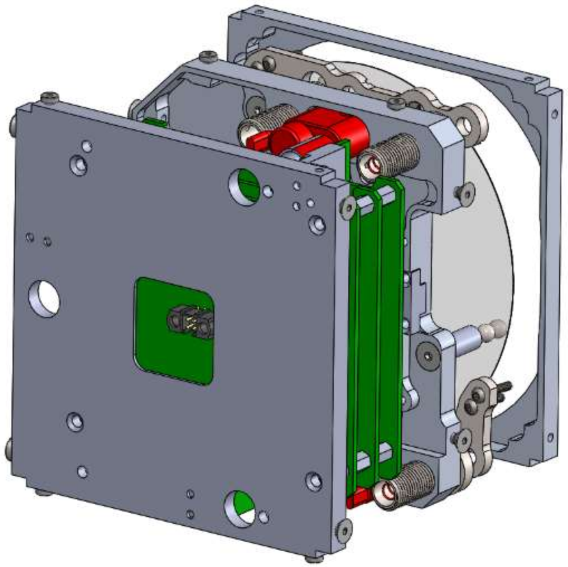
End 1 Connection	End 2 Connection	End 1 Connector	End 2 connector	# Wires	Qty	Image
Motherboard	Science Camera	Locking USB	Patch cable	4	1	
Motherboard	Boom Inspection Camera	Locking USB	Patch cable	4	1	
Motherboard	Baumer Camera	GigE	GigE	1 (Cat6 cable)	1	
Motherboard	Baumer Camera	Direct Solder	JST 03	2	1	
Shack Hartmann Board	Temp. sensors, mask motor, contact detectors	MDM	Direct Solder	20	1	
Shack Hartmann Board	CoreSat	Harwin M80	Harwin M80	4	1	
Shack Hartmann Board	Shack Hartmann Sensor	Hirose FX12	Hirose FX12	1 (Flex)	2	
Shack Hartmann Board	Baumer Camera	Hirose FX12	Hirose FX12	1 (Flex)	1	

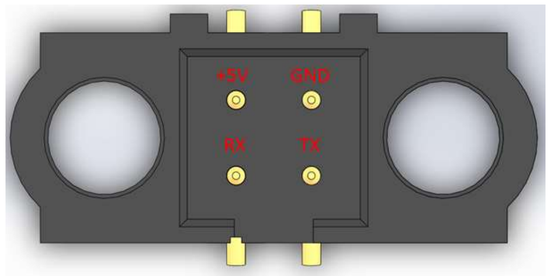
RMB and DMB Interface

- Harwin Datamate M80 connector with jackscrew
- 3.3/5 V UART

Mode	Power Consumption
Activate release mechanism	0.7 A / 3.5 W
Picomotor actuation	0.44 A / 2.2 W
Mirror Actuation	0.44 A / 2.2 W







Questions?

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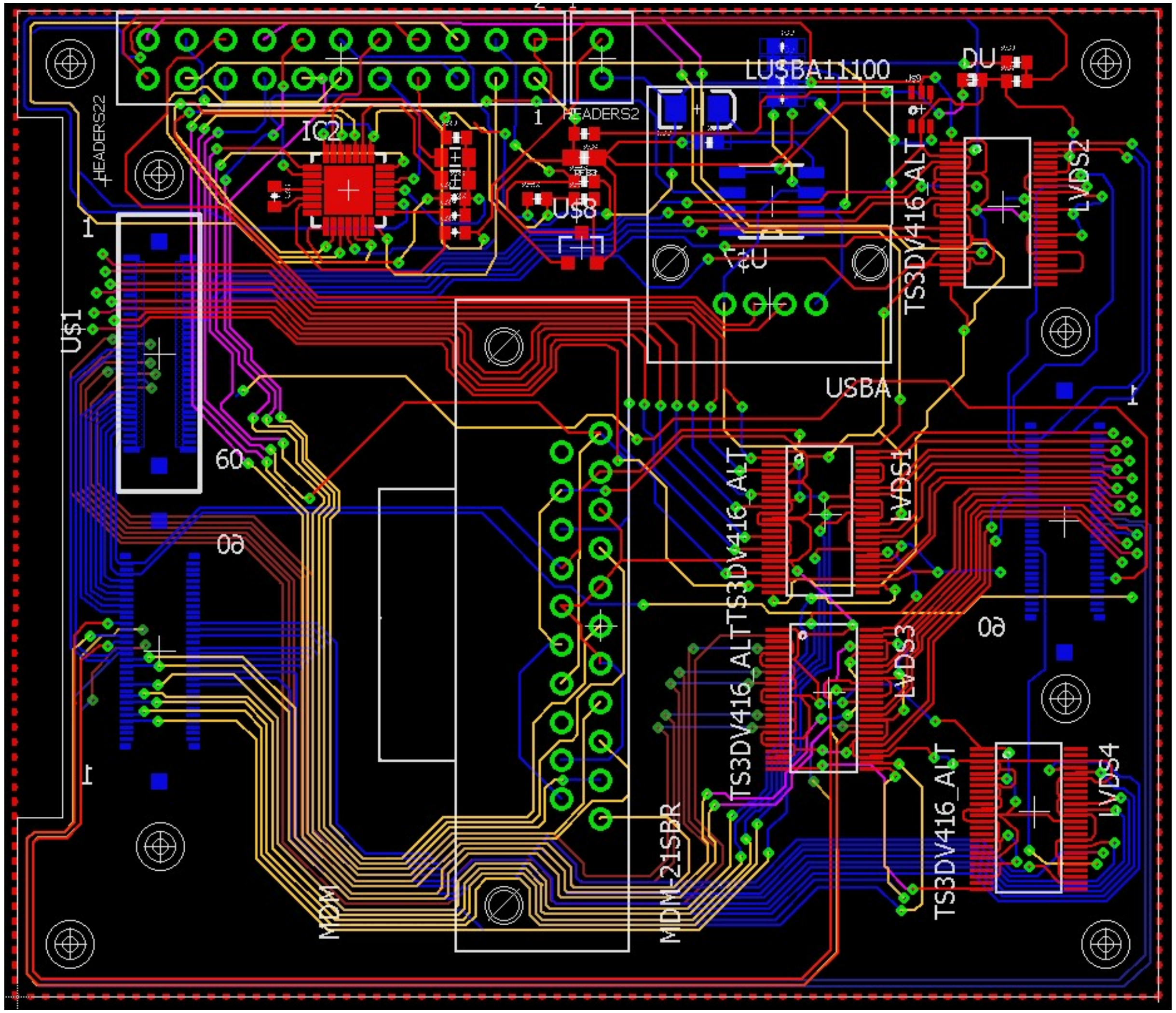
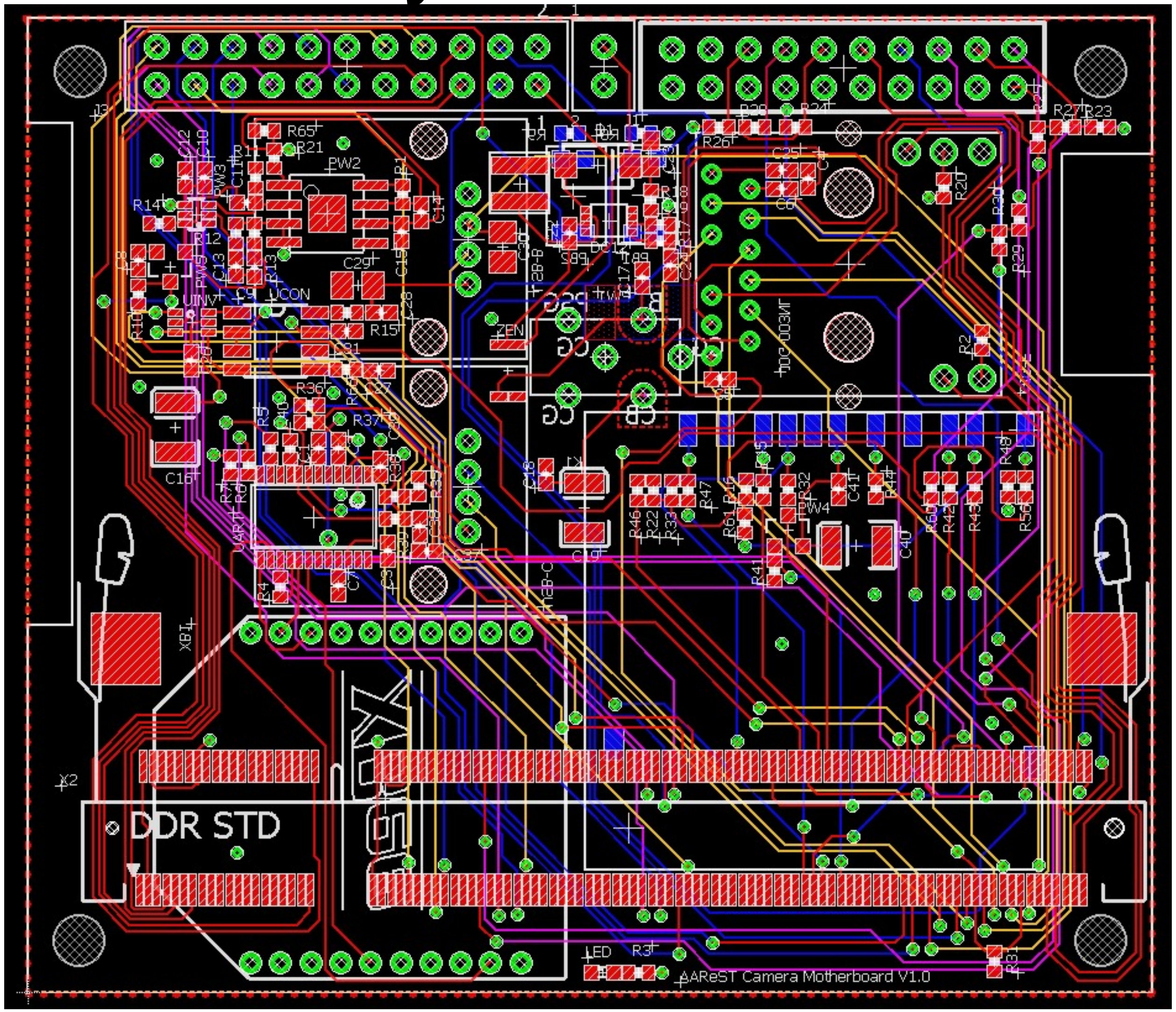
Backup Slide

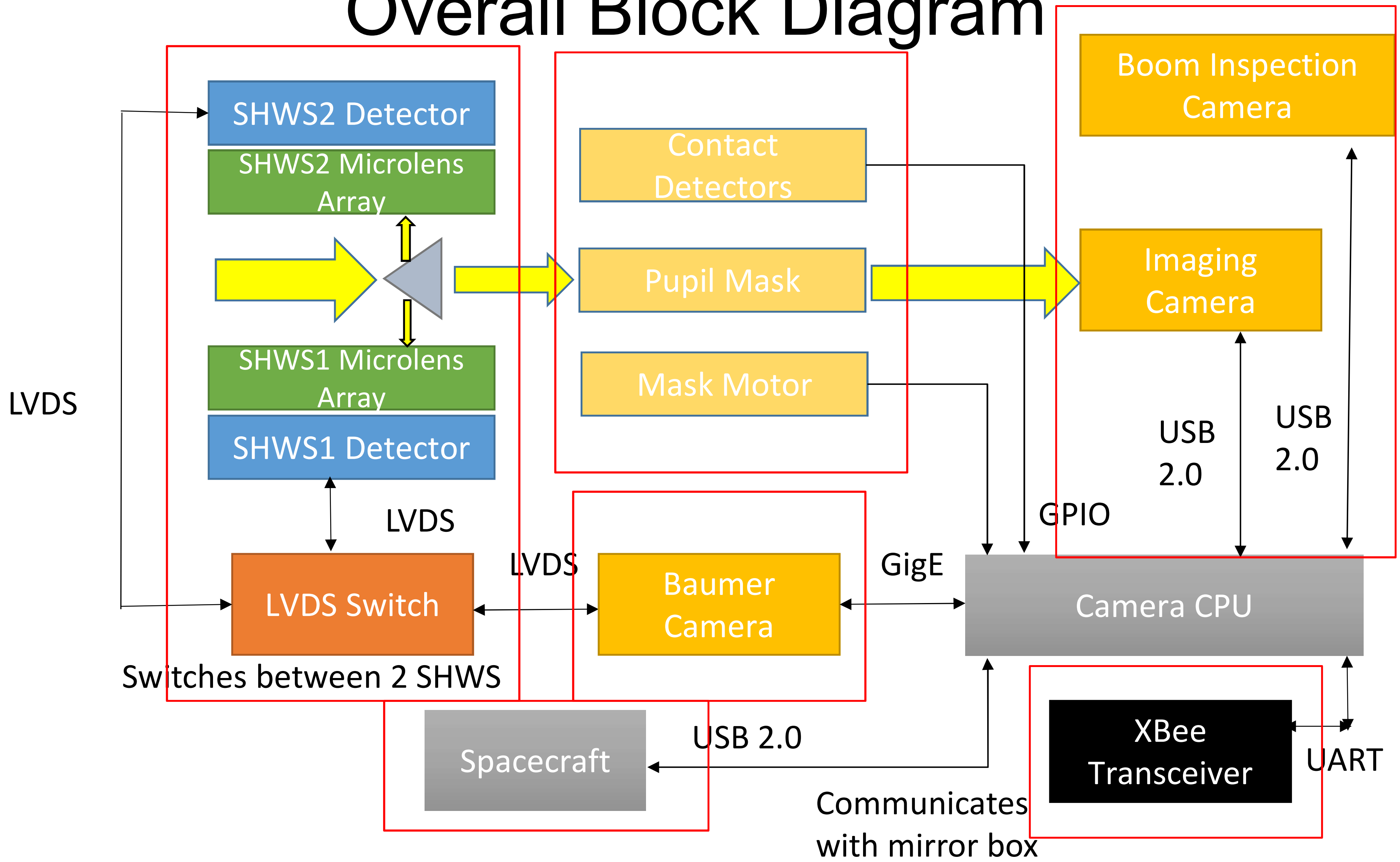
PCB Layout for Shack Hartmann



PCB Layout for Camera



Overall Block Diagram



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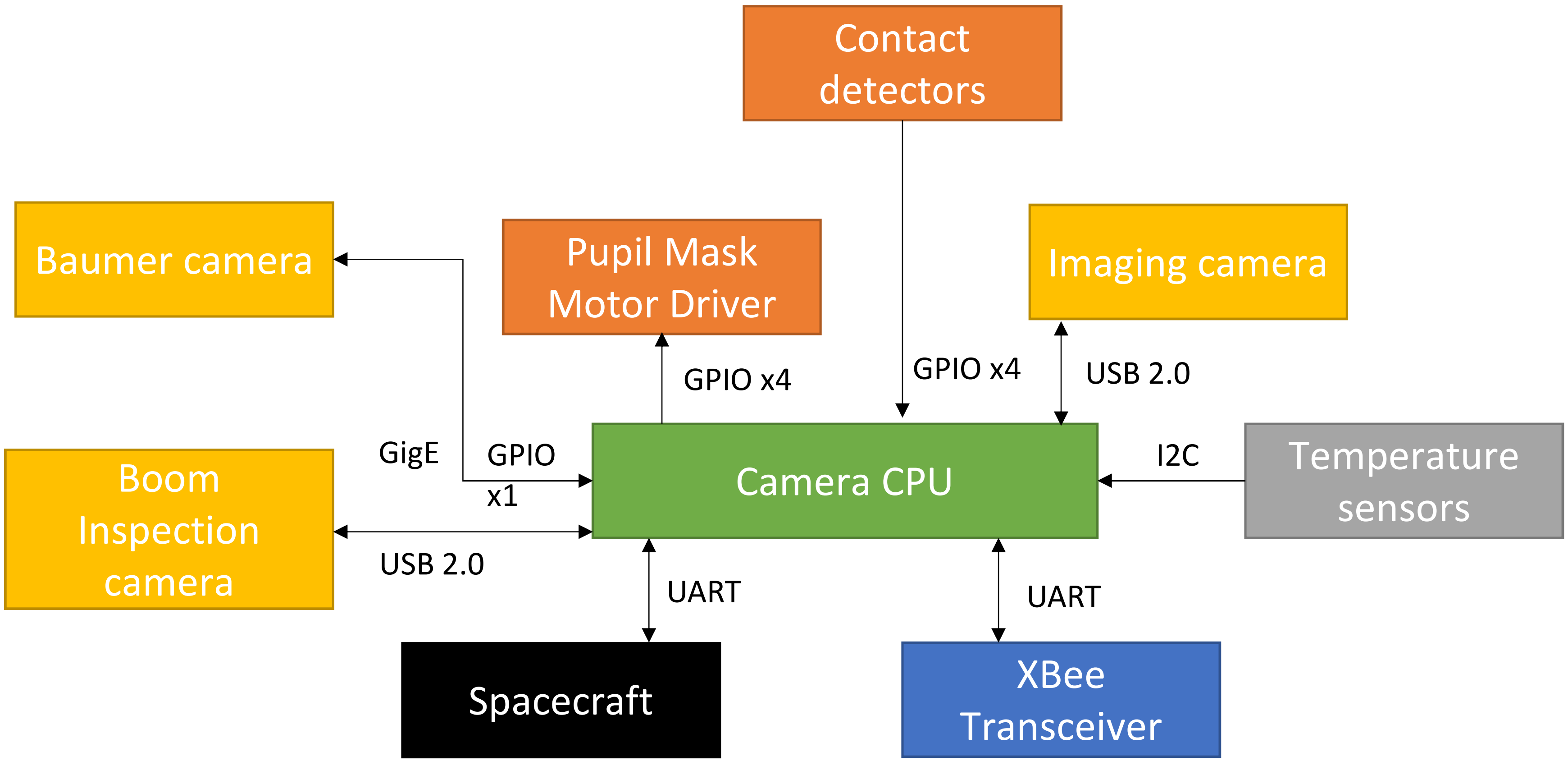
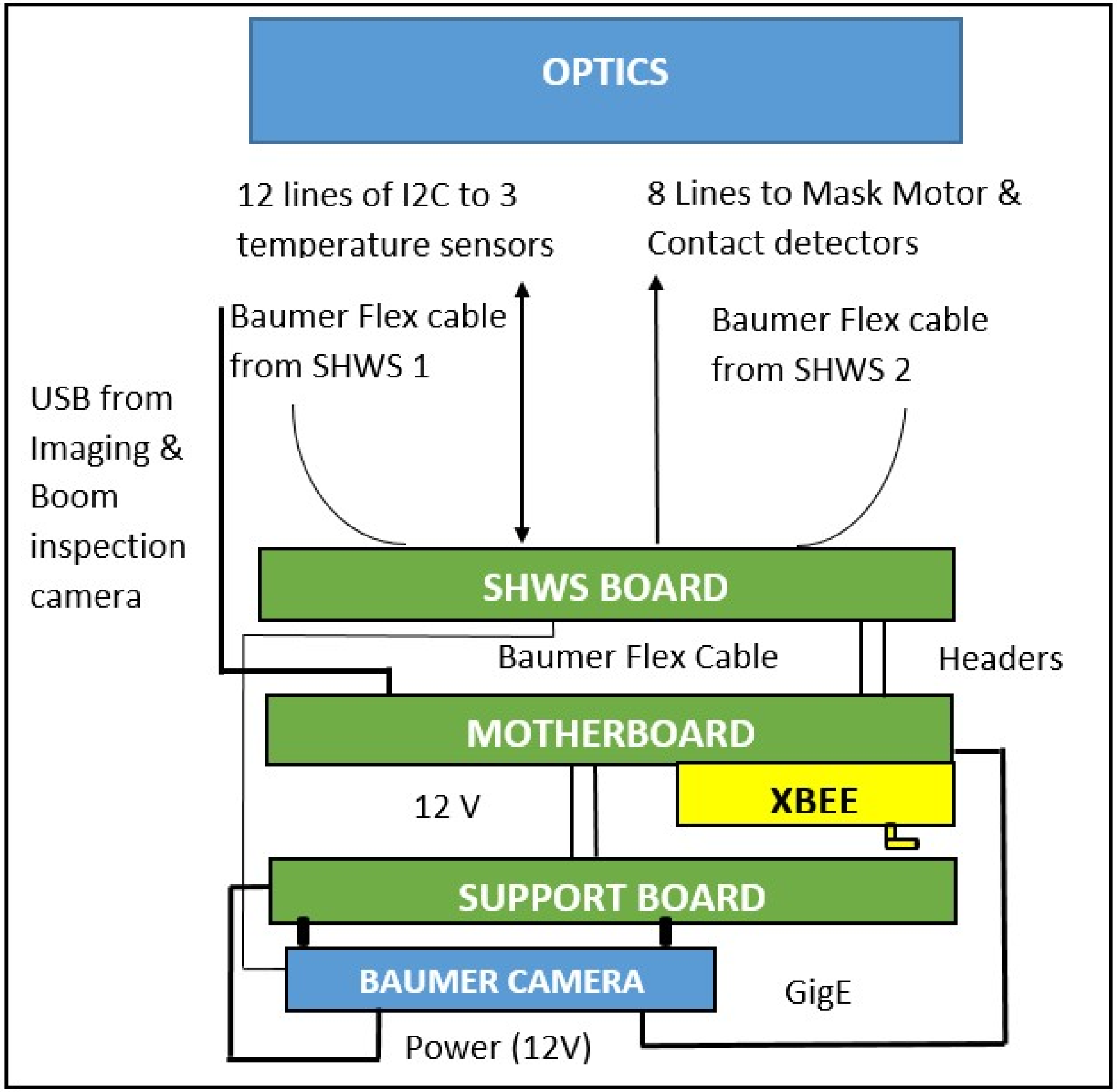
Motherboard Block Diagram



Camera Boards Stackup



Chassis

Presentation Agenda

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

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AAReST Onboard Software

Thibaud Talon
Yuchen Wei
Ashish Goel

Caltech

Outline

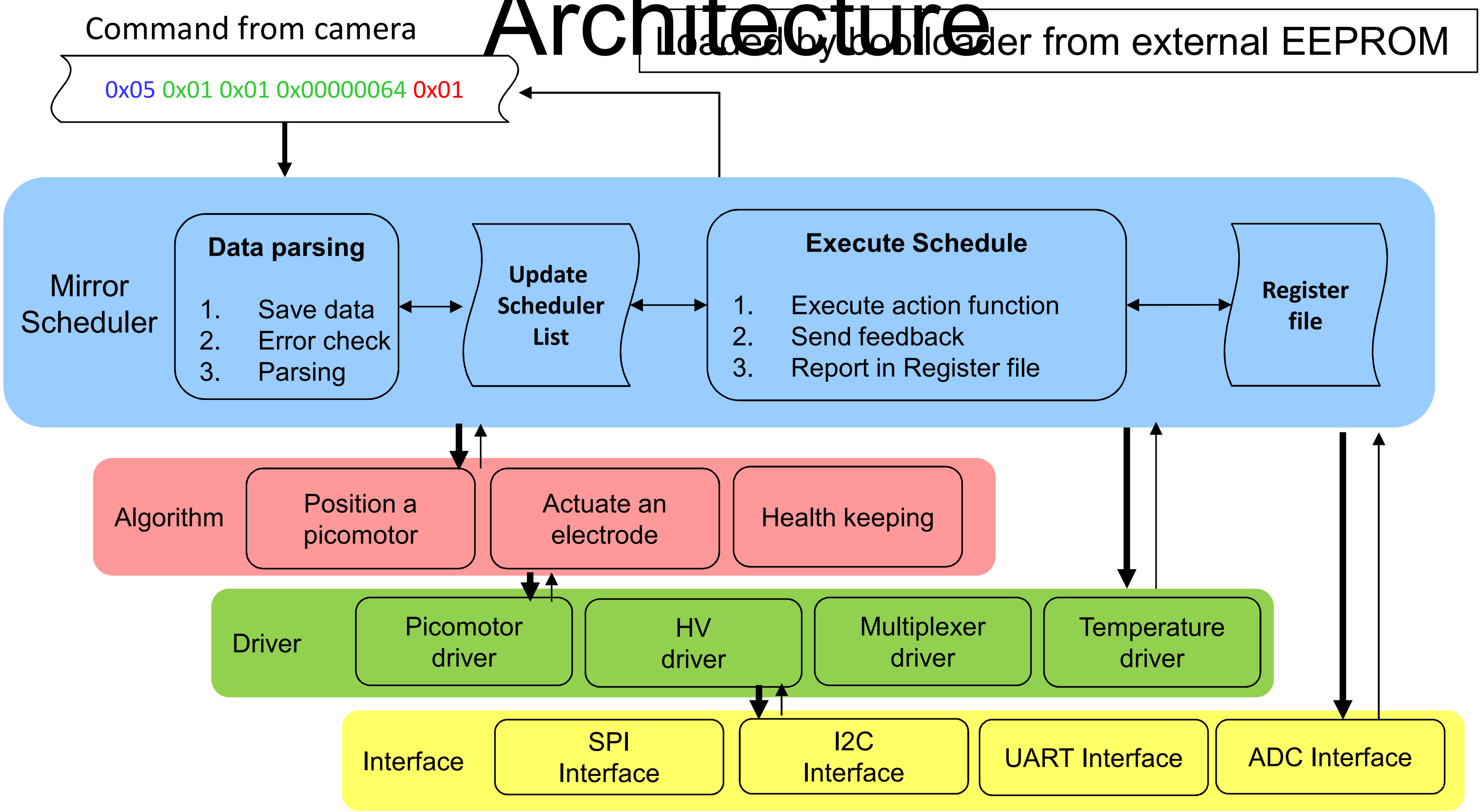
- Requirements
- Mirror box
  - Software architecture
  - Driver update
- Camera
  - Software architecture
  - Driver update
- Telescope startup procedure
- Error handling
- Future work

Requirements of AAReST OBSW

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

Both software run in non hard real time mode

Mirror Box Software Architecture



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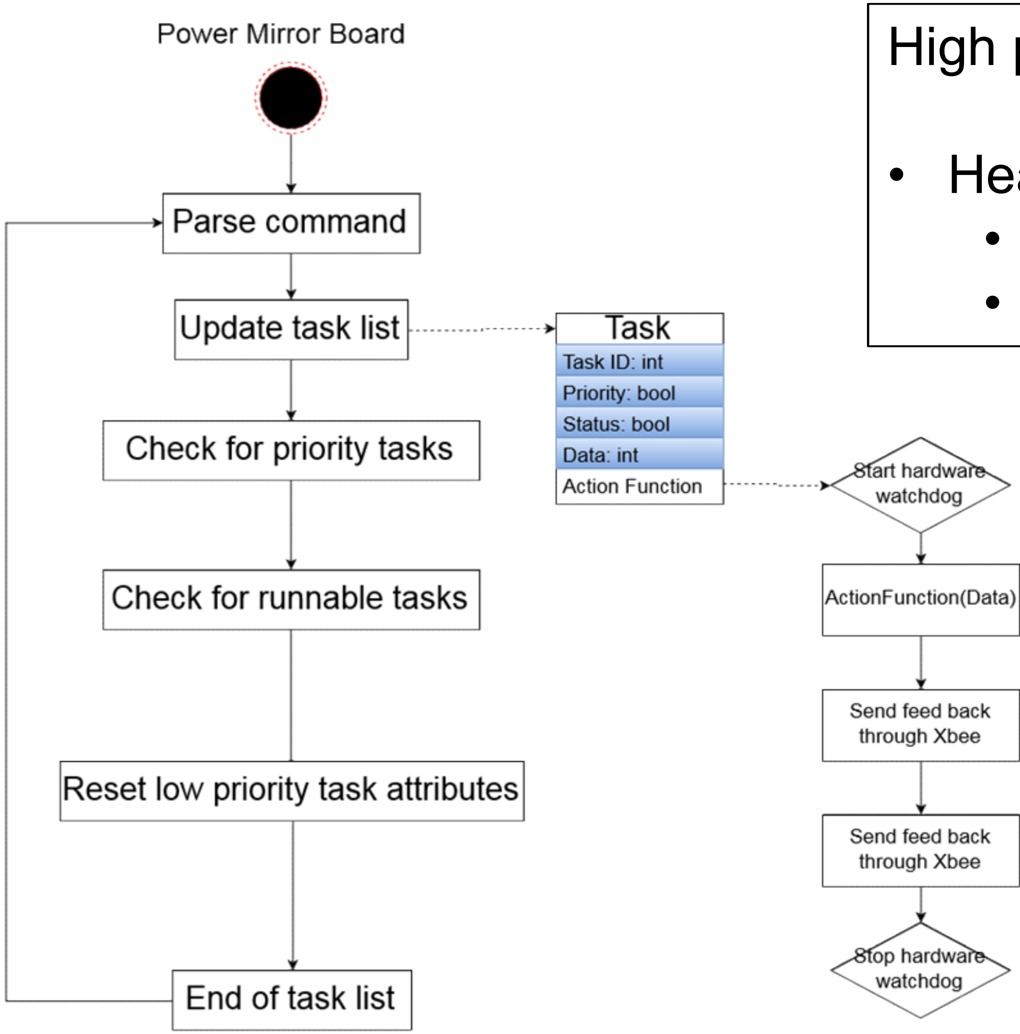
Mirror Box Scheduler



High priority tasks:

- Health keeping
  - Temp sensor check
  - Payload voltage/current check

Low priority tasks:
- Move picomotor
- Mirror actuation
- Retrieve picomotor position

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Mirror Driver Update

- Picomotor controller
  - Open loop actuation tested
  - Feedback algorithm to position each picomotor with ~50nm precision (from simulations): to be tested
- Electrode controller
  - Apply variable HV to each electrode: to be tested
- XBee
  - Independent communication established with Camera
- Temperature sensor
  - Need to ensure reliability of measurements

Mirror Box Software Test

- Bootloader
  - Loads code from an external EEPROM during each boot up
  - Starts code if no issue, otherwise allow camera to upload a new code to the Mirror via Xbee/MirrorSat
  - Tested on flight board
- Scheduler
  - Tested on development board with simple tasks (data transfer through UART)

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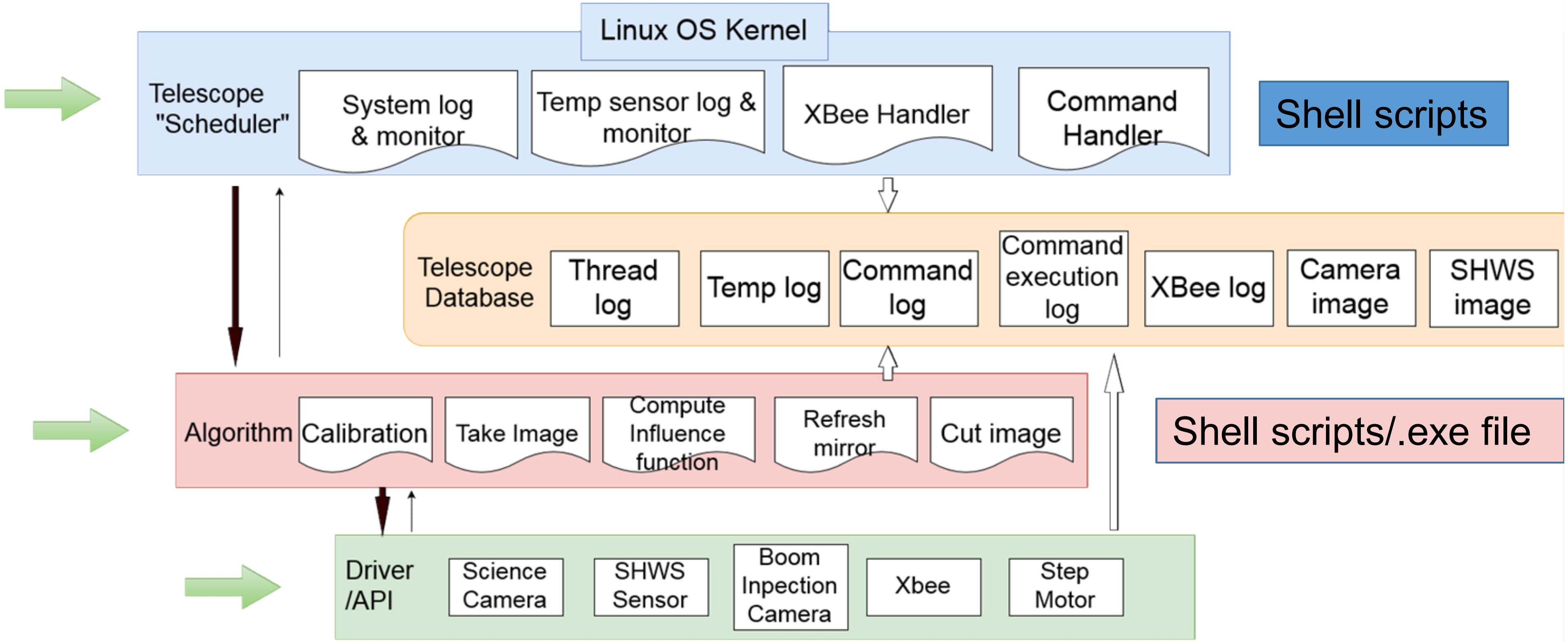
Camera Software Architecture



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

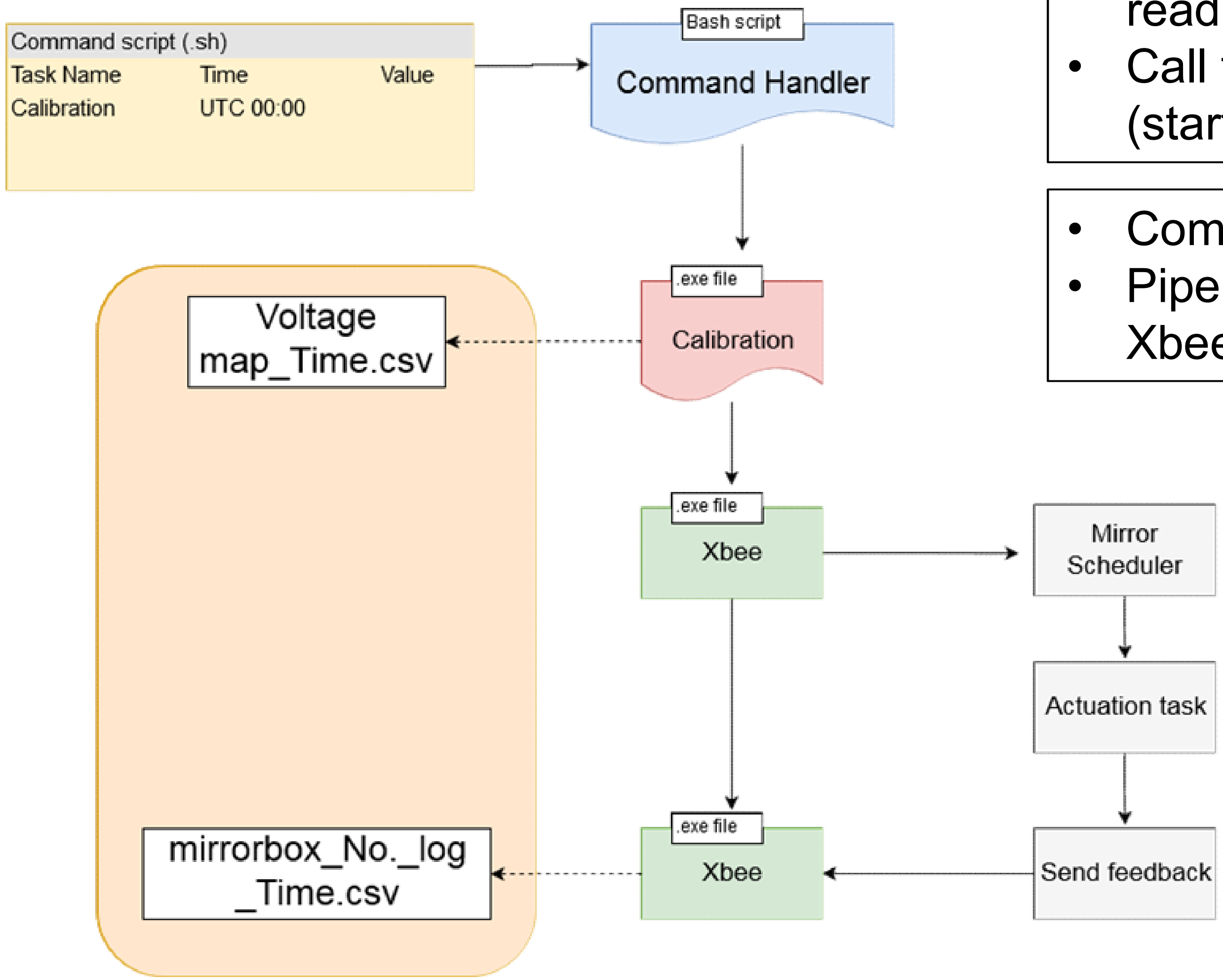
Camera Driver Update

- Science Camera
  - Connection, taking images and check proper functioning
  - Tested on flight CPU
- SHWFS
  - Connection, taking images and check proper functioning
  - Need to be tested on flight CPU
  - Need to include switching of image detector
- XBee
  - Connection to device and comms to 4 remote mirrors
  - Need to check proper functioning in flight
- Temperature sensors
  - Need to ensure reliability of measurements

Camera Software Test

- Google test
  - Framework to test software
  - Tested all image processing functions
- Telescope testbed GUI
  - Created a GUI to control the testbed and test the code
- Driver test
  - Science camera, SHWS and XBee/Mirror comms tested on the testbed through the GUI
  - Initial tests, in the process of improving the drivers

Cmd flow example: Calibration

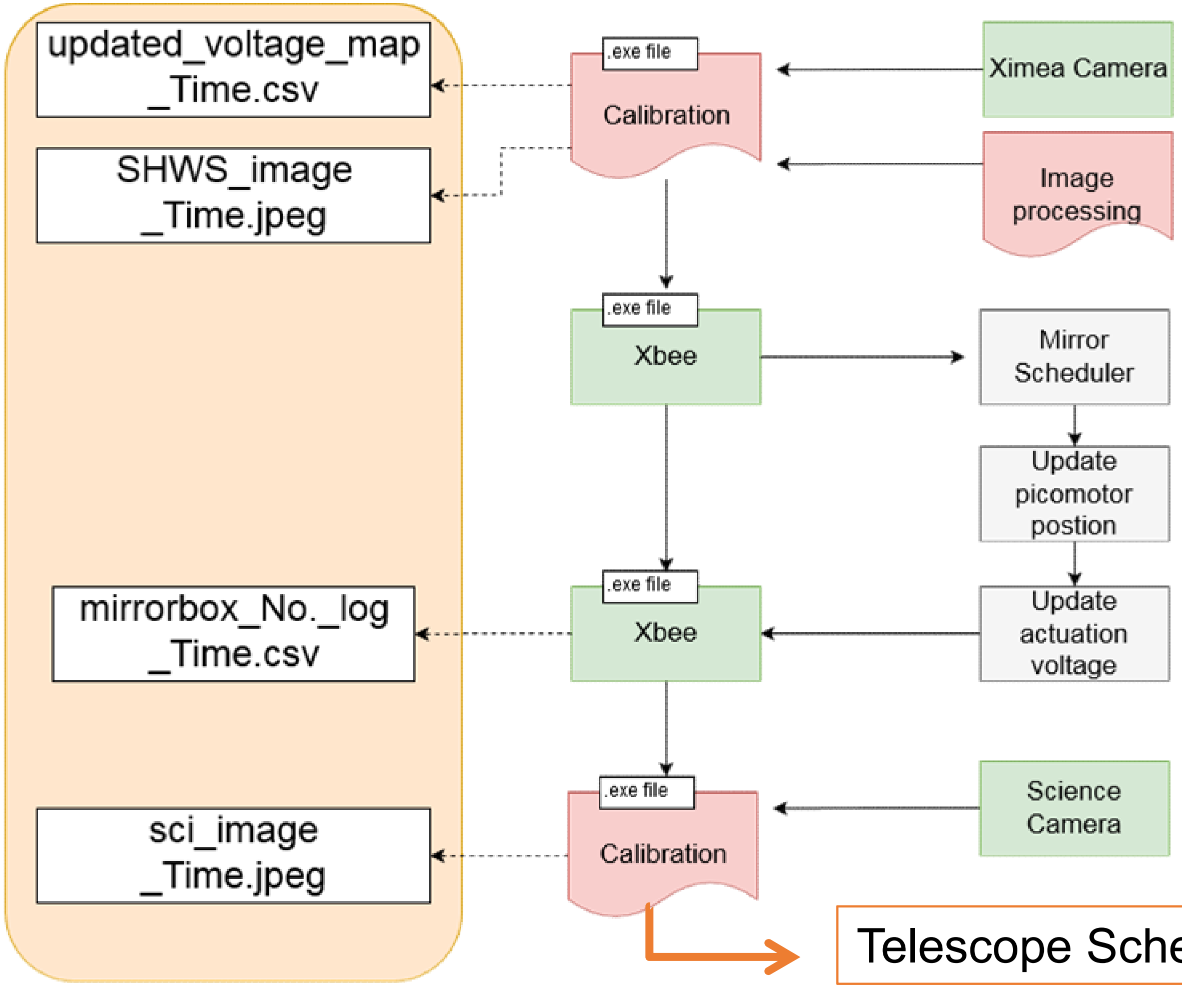


- Cmd handling process read command script
- Call target algorithm (start calibration process)

- Compute voltage map
- Pipe voltage map to Xbee process /

- Parse voltage map to atom commands
- Scheduler task receives voltage value

Cmd flow example: Calibration



- Call camera API, take image
- Call image processing module, read image & analyze wavefront error
- Pipe new voltage map to XBee process
- Voltage update through scheduler
- Feedback to XBee process
- Take image

Telescope Scheduler turns off all processes

Camera and mirror boxes idle state

- Definition of telescope "idle" state:

Camera side

- Power: CPU board, XBee module and temperature sensors
- Monitor power supply
- Establish XBee communication with mirror boxes
- Perform house keeping for system processes and peripheral sensors
- Check for incoming command from CoreSat

Mirror side

- Power: MCU board, XBee module and temperature sensors
- Monitor power supply
- Send house keeping info of power supply and peripheral sensors to camera
- Check for incoming command to update scheduler task list

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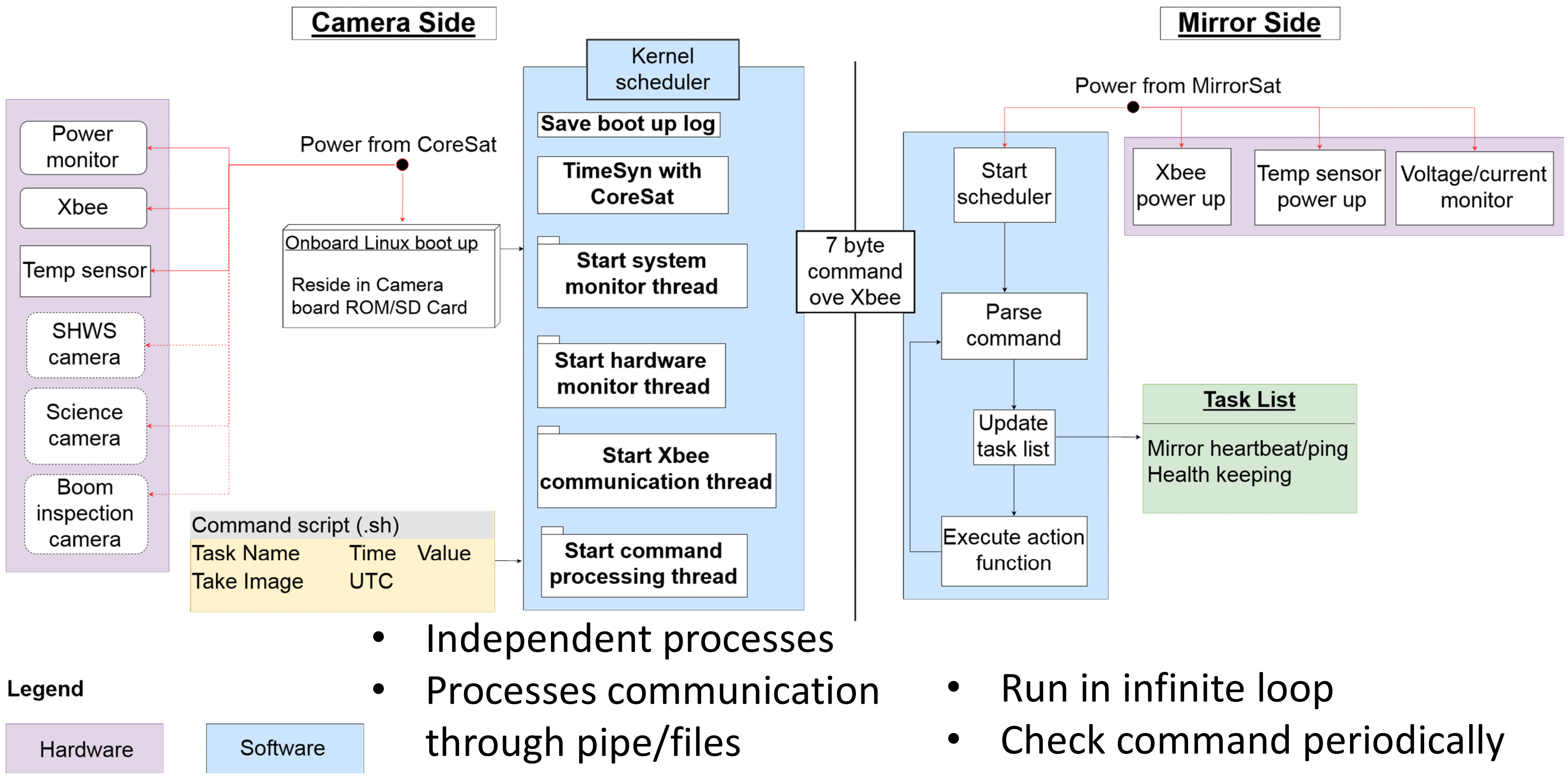
Camera and mirror boxes boot process



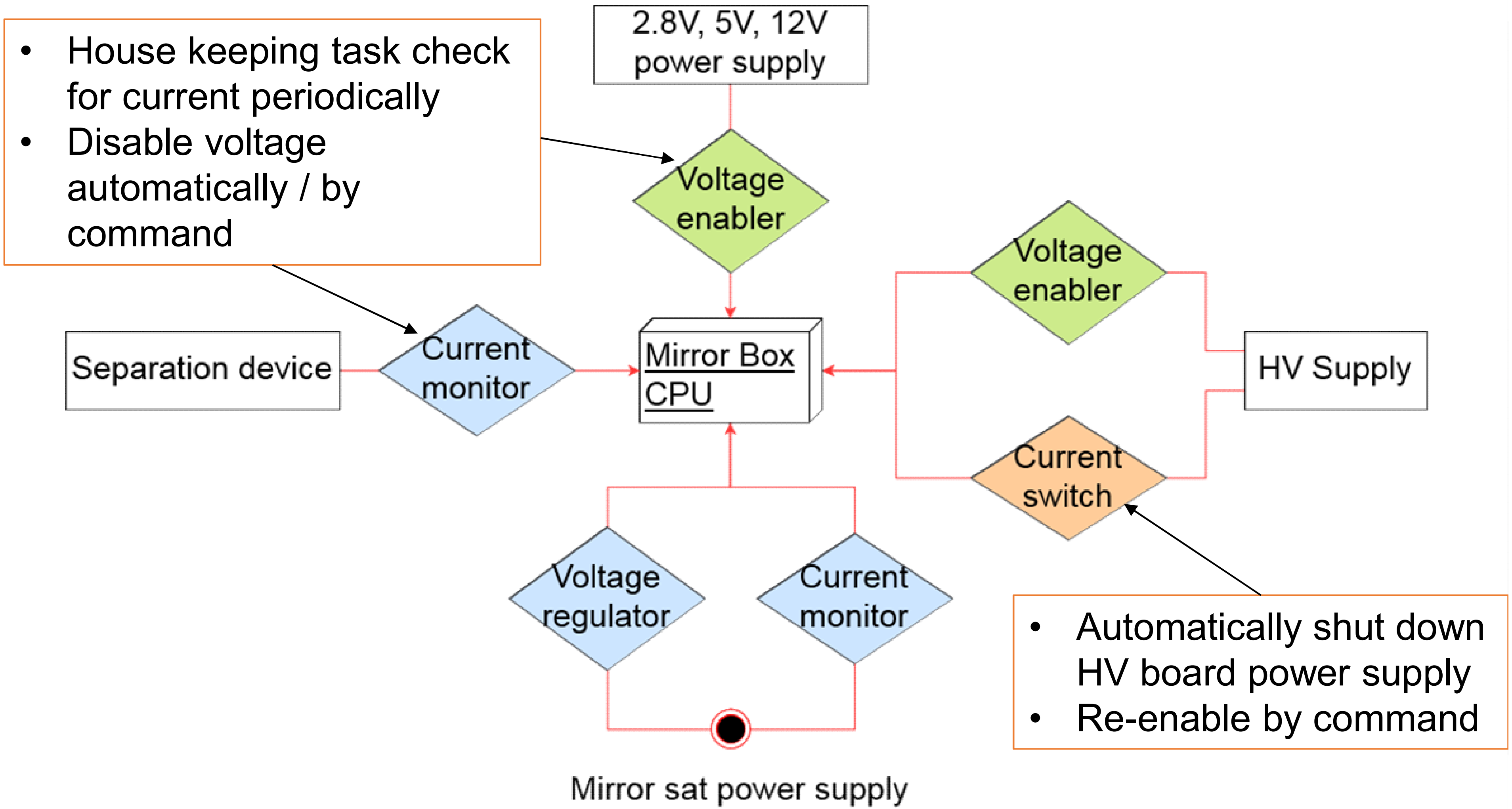
- Independent processes
- Processes communication through pipe/files
- Processes monitored by OS

- Run in infinite loop
- Check command periodically
- Task protected by watchdog timer

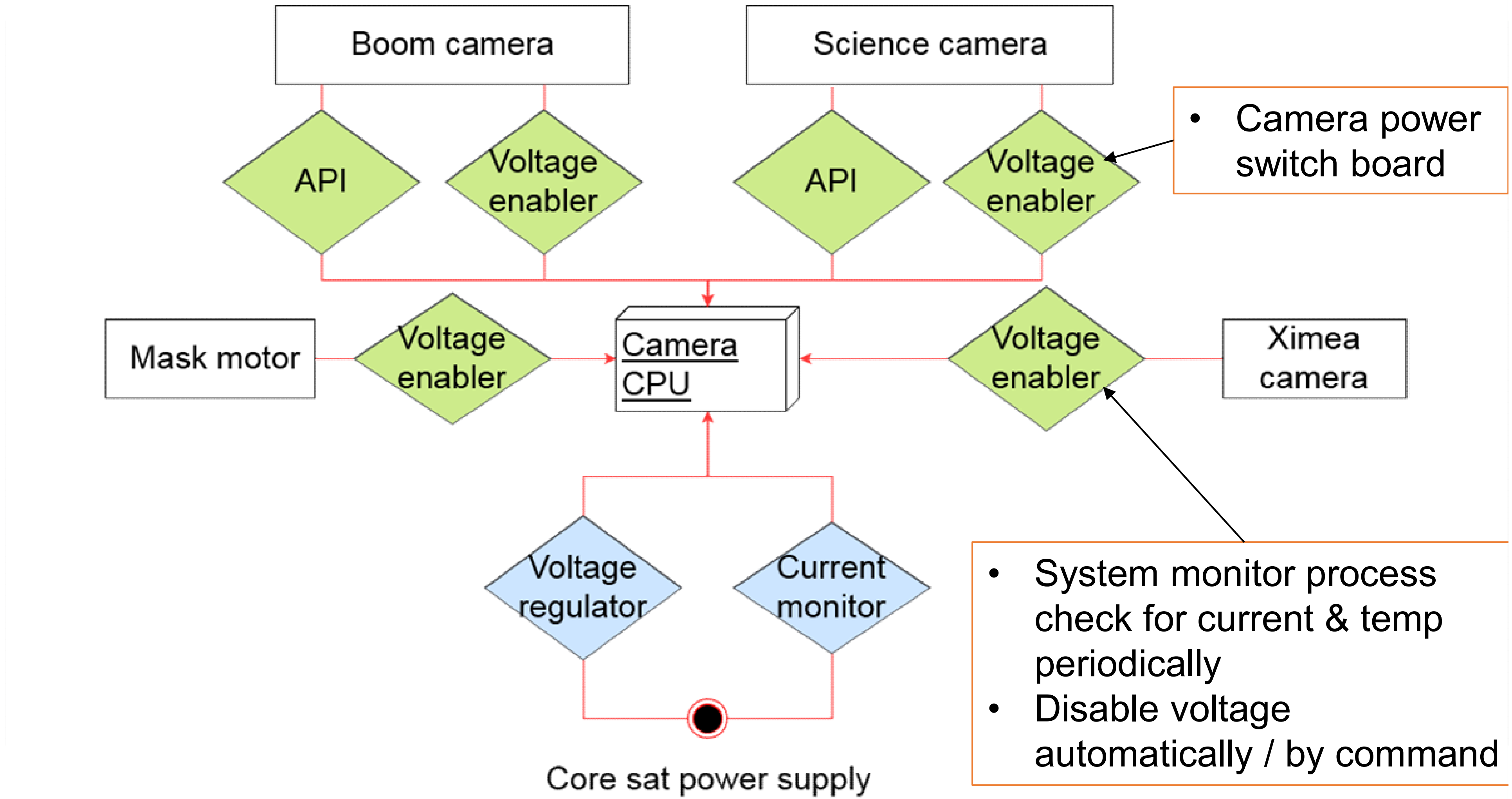
Error handling strategy

- Definition of camera/mirror safe mode:
  - Turn off all science payloads
  - Microcontroller/Camera CPU monitor temp & voltage
  - Keep camera - mirrobox communications
  - Keep communications with coresat & mirrorsat
  - 4 mirror boxes and camera have independent safemodes
- Automated safe mode trigger of camera/mirror :
  - Camera: system monitor process turns off payloads; command mirror boxes to disable payload; write system log
  - Mirror boxes: error handling task disable payload power supply; feed back to camera; write system log

Mirror error handling strategy



Camera error handling strategy



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Conclusion

- Finished drivers & scheduler on mirror side
  - Running on telescope testbed with GUI control now
- Finished 70% drivers & algorithms on camera side
  - Tested with
- Finished initial architecture design on camera side

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Future work

- Camera side
  - Implementation of camera scheduler layer
  - Finish and test camera drivers on telescope CPU
  - Tailoring of Linux kernel
- Mirror side
  - Test mirror actuation driver
  - Packaging of mirror tasks
  - Test of scheduler on telescope testbed

Presentation Agenda

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

Boom Subsystem

Christophe Leclerc

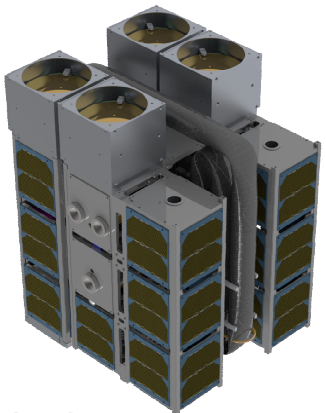
Subsystem Overview

Purpose:

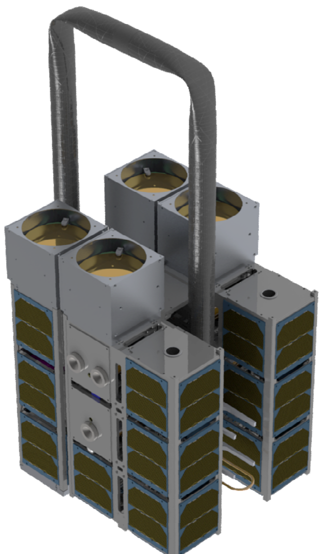
- Guarantee successful deployment of the composite boom
- Ensure alignment of optical systems after deployment

Main components:

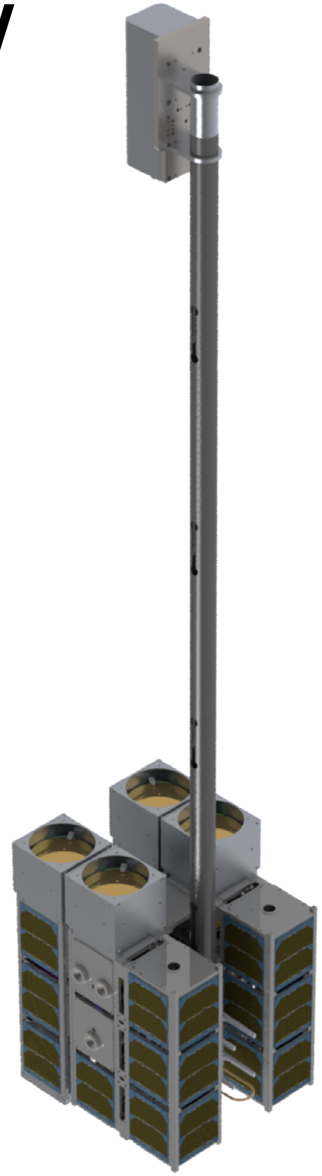
- Kinematic mounts
- Separation device
- Composite boom



Stage 1
Deployment



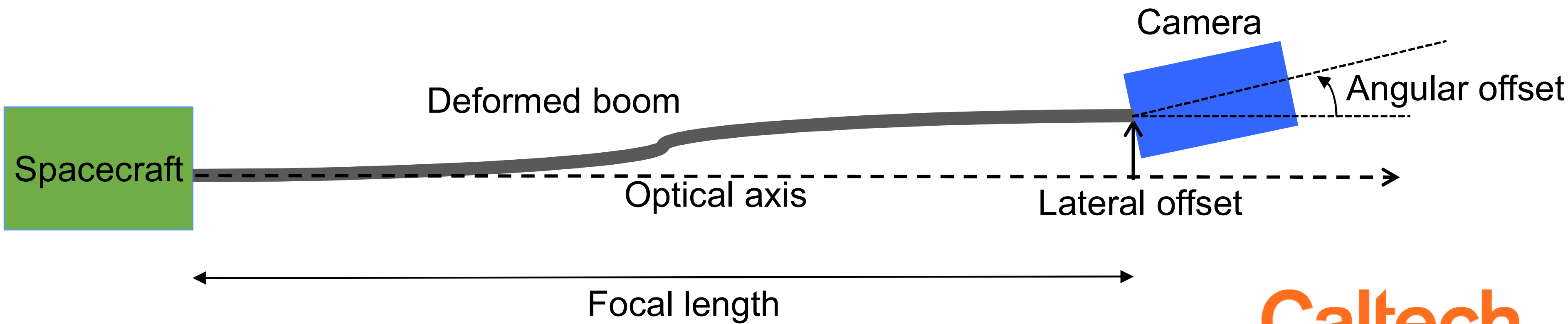
Stage 2
Deployment



Boom Subsystem Requirements

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

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



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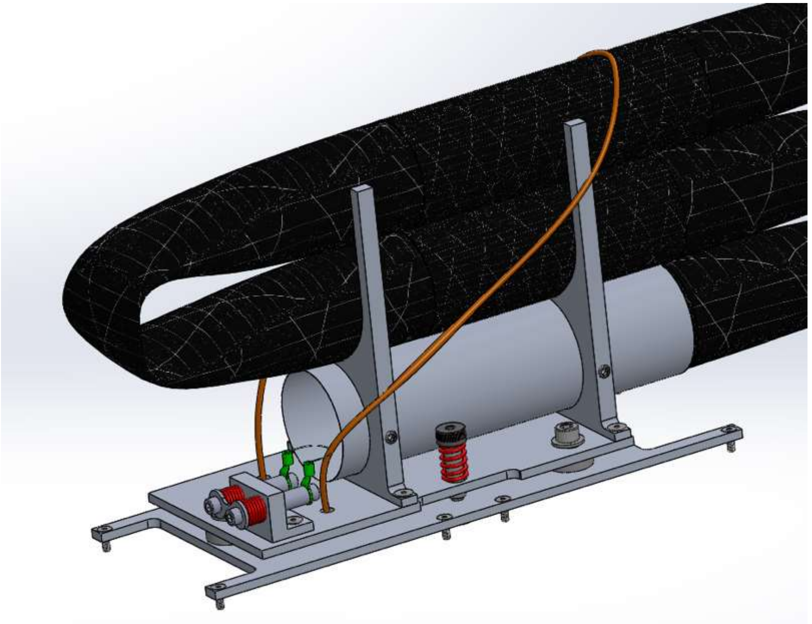
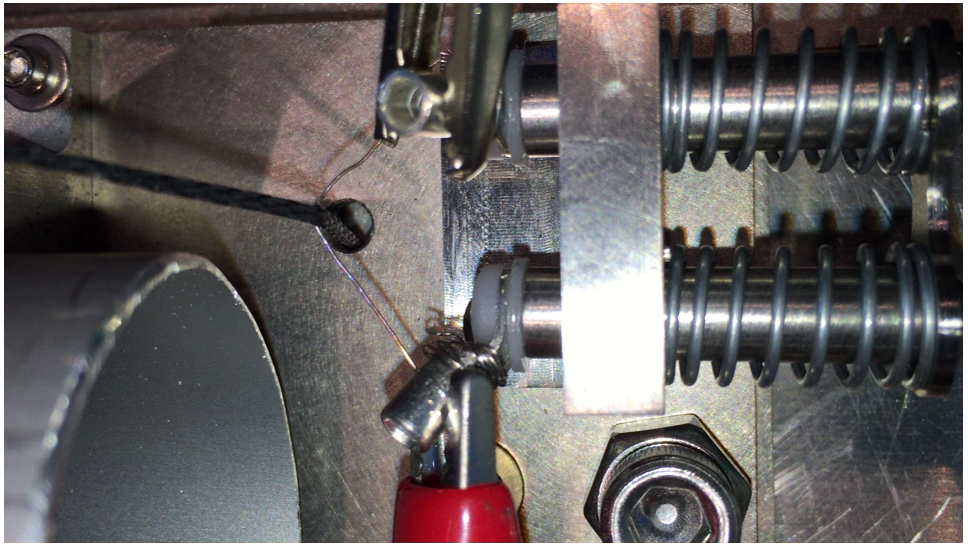
System Overview

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

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





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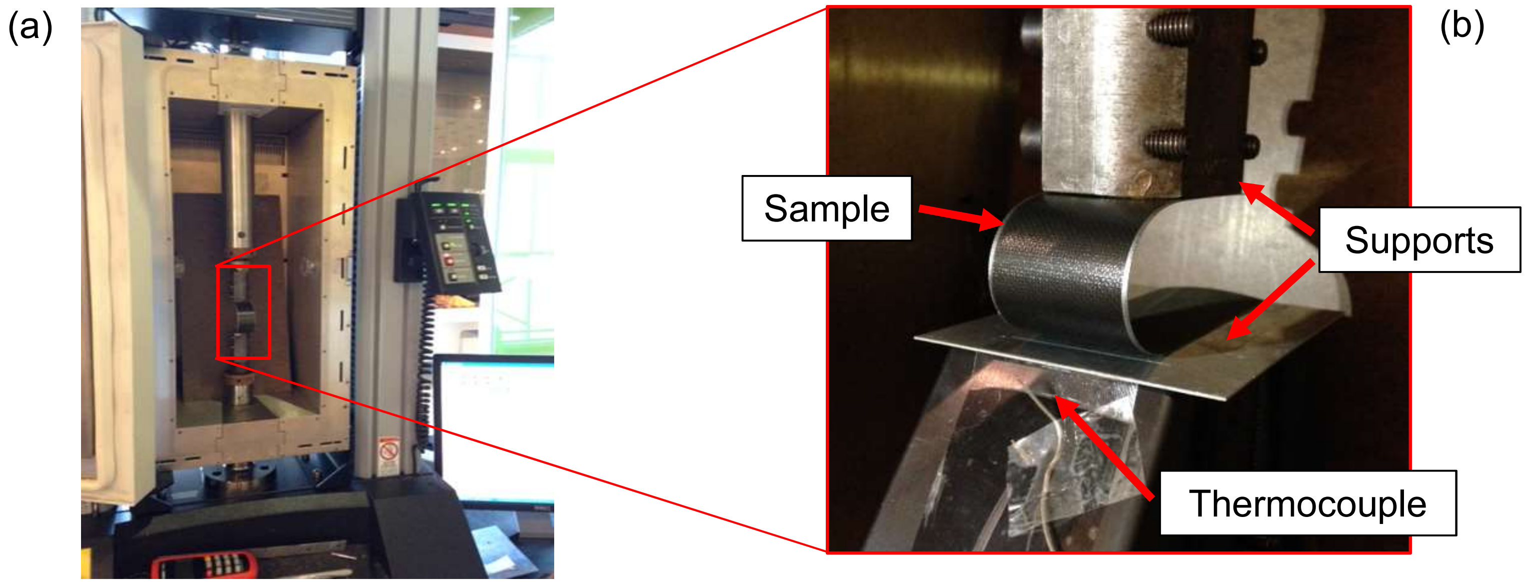
Viscoelastic Test

Objective: Ensure boom retains sufficient potential energy for deployment after long-term storage, and does not present any permanent deformation.

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 .

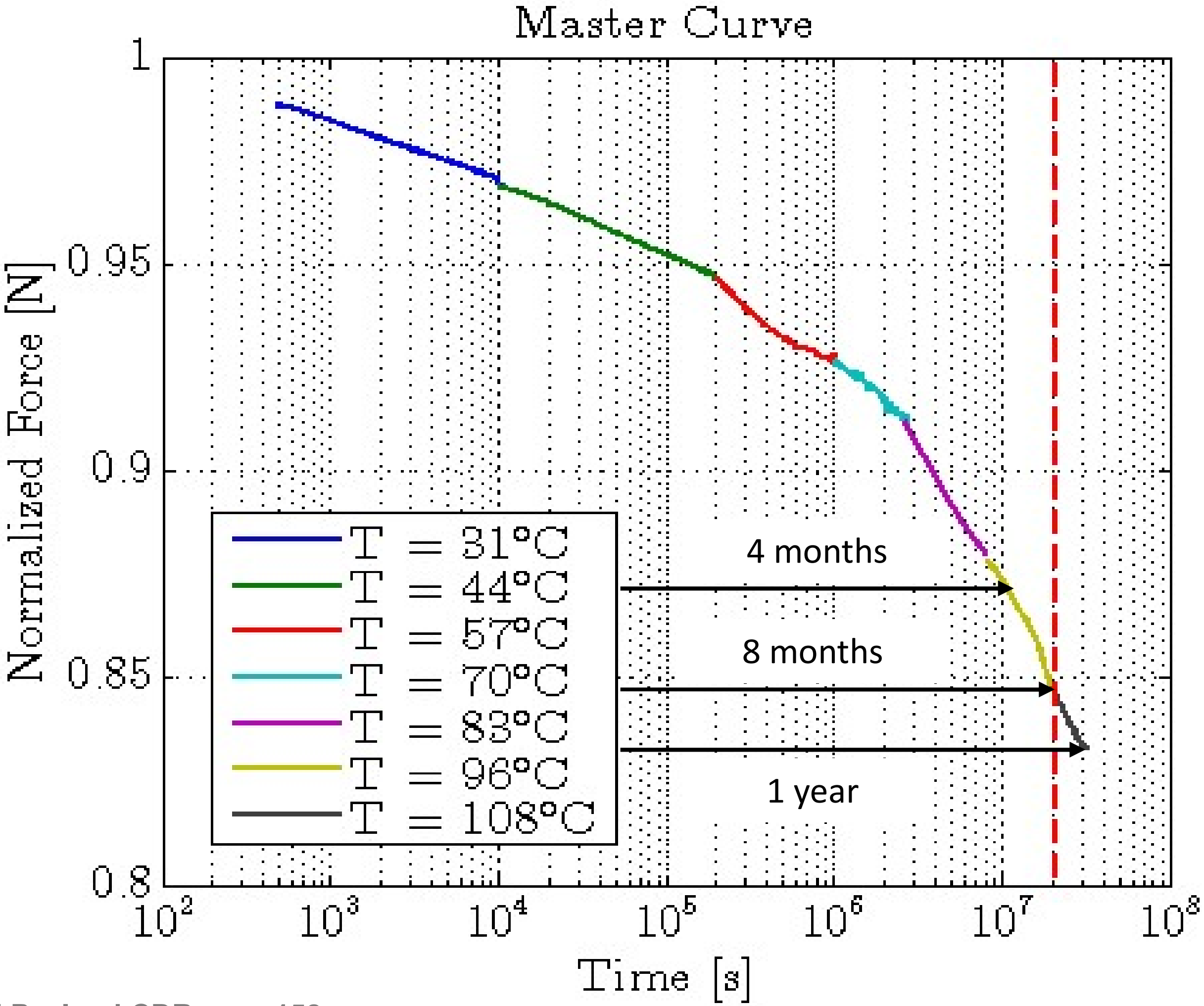
Viscoelastic Properties

Results: Obtained force-time relations over chosen range of temperatures, that allow to generate a master curve through the time-temperature superposition principle.

To simulate 7 months of storage time the sample need to be <u>aged 50 hours at 60 °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.



Vibration Testing Objectives

Survive launch vibration phase

Acceptance level test (10 gRMS, 30g peak)

Random vibration
Input direction:
- X-axis (old design)
- Y-axis (old design)
- Z-axis (final design)

Accurate position of the camera

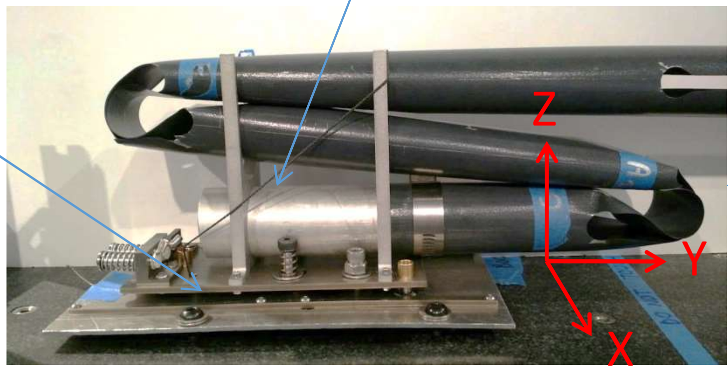
Vibration induced displacements of the adjustable components

Separation device functional

Evolution of the Vectran cable tension

System undamaged

Structural integrity and mechanical response



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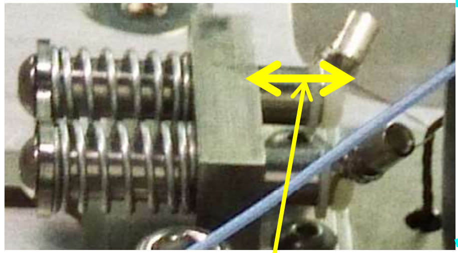
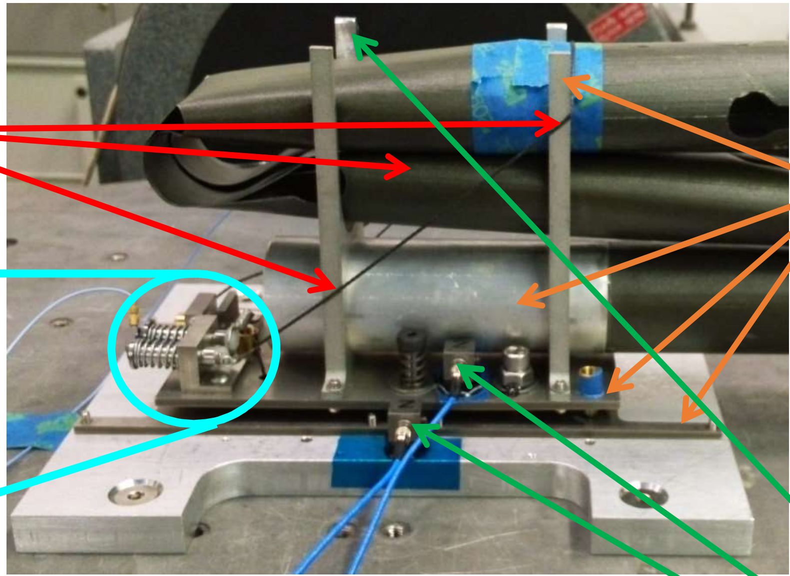
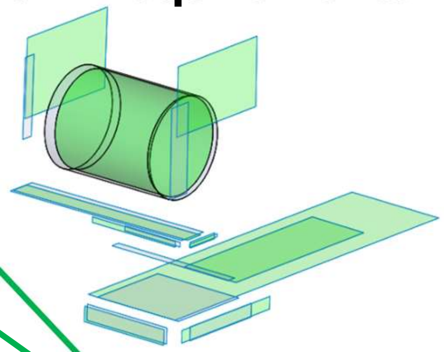
Vibration Testing Results

Thorough visual inspection
No damage was observed

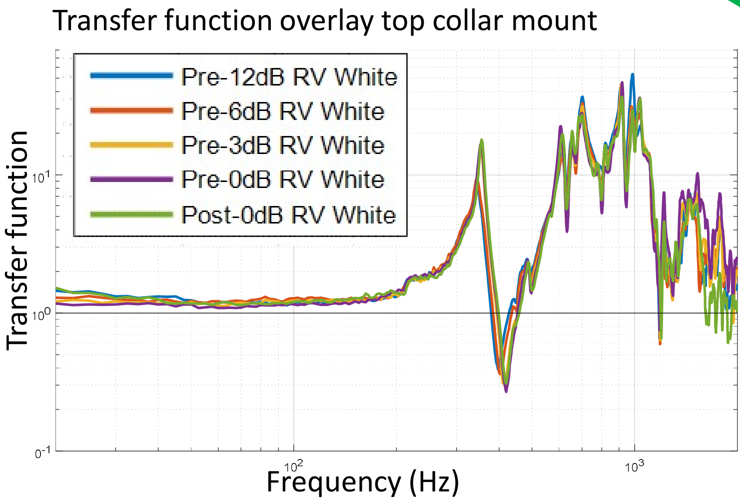




Faro arm measurements: relative displacements
Displacements measured well within requirements



Stroke of the separation device: Tension of the Vectran cable
Almost no change in stroke

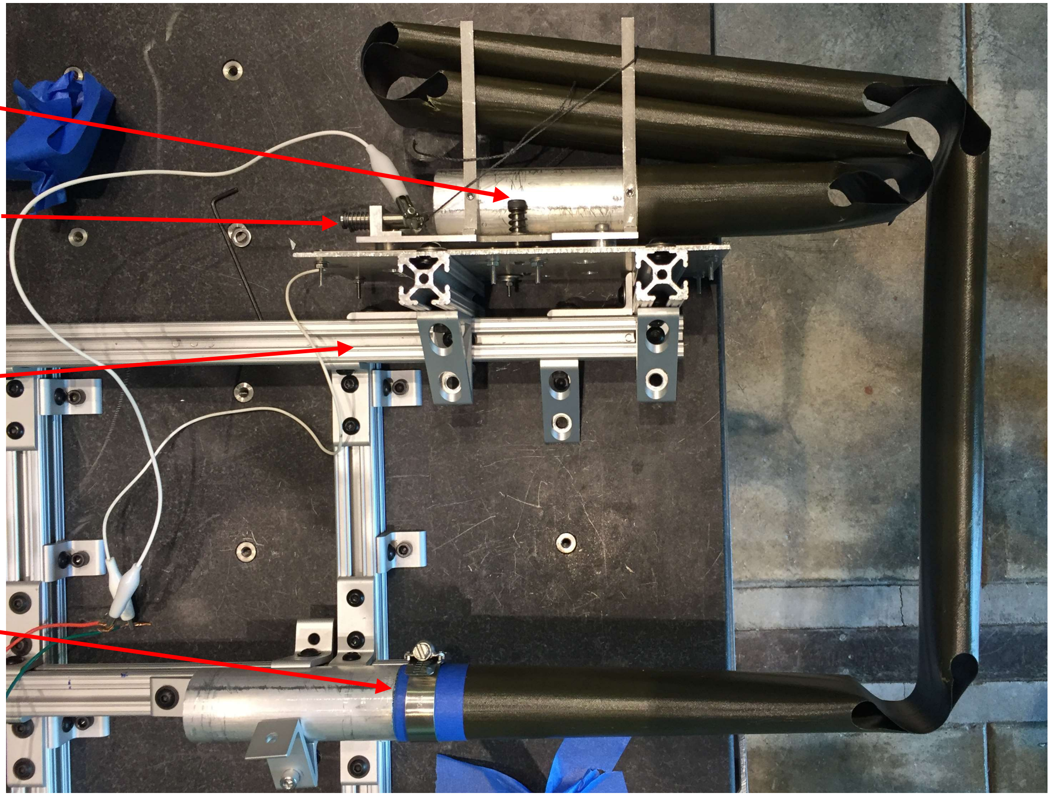


Accelerometers: Structural integrity
No major frequency shift were observed

Stage 1 Deployment

Objectives:

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



Kinematic Mount

Separation Device

Rigid Frame
(Coresat)

Clamped
(Camera end)

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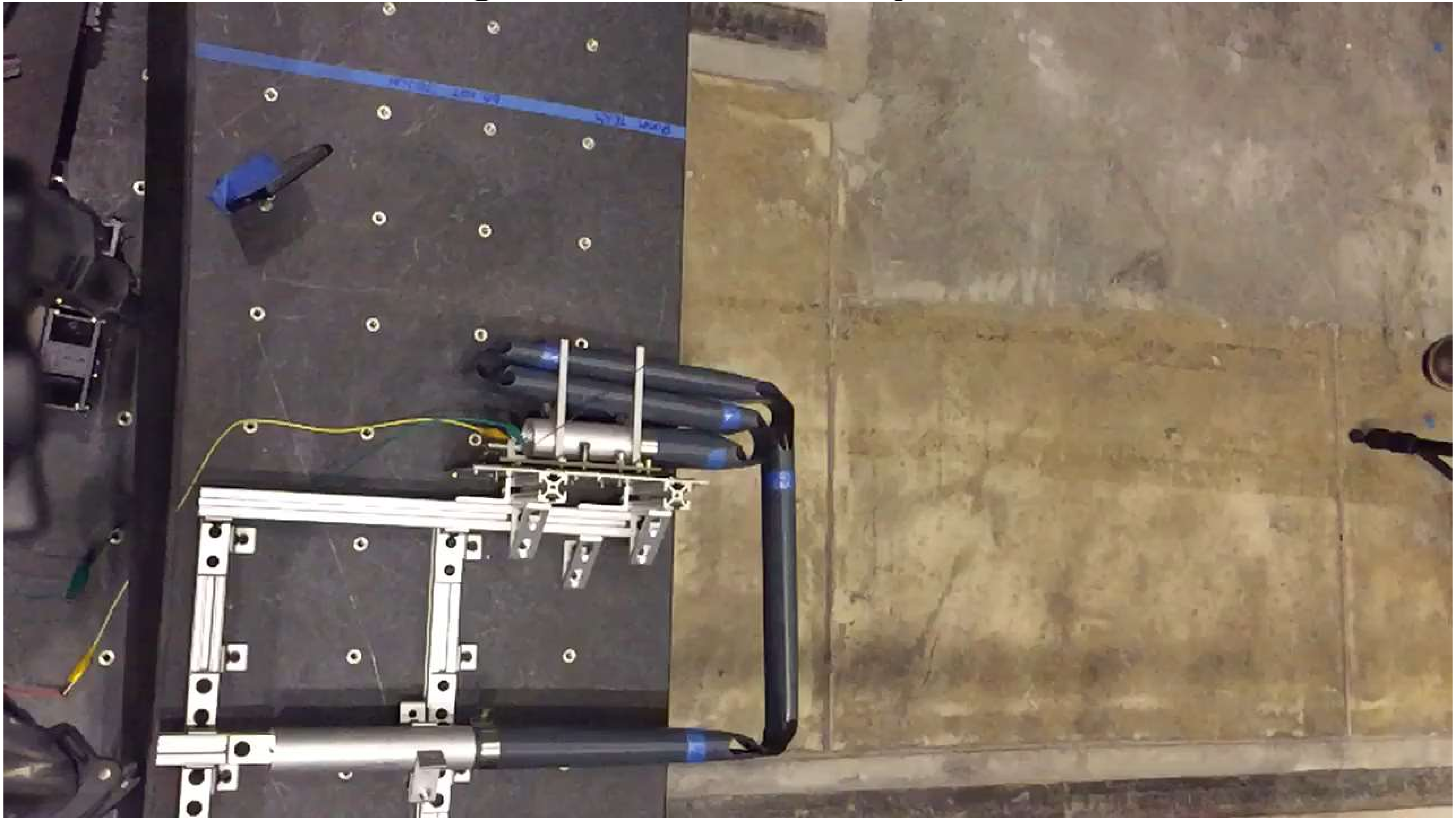
Stage 1 Deployment



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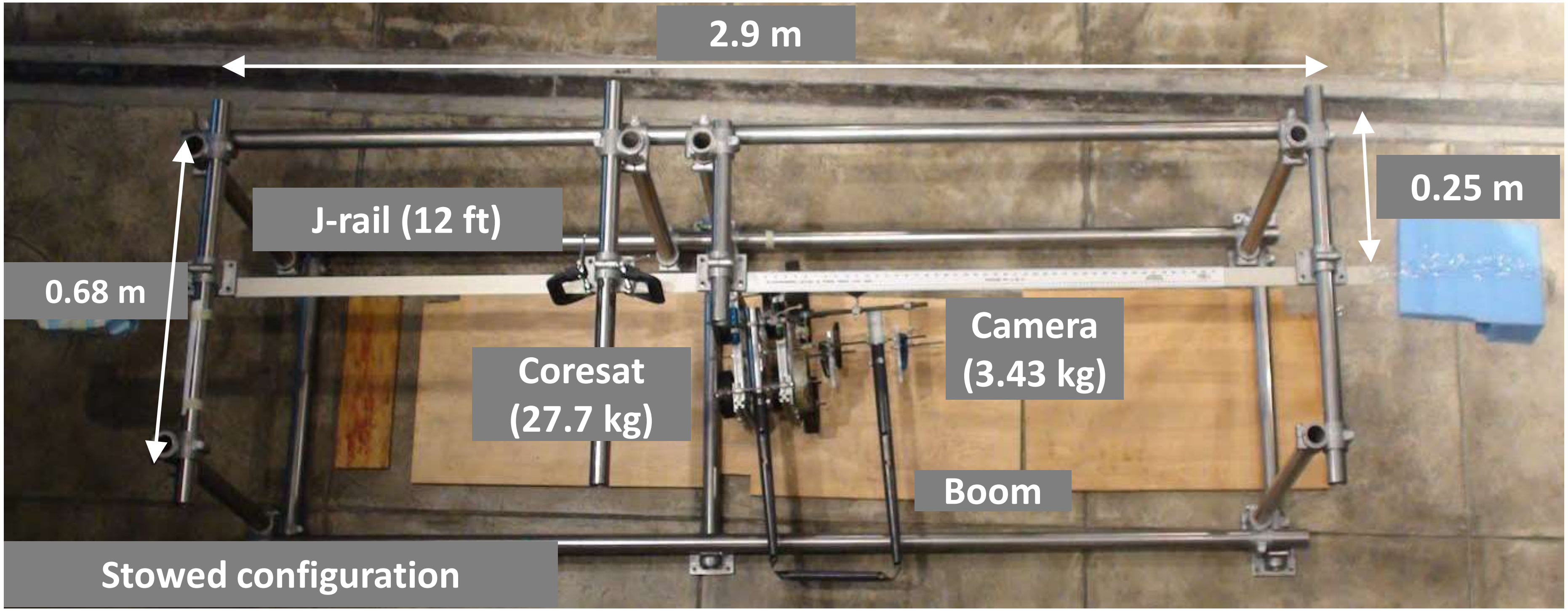
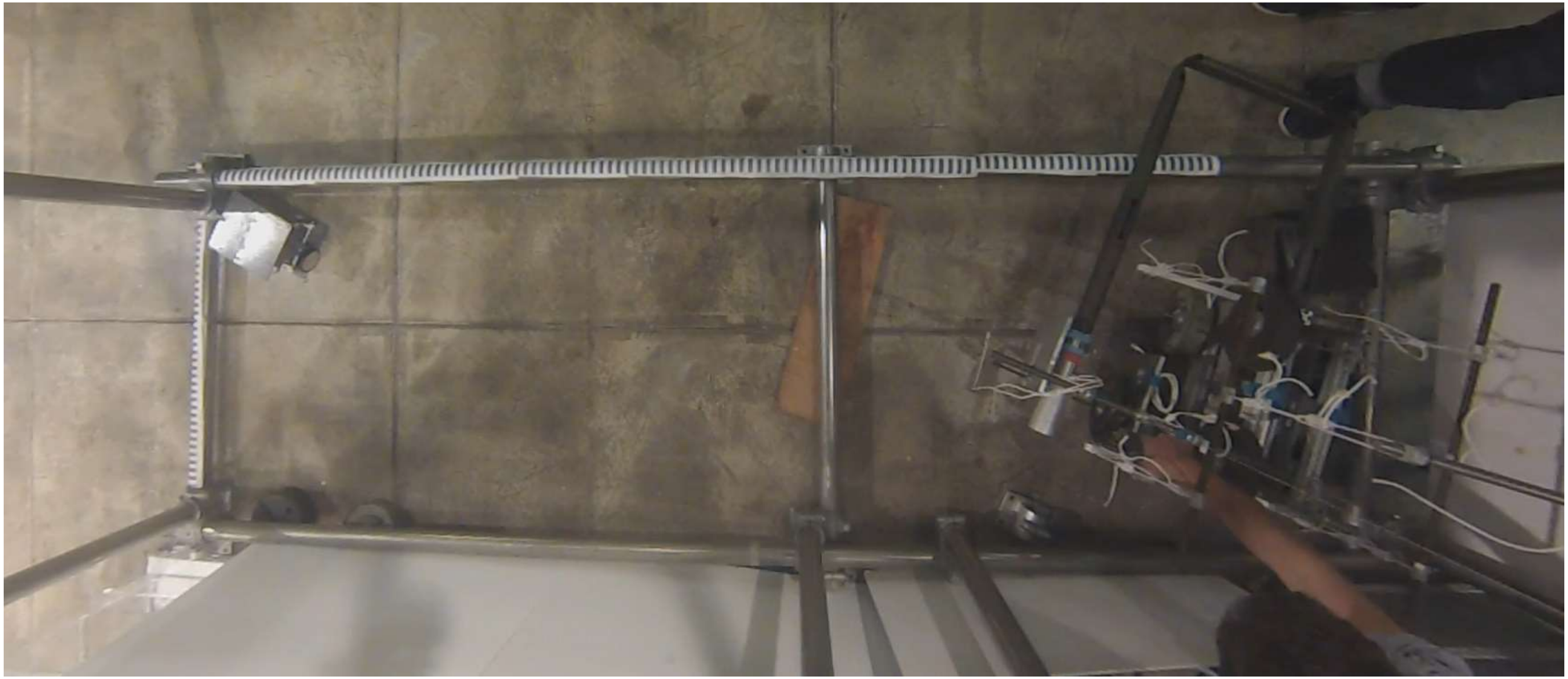
Stage 2 Deployment Test

Objectives:

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



Stage 2 Deployment



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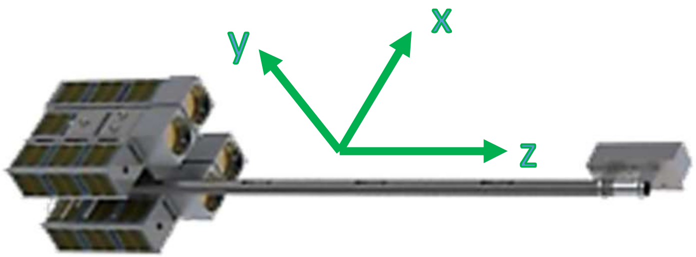
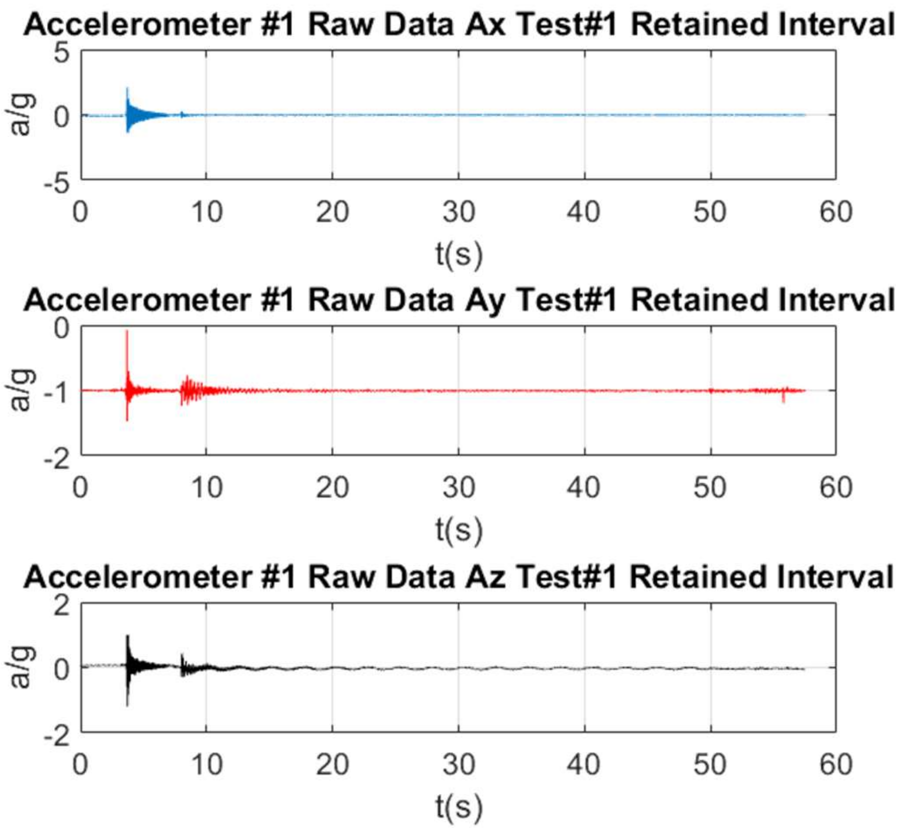
Stage 2 Deployment

- Reliable deployment: always successful
- Very sensible to initial conditions
  - Small variations can significantly modify the deployment behavior
  - Hinges latching order can reverse
  - Camera could potentially contact the Corsat
- Maximum accelerations on camera: About **1g**
- Loads due to deployment are expected to be smaller than those during to launch





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Accuracy Testing

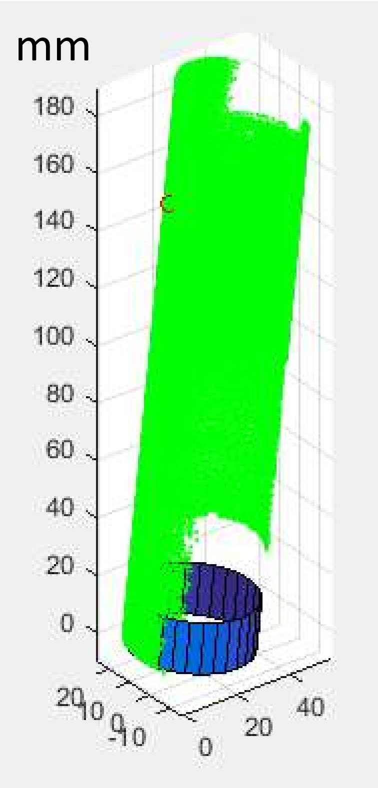
Objectives:

- Ensure a reliable and repeatable positioning of the camera after aging in the stowed configuration

Procedure:

1. Scan the camera end of the boom
2. Scan the coresat end of the boom
3. Fit each point cloud to a cylinder in matlab
4. Determine the position of the camera end relative to the coresat end
5. See how the position changes after folding and aging

Accuracy Testing



Cylinder Fit to Point Cloud

	Length Change	Lateral Change	Angular Change
Requirement	± 1mm	± 3mm	± 1º
Folding	0.1 mm	0.5 mm	0.1º
Aging	0.1 mm	1.1 mm	0.2º

- All three values are well within requirements
- However, aging process deformed the cross section of the boom from circular to ellipsoid
  - No effect on deployment or accuracy

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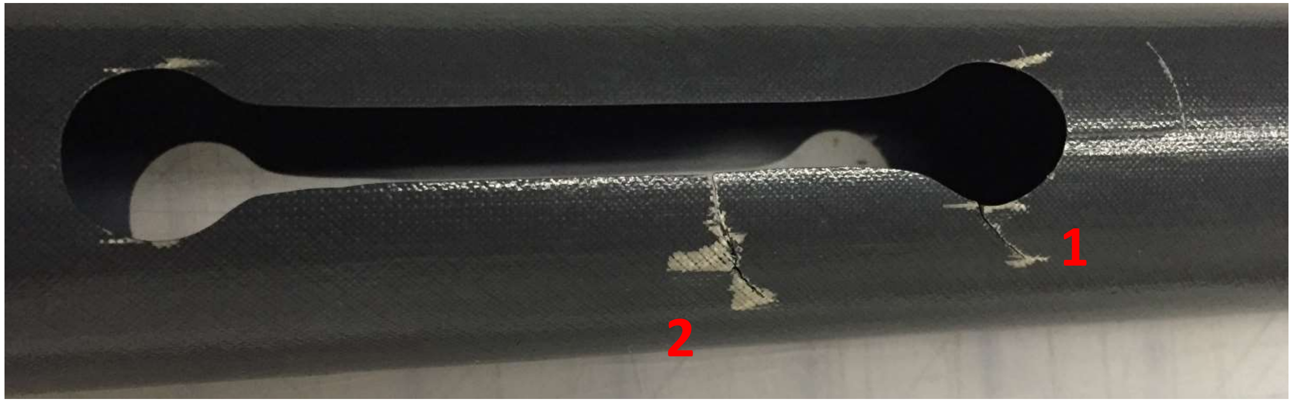
Boom Damage

- One issue that was observed with the boom is the cracking at the hinges location
- Ever samples were continuously monitored:
  - Each folding/unfolding cycle was recorded for each hinge
  - Crack initiation and growth were documented
- Cracks appear from the first time the boom is folded, and propagate with each folding-unfolding
- However, it does not seem to affect deployment even after multiple (more than 10) folding-unfolding cycles



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Summary

- We completed the design of the boom subsystem
- We studied the viscoelastic behavior of the composite boom
- We successfully performed:
  - Vibration testing
  - Deployment testing (both stages)
  - Accuracy testing following aging
- Composite boom damages are continuously monitored and do not prevent successful deployment

Future Work

- Stage 1 and stage 2 deployment following aging
- Integration of cabling (connecting the Camera to the Coresat)
- Update thermal deformation analysis

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