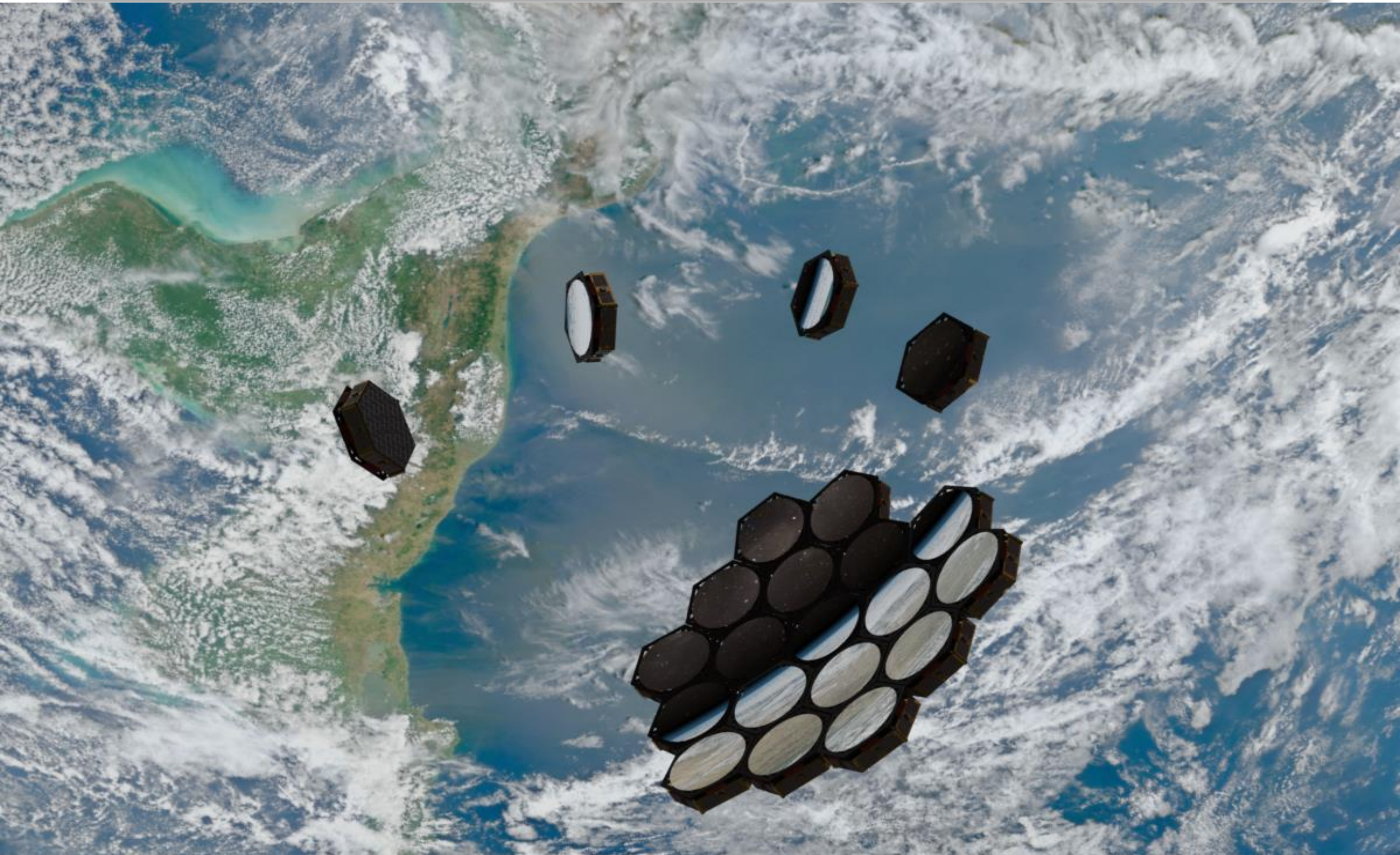
AAReST Detailed Design Review
Mission Overview

John Baker

September 8, 2014

Caltech

The Vision



Review Objective

Objective:

- Demonstrate the readiness to proceed to a flight technology Project CDR.
  - Does the detailed design appear feasible?
  - What concerns do you have that we need to address as we go forward?

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Review Outline

1. Mission Overview (15 mins)
   – Telescope overview
2. Spacecraft Design (150 mins)

   < Coffee Break>
3. Telescope Design (150 mins)
   a) Telescope Concept of Operation (Melanie)
   b) Camera (Manan)
   c) Mirrors (John)
   d) Electronics (Yamuna)
   e) Boom (Lee)
   f) Telescope System Modelling (Lee / Marie)
   g) Telescope Breadboard/Test (Marie)
4. Summary & wrap up (15 mins)

Please send comments to Dr. Greg Davis (Gregory.L.Davis@jpl.nasa.gov)

Team Responsibilities

UNIVERSITY OF SURREY

- NanoSat and MirrorCraft
- Docking system
- Integrated spacecraft & mission ops

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- Deformable mirrors
- Telescope system
- Optical focus algorithm
- Boom w/AFRL

AIR FORCE RESEARCH LABORATORY

- Composite Boom

TBD

Launch

JPL

Class instructors
Manufacturing facilities

** Planning to have discussions with ISRO*

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Project Approach

- Partner with Univ of Surrey for spacecraft development
  - Use proven cubesat elements with some new technology and some redundancy to ensure we can accomplish the objectives
- Well defined objectives and short duration mission with clear goals for an extended mission
- Keep spacecraft to payload interfaces simple
- Automate telescope to maximum extent possible
- *Modularize design for future applications*
- AE105 classes do design, analysis, test and operations tasks as the Project matures. JPL instructors teach the class.
- Caltech grad and SURF students do research and technology development for the telescope
- JPL provides class instructors, access to the Micro Devices Lab (MDL) and other facilities as requested.

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AAReST Mission Objectives

- Accomplish two key experiments in LEO by demonstrating new technologies for
  1. A low-cost active deformable mirror (one star image with 80% encircled energy)
  2. Autonomous rendezvous and docking with small spacecraft for telescope re-configuration
- Operate as long as necessary to accomplish the objectives (90 days) post spacecraft commissioning
- Accomplish the mission inexpensively for a 2016 launch
- Gather engineering data that enables the next system development (eg. mirror performance over temp and time)

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Mission Objectives→System Requirements

- 80% encircled energy
- Rendezvous & docking
- Lifetime

Telescope

- Optical Design

Spacecraft

- Pointing knowledge, control & stability
- Jitter
- Docking port vertical offset
- Reconfiguration
- Lifetime (90 days)

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Extended Mission Objectives

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 (eg Earth and Moon) for outreach purposes.

- Requirements flowed down to the subsystem level last year
- Surrey will discuss spacecraft system and subsystem requirements and updates
- Telescope requirements will be discussed in each presentation along with updates.

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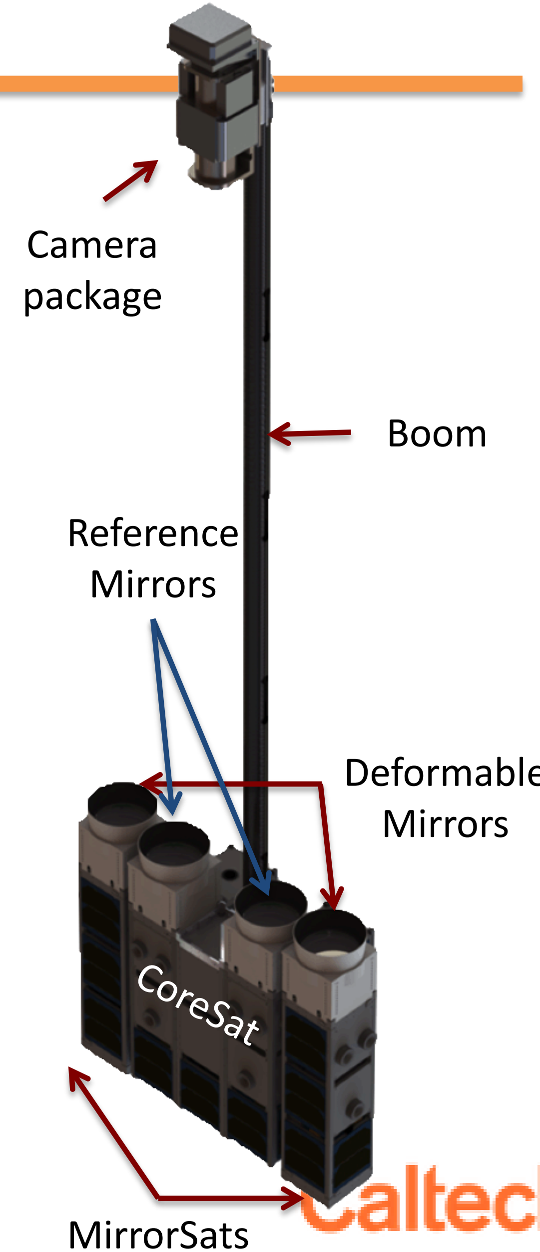
Spacecraft & Payload Elements

1. MirrorSat (x2) – 3U cubesats with deformable mirrors on top with rendezvous and docking capability
2. CoreSat – main spacecraft with primary power, communications, primary ACS, docking capability

Payload

1. Mirror assemblies – 2 active deformable mirrors, 2 fixed glass reference mirrors with tip/tilt positioning
2. Instrumentation package – Telescope optics, detectors, wave front sensor, aperture mask
3. Boom – 1.2m deployable composite



Operation timeline

Pre-launch & Launch

Deployment → Calibration → Imaging → Reconfiguration → Calibration → Imaging → Extended mission

Desorbit

(a) (b) (c)

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Deployment

t=0
- Launch
- Detach from launcher & Verify orbit

2 orbits
- Turn on satellite
  - Turn on low voltage
  - Switch from battery to solar power

4 orbits
- Verify and stabilize satellite
  - Power, Thrusters, Communications
  - Tumble rate, Temperature, Attitude
  - Camera functioning (dark measurement)

8 orbits
- Telescope deployment
  - 1st stage boom deployment
  - 2nd stage boom deployment w/ camera
  - Uncage DM1, DM2, RM1 & RM2

9 orbits
- Adjust and stabilize satellite attitude
- Point spacecraft to first target and begin telescope calibration

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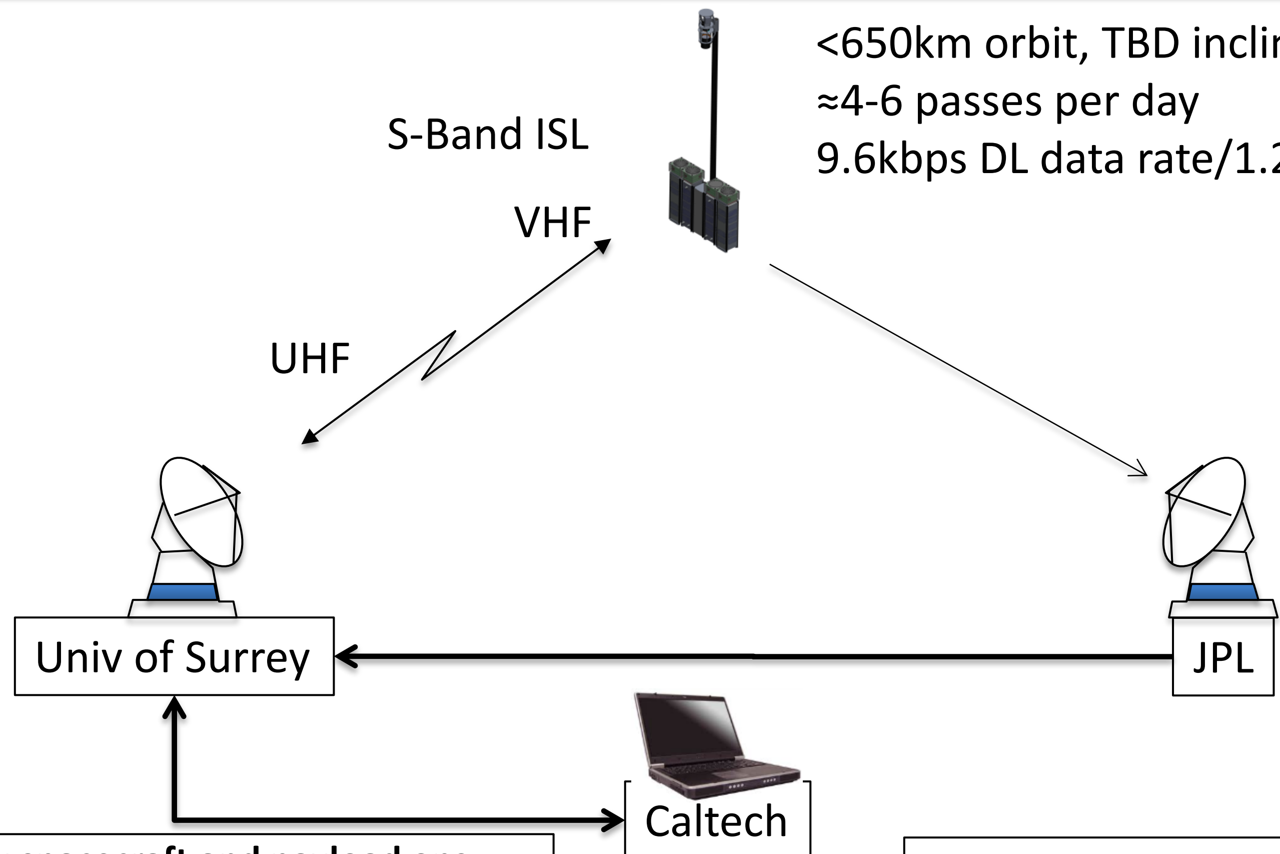
Mission Architecture

<650km orbit, TBD inclination
≈4-6 passes per day
9.6kbps DL data rate/1.2 kbps UL



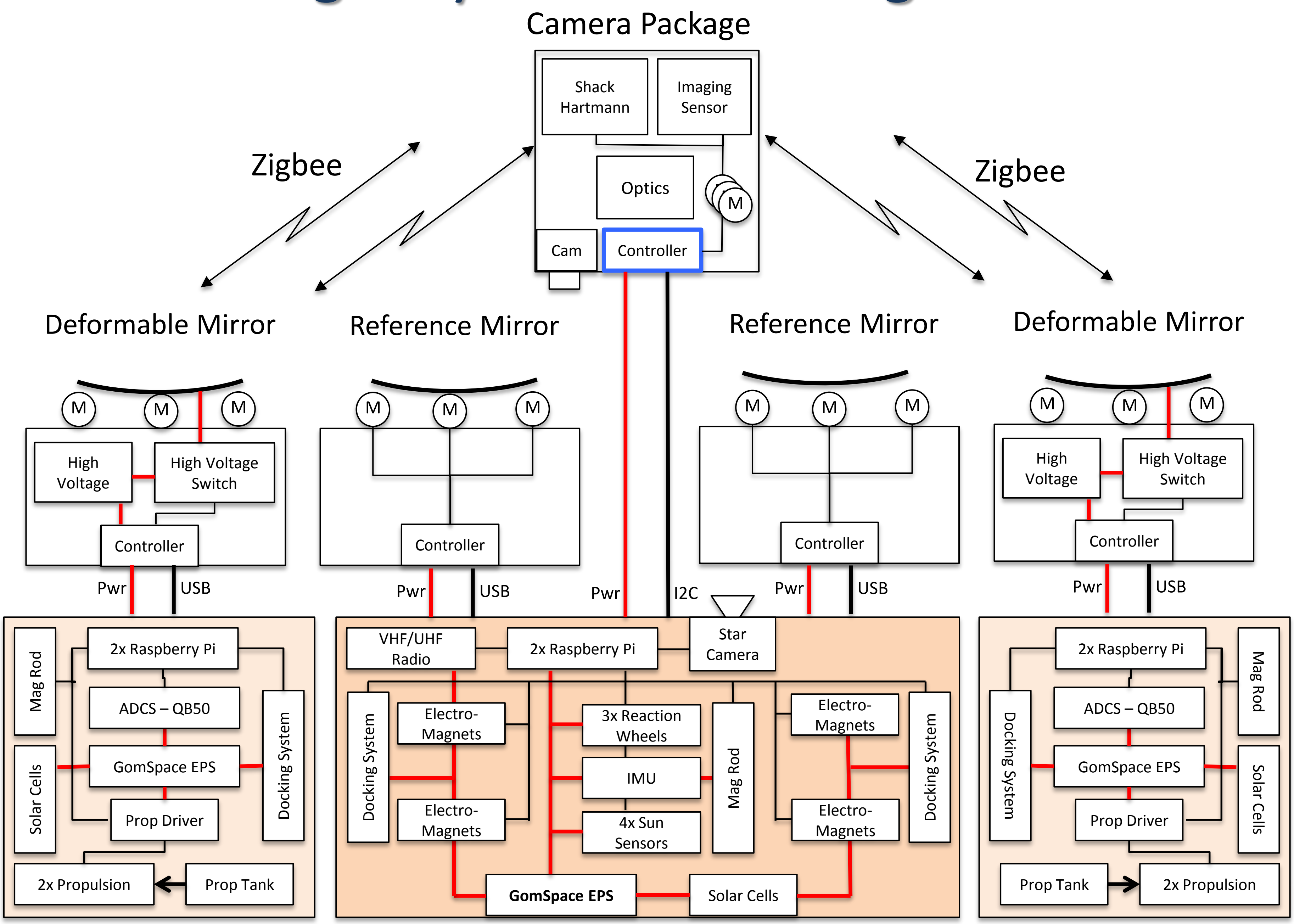
Primary spacecraft and payload ops will be run by Univ of Surrey

- Existing comm and ops infrastructure
- Includes spacecraft commanding and health monitoring
- Outreach

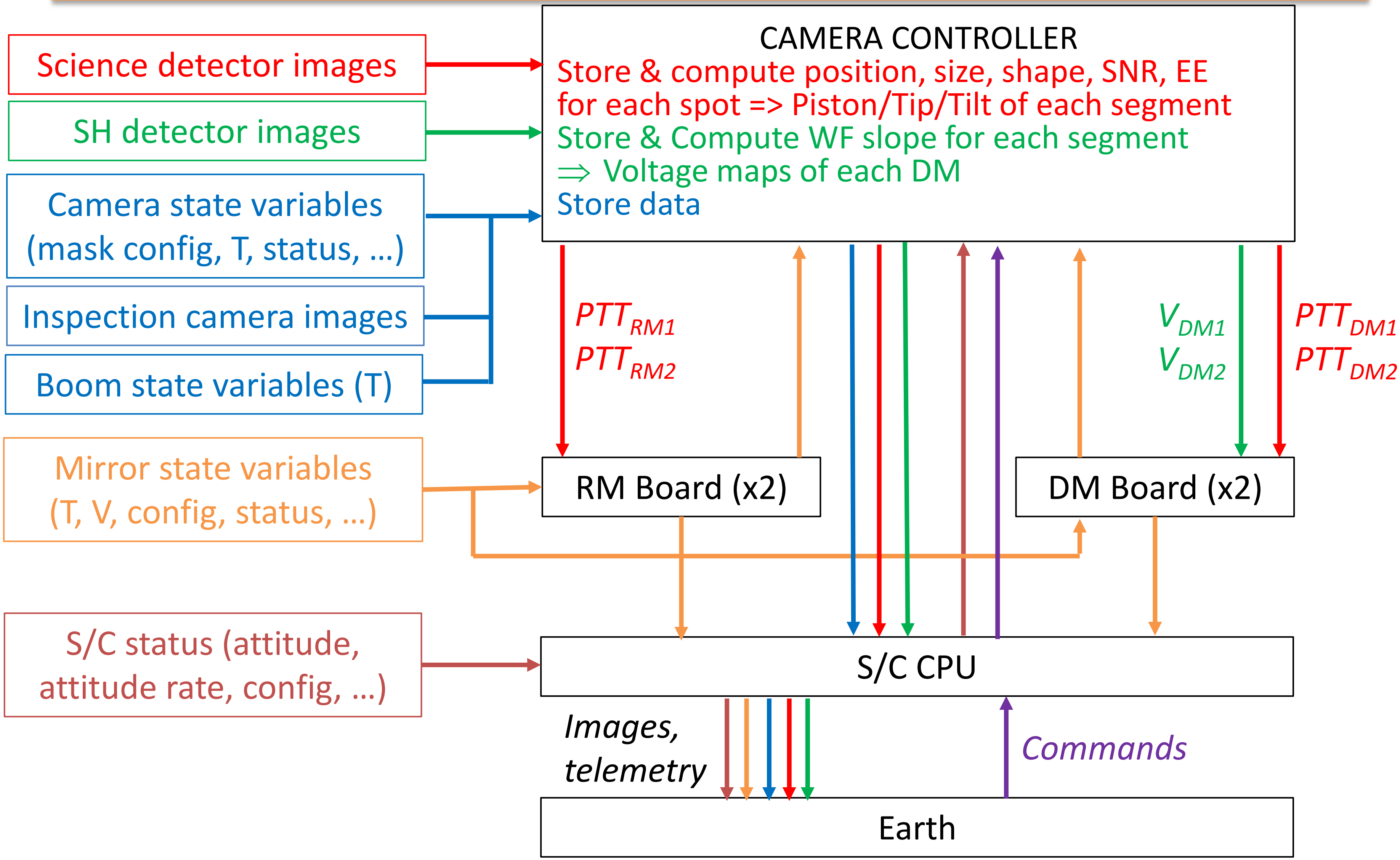
Remote payload monitoring will be done at Caltech

- Initial mirror calibration
- Mission planning (target selection)
- Engineering data analysis and reduction
- Outreach

Flight System Block Diagram

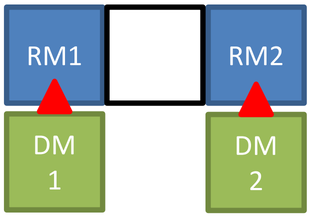


Information System



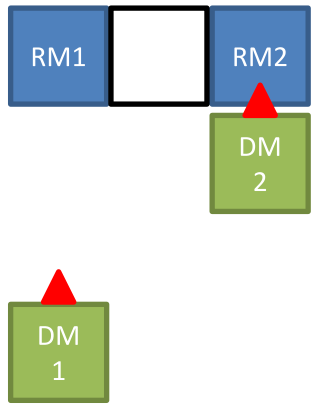
Reconfiguration

1.



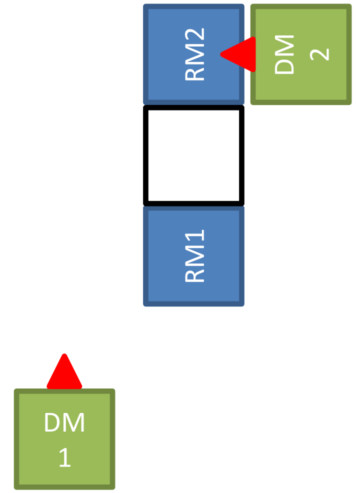
Power up MirrorCraft1
Verify thrusters, T, communication and attitude control

2.



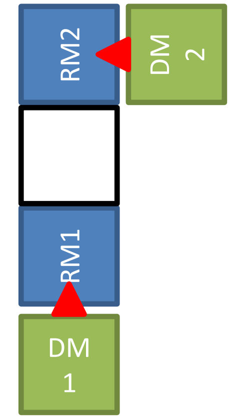
Undock MC1: free-flyer
Check MC1 properties
Move MC1

3.



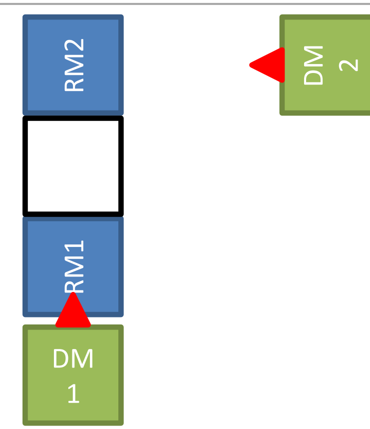
Rotate spacecraft

4.



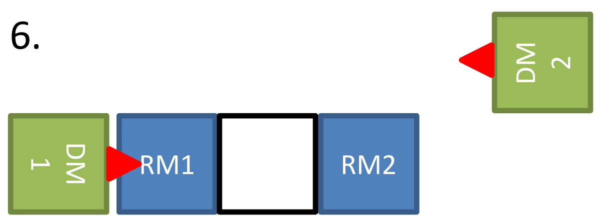
Capture and lock MC1
Check spacecraft
Power up MirrorCraft2
Check MC2 properties

5.



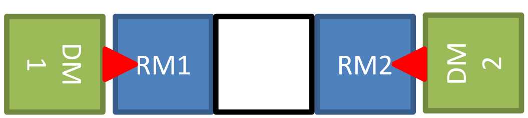
Undock MC2: free-flyer
Move MC2

6.



Rotate spacecraft

7.



Capture and lock MC2
Check spacecraft

Accomplishments in the Past Year

- Production of the propulsion components
- Fabricated the docking system from last year
- Evaluation of the C&DH candidates and laser rendezvous system
- AE105 Systems team evaluated risks and improved ConOps
- Finalized Telescope optical design
  - Sensor selection resulted in minor changes/optimization
  - Star tracker on Coresat allowed for better optical design
- Assembled Optical Test Bed
- Assembled Thermal vaccuum chamber and began mirror thermal testing
- Acoustically tested the mirror to verify launch survivability
- Mirror control algorithm development and coding
- Tested component interfaces and refined the electronics design
- Boom deployment testing
  - Eliminated the need for any damping mechanism
  - Defined mounts which allow for post installment alignment

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Telescope Design

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Telescope Concept of Operation

Melanie Delapierre, Marie Laslandes,
Eric Grohn

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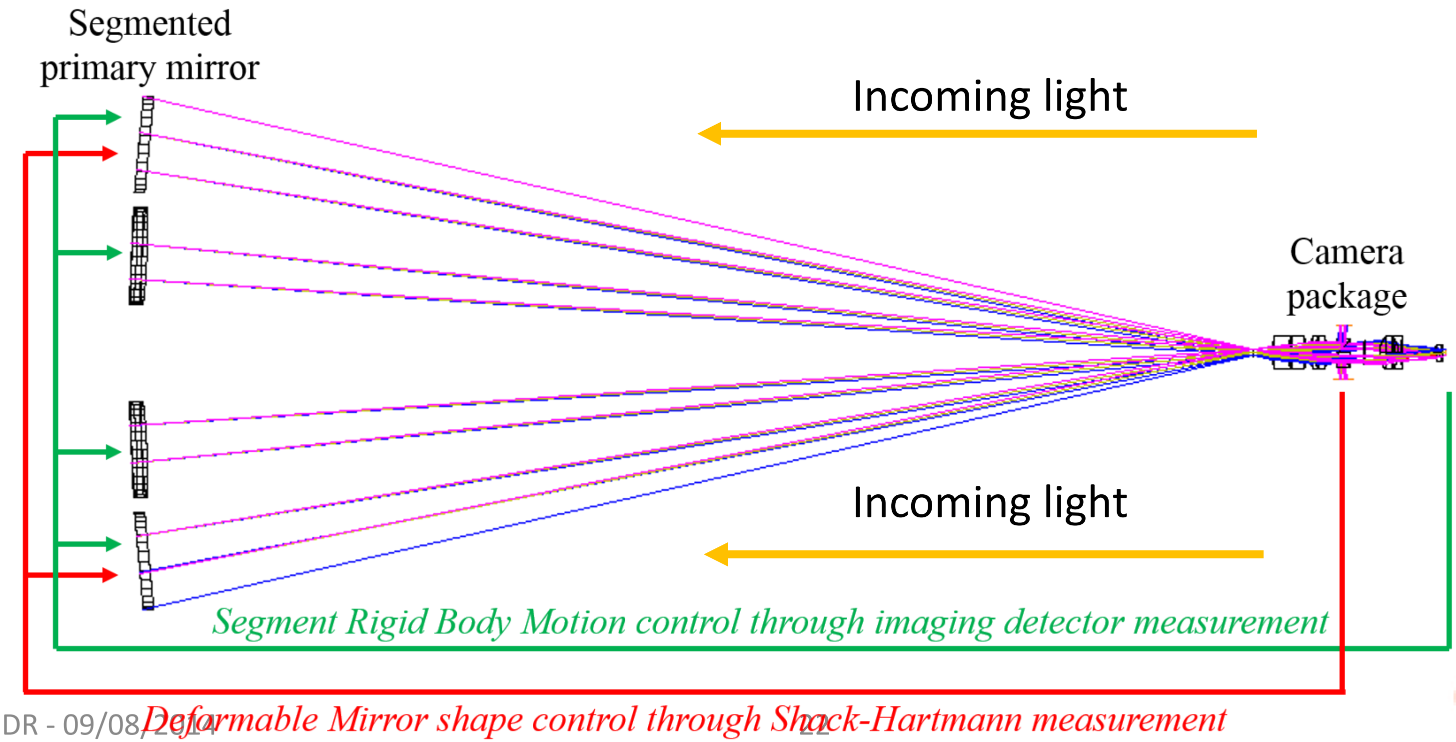
Telescope control

- Purpose: Automatically correct in space for deployment imprecision, manufacture errors and thermal disturbances with active calibration.
- Degrees of freedom:
  - 3 Rigid Body Motion actuators per segment (control through imaging detector)
  - 41 piezo-electric actuators per deformable mirror (control through Shack Hartmann)



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Concept of operations

Step 1: Setup initial operational settings for mirrors' position and mirrors' shape

Step 2: Point telescope to a star.

Step 3: Space Calibration concept

1. **Blind search** to bring spot on detector
   - Using 2 Rigid Body Motion Actuators
2. **Centering** to center the spot on the detector
   - Using 2 Rigid Body Motion Actuators
3. **Focusing** to minimize the spot size on the imaging detector
   - Using 3 Rigid Body Motion Actuators
4. **Shape control** to minimize the wave-front error on the Shack Hartmann
   - Using 41 embedded mirror actuators

Calibration operations

Start Calibration

TIME ~10 min

IF NECESSARY

Camera CPU (Observe, command)	Image Detector (Position)	SHWS (Shape)	Zigbee (Transmit)	Mirror CPU (execute)	Picomotor (position)	Def. Mirrors (Shape)
1-Order Initial image :	**a**- Standby	**a**- Standby	**a**- Transmit Voltages →	**a**-Set DM voltages	**a**- Standby	**a**- Set Voltages
	b-Take Image	**b**-Take image	**b**-Transmit DONE ←	**b**-DONE	**b**-Standby	**b**-keep Voltages
2-Im. Processing Eval. Update	Standby	Standby	Standby	Standby	Standby	Keep Voltages
3-Execute update	Standby	Standby	Transmit update →	Execute update	Translate	Set new Voltages
4-Standby	Standby	Standby	Transmit DONE ←	Update DONE	Standby	Keep Voltages
5-Order Image	Take Image	Take Image	Standby	Standby	Standby	keep Voltages
6-Im. Processing Eval. Update	Standby	Standby	Standby	Standby	Standby	keep Voltages
7-Value achieved	Standby	Standby	Transmit DONE →	Put all in Standby	Standby	Standby

☐ STANDBY ☐ ACTIVE

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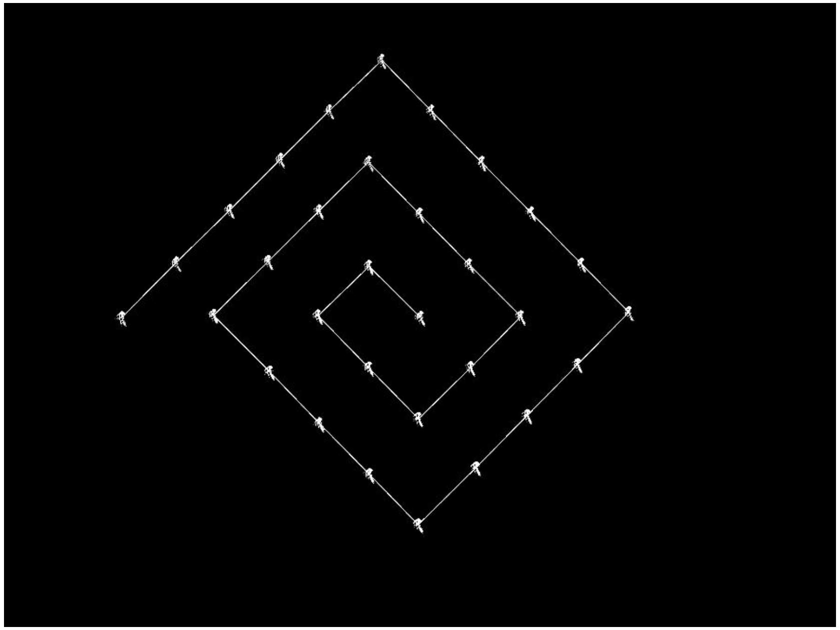
Blind Search algorithm

Aim: Put the optical image in the image detector.

Actuators: two picomotors (to tip and tilt the mirror, 2 dofs)

Detector: Image detector

Open loop: Move optical image on a spiral until reaching the camera (intensity threshold on image detector).



Experimental spiral

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Centering algorithm

Aim: Center optical image on image detector.

Actuators: two picomotors (to tip and tilt the mirror, 2 dofs)

Detector: Image detector

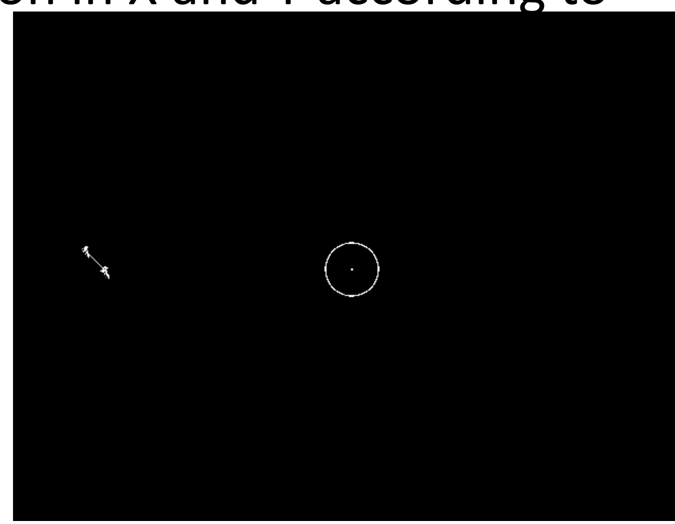
Closed loop: Find the zeros of the position in X and Y according to actuator length l_1,l_2.

Find l_1,l_2 s.t. $\begin{Bmatrix} X(l_1,l_2) \\ Y(t_1,t_2) \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix}$

Uses a standard **Newton Method**

$$\begin{pmatrix} \Delta X \\ \Delta Y \end{pmatrix} = \begin{bmatrix} \delta X / \delta l_1 & \delta X / \delta l_2 \\ \delta Y / \delta l_1 & \delta Y / \delta l_2 \end{bmatrix} \begin{pmatrix} \Delta l_1 \\ \Delta l_2 \end{pmatrix}$$

=> About 1 min algorithm



Experimental centering

Focusing algorithm

<u>Aim</u>: Translate mirror to put its focal plane in the image detector plan.

<u>Actuators</u>: three picomotors (to piston without tip and tilt, 1 dof)

<u>Detector</u>: Image detector

<u>Closed loop</u>: Find the minimum radius R of optical image according to the length of the actuators $\boldsymbol{l}$.

$$Min_l \; R(l)$$

<u>Method 1</u>: Impose small increments δl in the direction that decreases R and stop when it changes direction: Long, imprecise

<u>Method 2</u>: Experimentally evaluate the convexity of R(l) and implement better minimization algorithms (convex ?...)

Shape control algorithm

- Objective: Minimize Wave-Front Error (WFE)
  => Uses a standard technique with Shack-Hartmann sensor.
  => Perform a WFE slope minimization

- Knowing the influences of the n=41 actuators of the system, the optimal voltages can be deduced:
  - Influence Functions: $\boldsymbol{A} = [\boldsymbol{a_1}, \boldsymbol{a_2}, \dots, \boldsymbol{a_n}]$, $a_i \epsilon \mathbb{R}^m$,m~176 (# lens on SHWS)
  - Measured WFE slopes: $\boldsymbol{d}\ \epsilon \mathbb{R}^m$

  $\Rightarrow$ Voltages: $\boldsymbol{\delta v} = min_{\boldsymbol{x}} \|\boldsymbol{d} - \boldsymbol{A}\boldsymbol{x}\|_{rms}$,
  with $-v_l - v_n < \boldsymbol{x} < v_l - v_n$

$v_{n+1} = v_n + \delta v$

- Control loop
  - Input: influence matrix $(\boldsymbol{A})$
    voltage limit (v_l)
    loop gain (α)
  - Output: corrected WF

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Conclusion

- Blind Search, Centering and Focusing algorithms should be executed mainly after deployment.

- Shape control algorithm could be needed after each pointing because of different thermal disturbances.

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Camera

Manan Arya, Maria Sakovsky, Marie Laslandes, Mélanie Delapierre, Eric Grohn

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Camera
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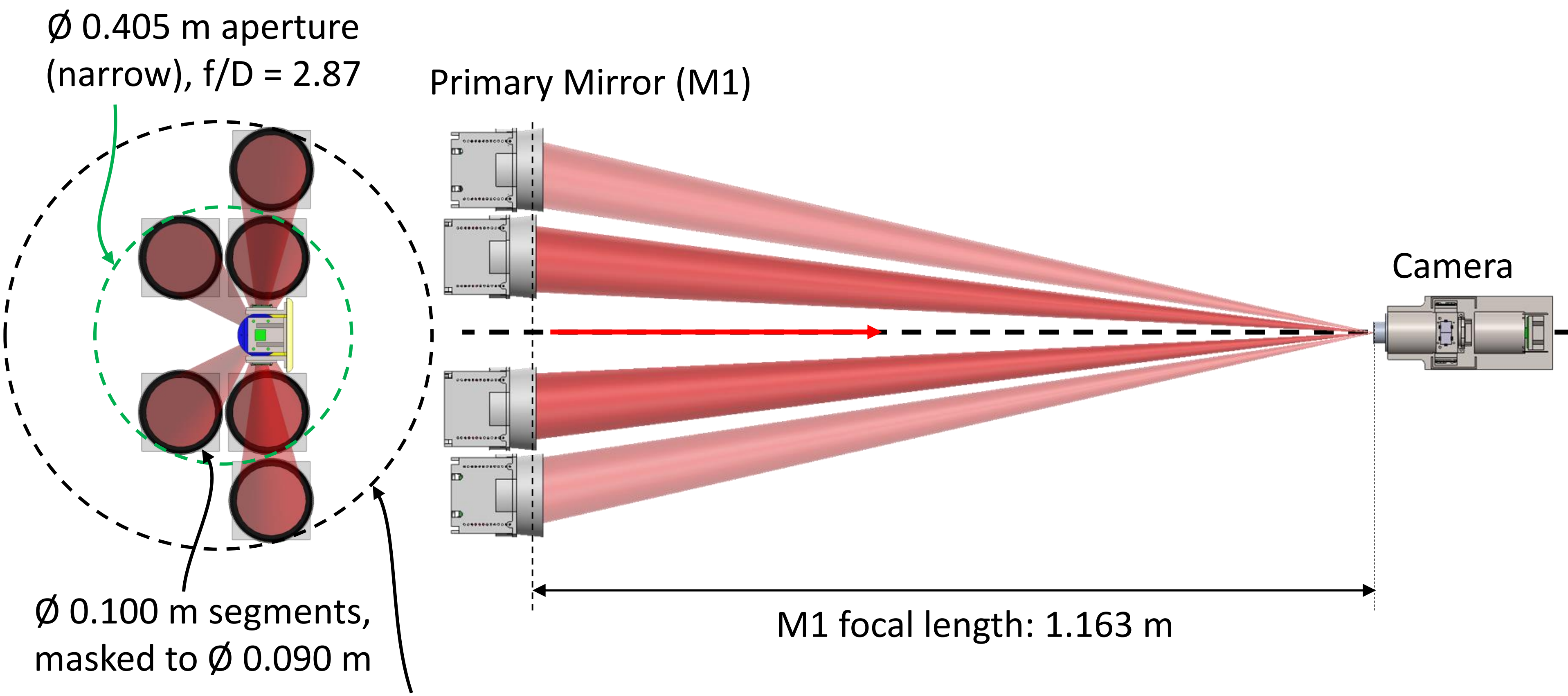
Telescope Optical Overview



- Full Field of View : 0.3°
- Optical bandwidth: 465 – 615 nm (540 nm center)

Camera Requirements

- Functional
  - Image star field using sparse aperture primary mirror (M1)
  - Provide feedback for primary mirror segment calibration
    - Deformable mirror (DM) wavefront errors (WFE)
    - Segment rigid body motions (RBM)
  - Take engineering images of CoreSat during MirrorCraft reconfiguration
- Performance
  - 80% encircled energy (EE) diameter at image plane $< 50\ \mu m$
  - Full field-of-view (FoV) $> 0.3°$
  - Signal-to-Noise Ratio (SNR) > 100
  - Optical bandwidth: 465 nm – 615 nm (540 nm center)
- Constraints
  - Mass < 4 kg
  - Volume $< 10 \times 10 \times 35$ cm
  - Power < 5 W

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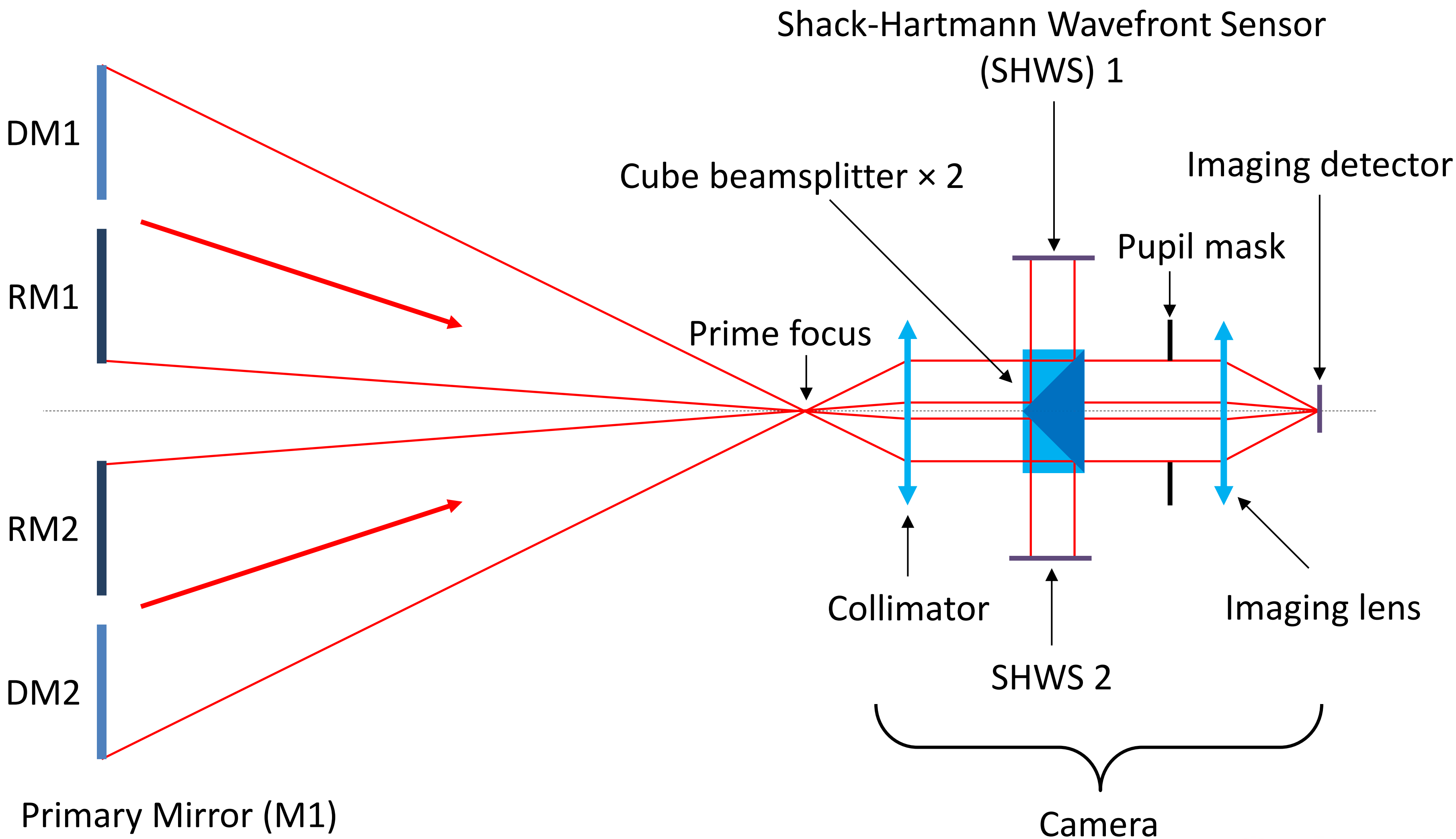
Camera Optical Design



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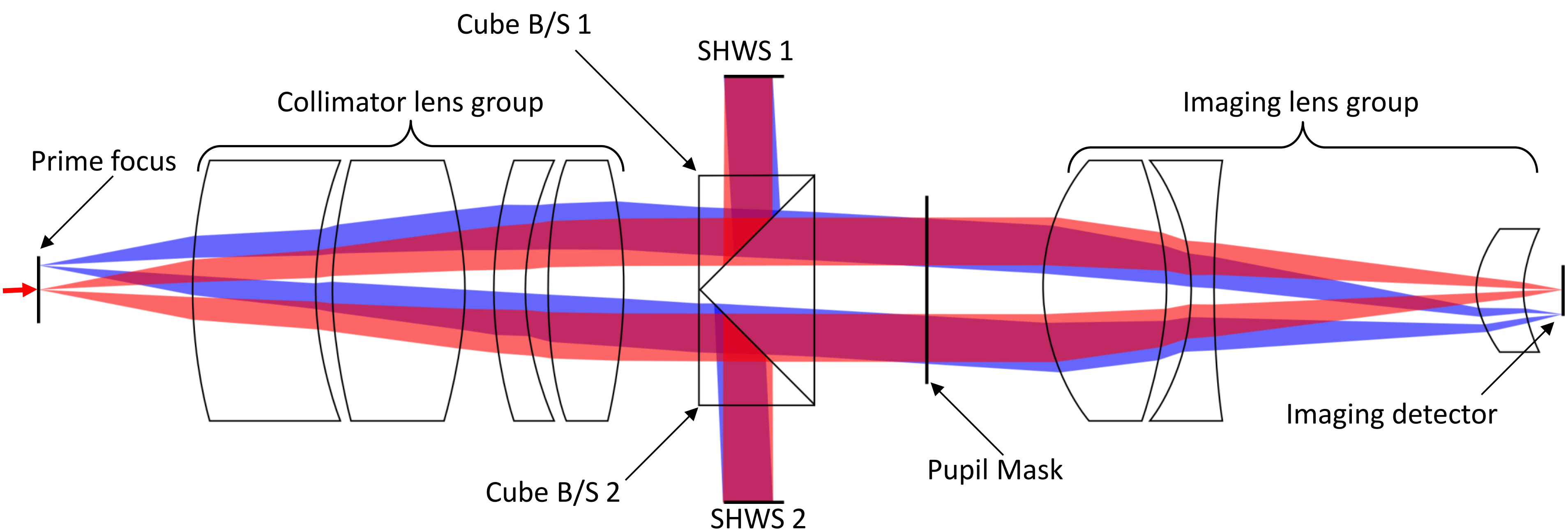
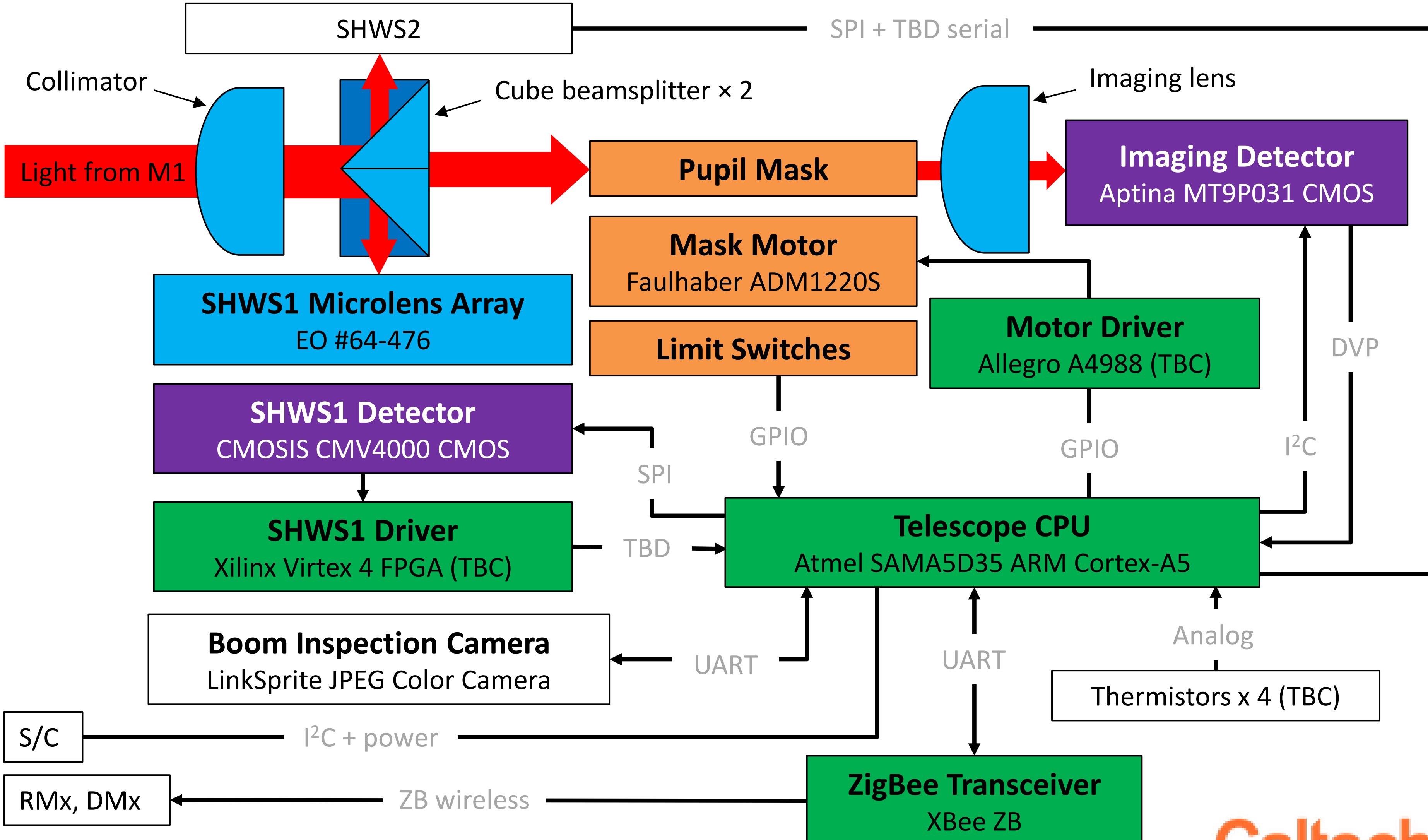
Camera Optical Elements



- Collimator designed for pupil conjugate size (< 10 × 10 mm) and good conjugation (min. WFE) using Zemax
- Imaging lens designed for min. spot size using nominal primary mirror figure
- Transmissive optics (as opposed to reflective optics e.g. OAP mirrors) because of volume limitations

Camera Block Diagram



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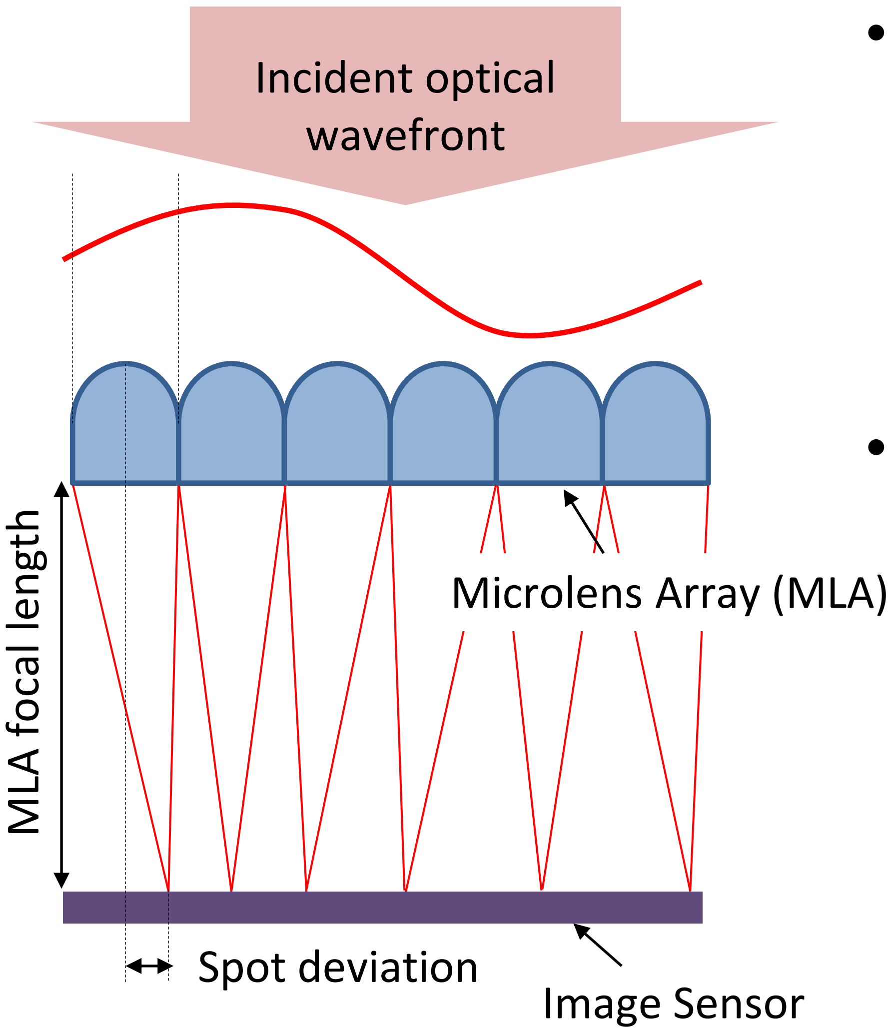
Shack-Hartmann Wavefront Sensor



- 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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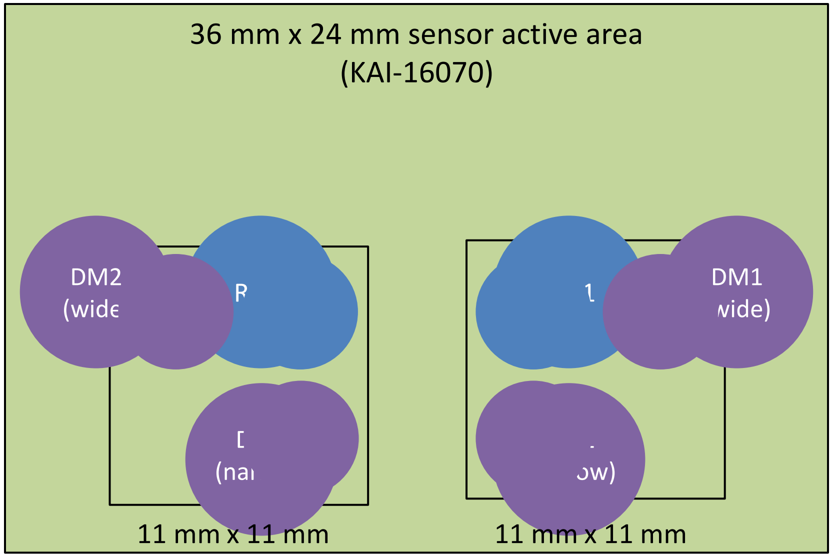
SHWS Spilt

- Collimator complexity drives lower magnification
  - i.e. larger pupil image
- Detector cost drives smaller pupil image
  - i.e. higher magnification
- High aspect ratio pupil topology leads to wasted pixels if imaged onto a single sensor



- Before: one monolithic sensor (KAI-16070)
- Now: two smaller, cheaper sensors

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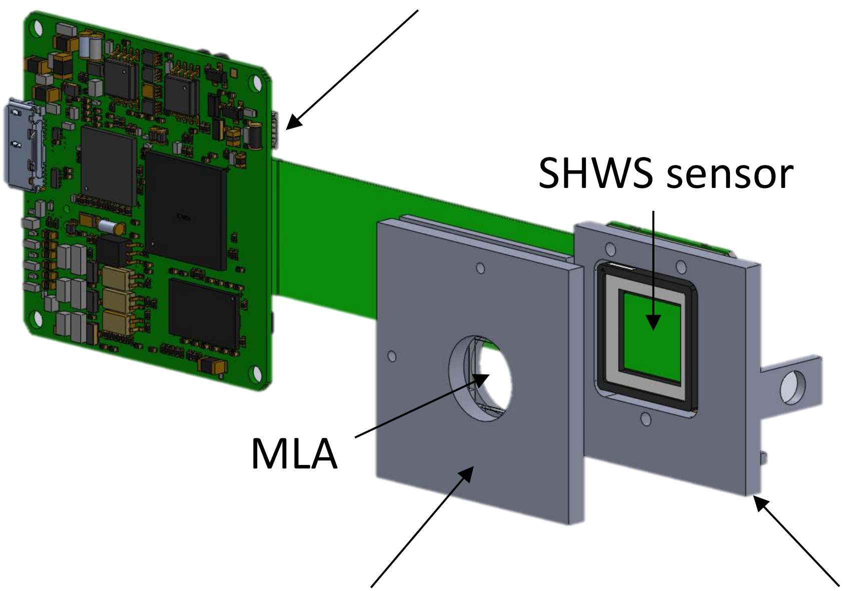
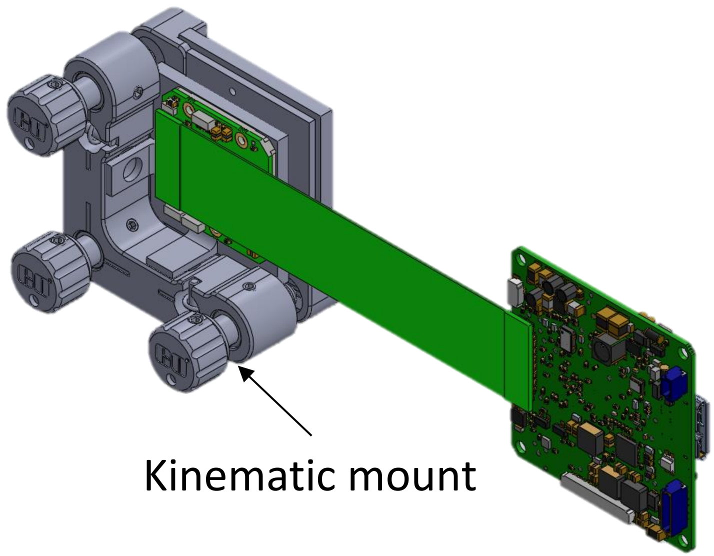
SHWS Prototype

- Baumer MXUC40 camera for sensor readout (flight-like CMV4000)
- Flight-like MLA (EO #64-476)
- EO tip/tilt/piston kinematic mount to position MLA wrt sensor
- 3D printed parts to attach sensor and MLA to kinematic mount





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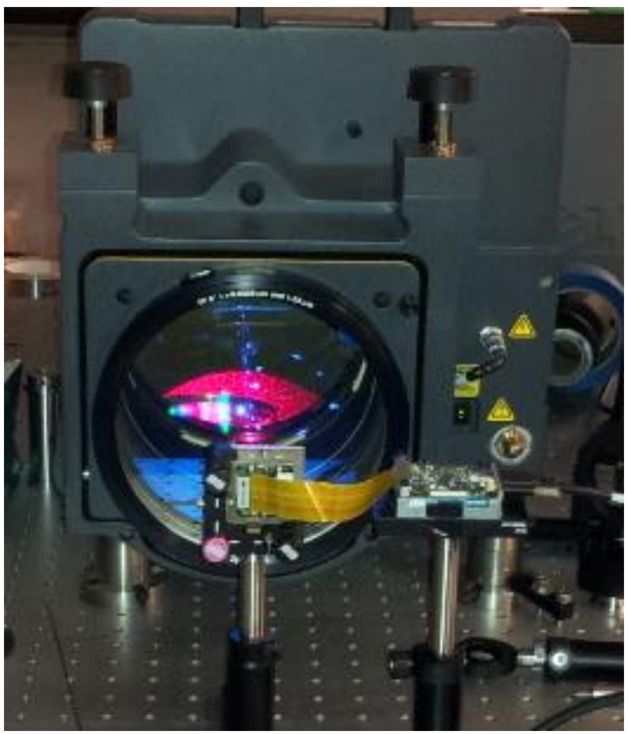
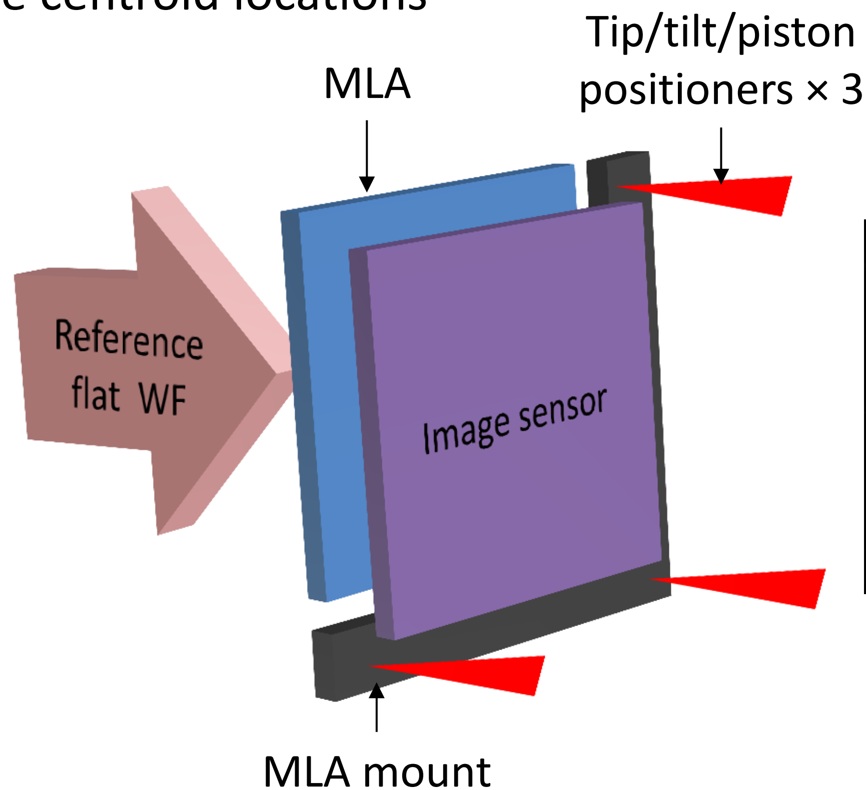
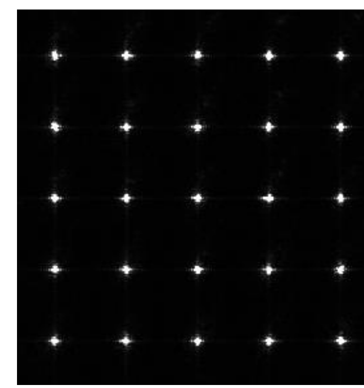
SHWS Prototype Alignment

- MLA position adjusted using flat WF from an interferometer
- Tip/tilt/piston between MLA and image sensor adjusted until we see regular centroid positions
  - Also gave reference centroid locations







SHWS raw output

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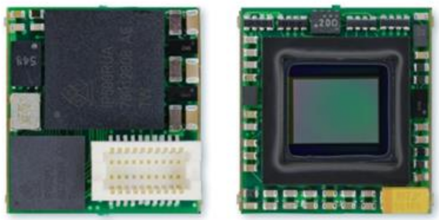
Imaging Detector

- Aptina MT9P031 CMOS sensor
  - 2592 × 1944 pixels, 5 Mp
  - 2.2 µm square pixels oversample the Ø14.2 µm spot from a single primary mirror segment
  - 5.70 × 4.28 mm active area
  - 0.34° FoV (diagonal)
  - $(QE)_{peak}$ = 0.62 at 482 nm



- Prototype: Ximea MU9PM-MBRD camera

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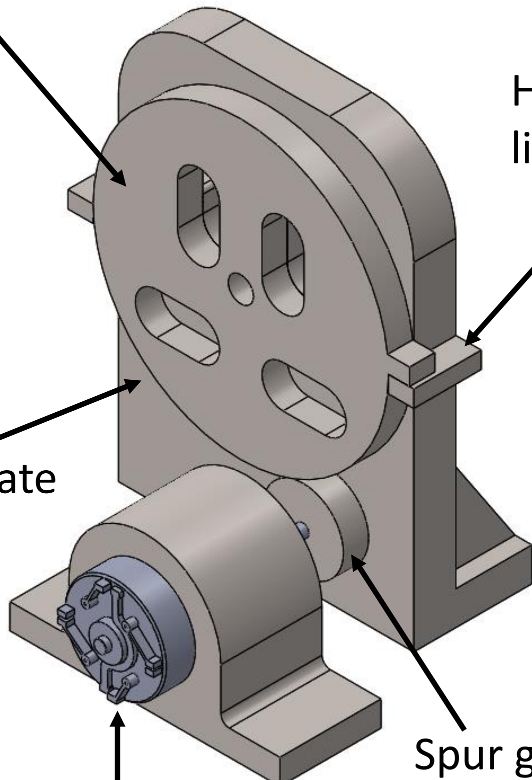
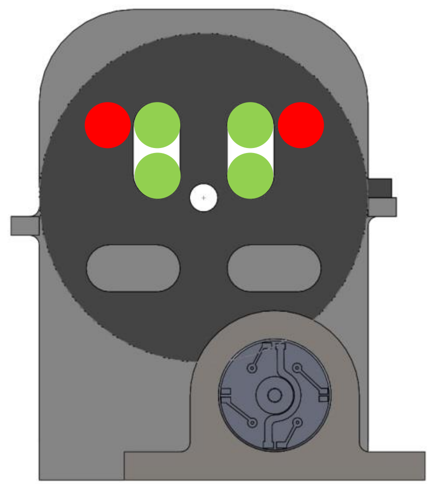
Telescope CPU

- Atmel SAMA5D35 ARM Cortex-A5 MPU
  - 536 MHz, 512 Mbyte DRAM
  - Arch-based Linux kernel
    - Leverage existing libraries (OpenCV), drivers (I^2C, SPI, UART), file system, etc.
  - Using evaluation board for prototyping; will adapt evaluation board design for flight

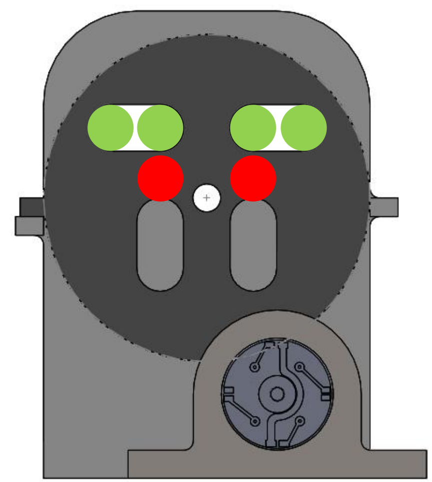
Pupil Mask Configuration

- Pupil mask switches modes after MirrorCraft reconfiguration
- Blocks stray light coming from vacant segment positions



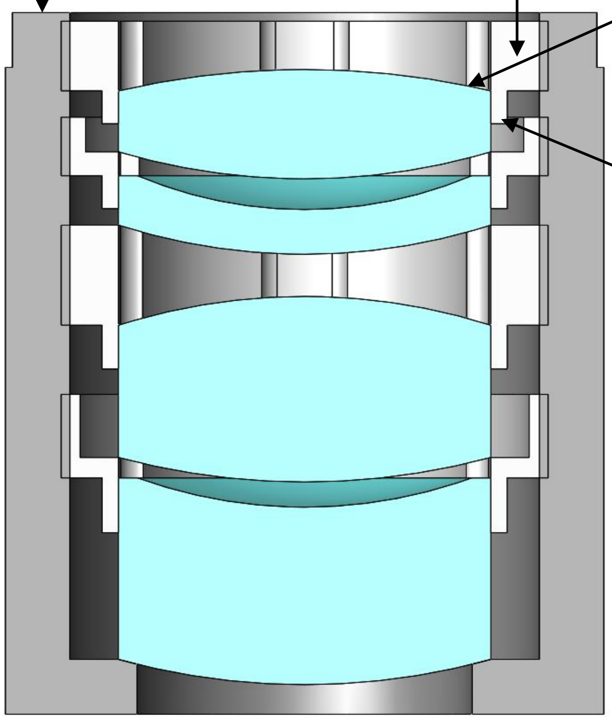


Compact configuration

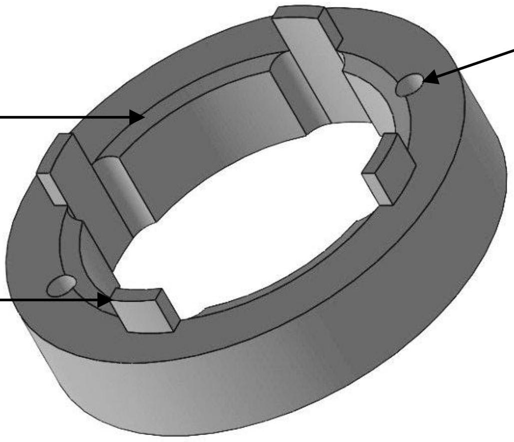


Wide configuration

Lens Barrel Design



Collimator section



Spacer

- Tangential interfaces between spacers and lenses
- Radial tabs prevent lens decentering
- Spacers provide designed separation between lenses
- Titanium construction
- Assembled sequentially

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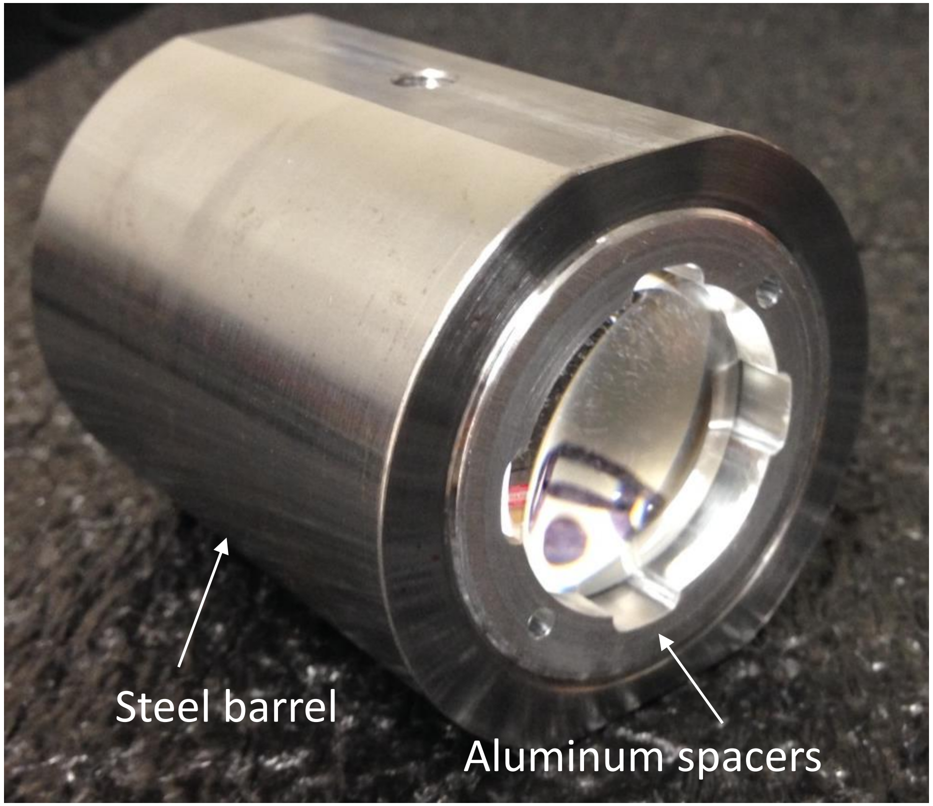
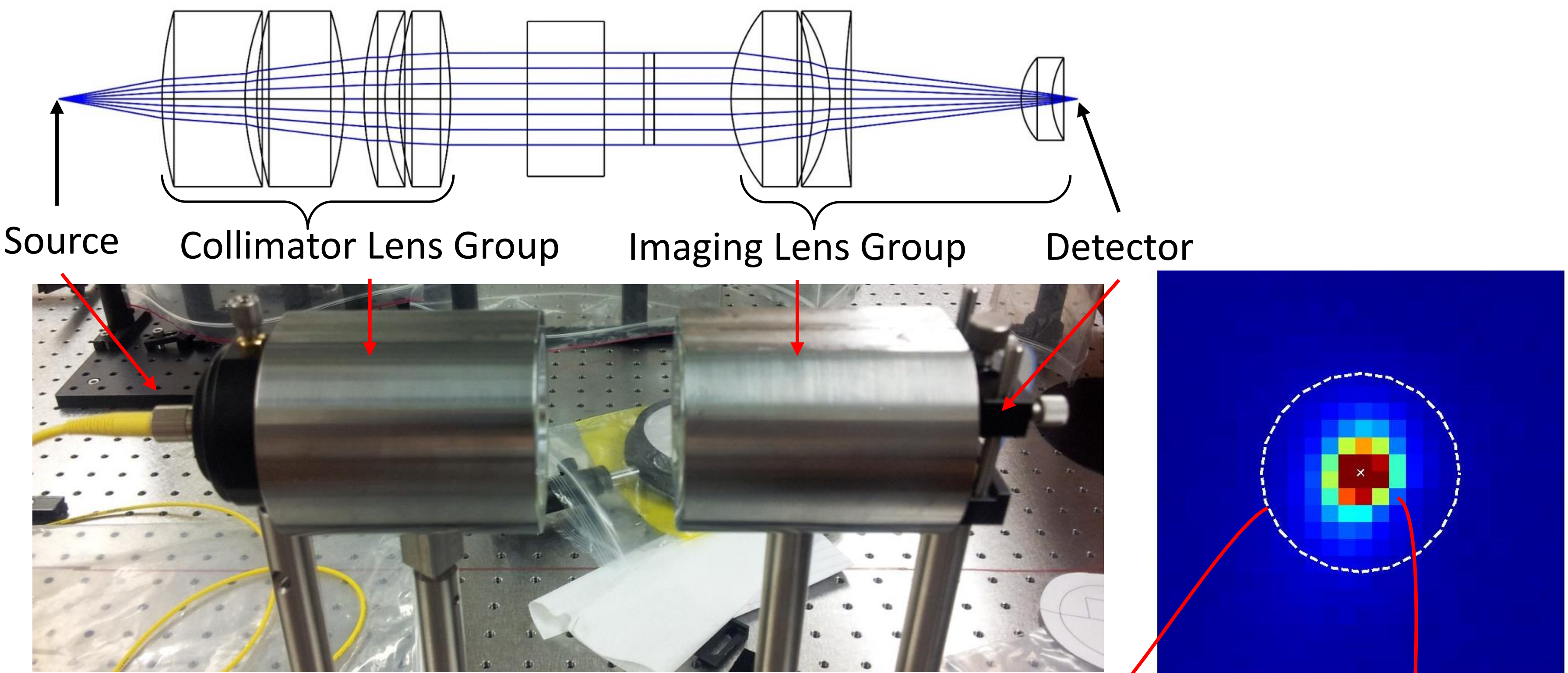
Lens Barrel Prototypes

Collimator 1 resting on spacer



Assembled Collimator

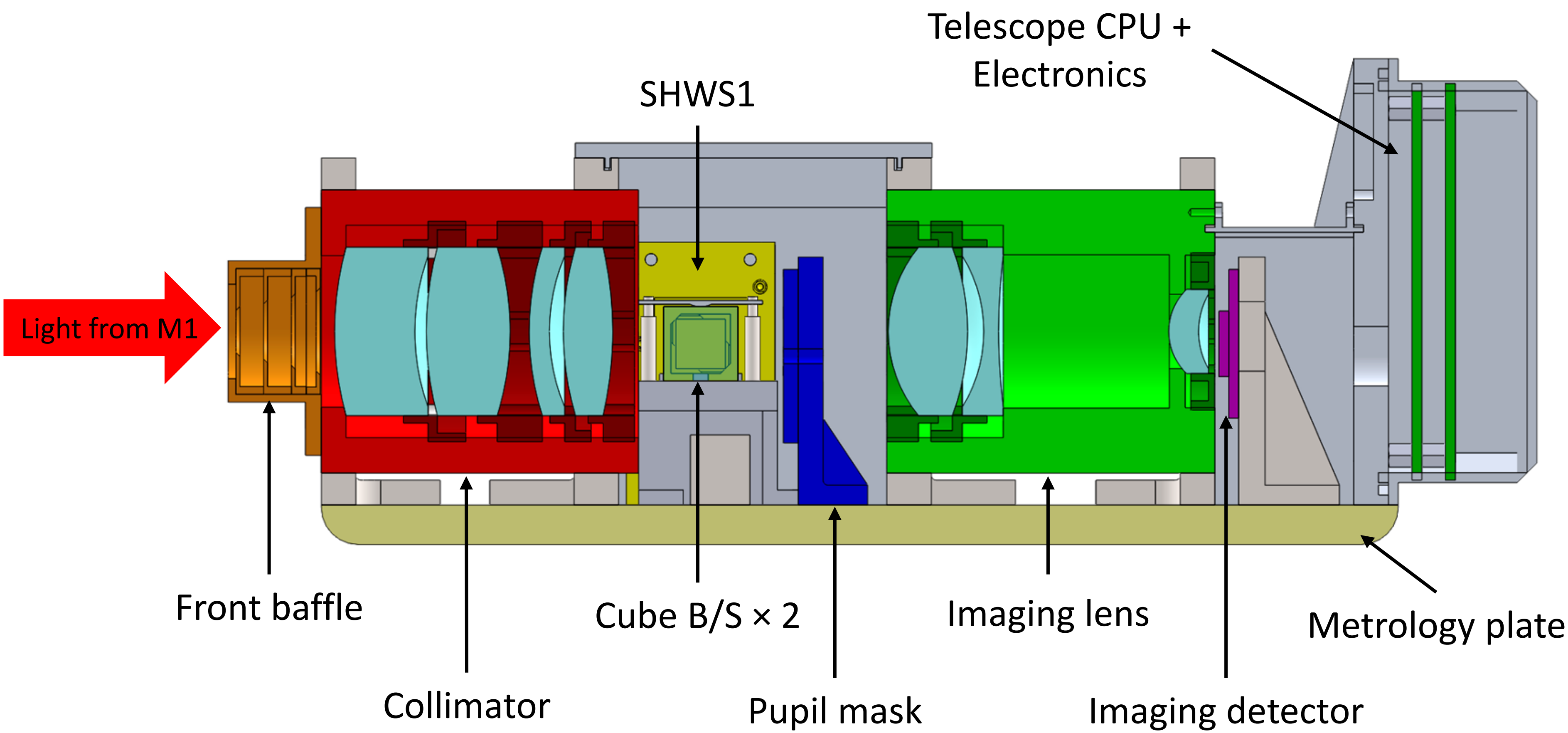
Lens Group Testing



Geometric spot size estimated
using raytracing Ø 25.8 μm

Measured spot
size ~Ø 17.6 μm

Camera Mechanical Design



- Envelope requirement: < 10 × 10 × 30 cm
- Current best estimates: 9.8 × 9.5 × 26.5 cm

Camera Tolerancing

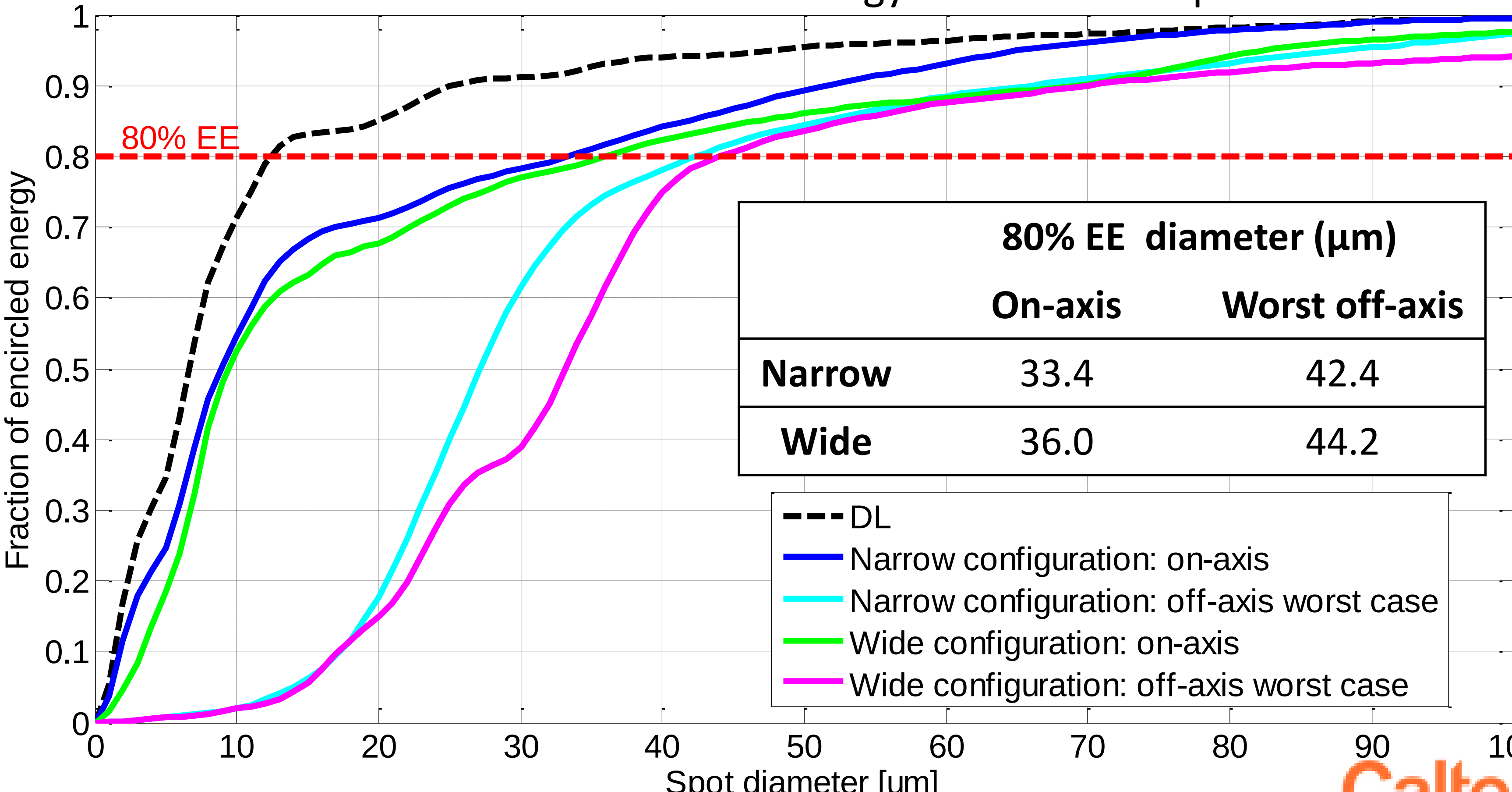
- Monte Carlo analysis with 500 trials
  - Lens manufacturing errors
    - Thickness: ± 0.1 mm
    - Radius of curvature: ± 0.1 %
    - Sphere centration: ± 0.01 mm
    - Wedge : ± 0.01 mm
  - Alignment errors
    - Decenter: ± 0.1 mm
    - Tip/Tilt: ± 0.1°
    - Element spacing: ± 0.1 mm

- Spot size increased by 12% on average
- Spot size increase by less than 28% in 90% of the cases

- Impact on performance is not significant
- Allowable errors values guide camera hardware design and fabrication

Encircled Energy Analysis

- EE computed in both configurations, over entire bandwidth, at various field angles, using sparse aperture primary with a nominal figure
- Performance criterion: 80% encircled energy diameter < 50 µm



	80% EE diameter (µm)	
	On-axis	**Worst off-axis**
Narrow	33.4	42.4
Wide	36.0	44.2

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SNR Considerations

- SHWS dictates the limiting photon flux
- For a 50 ms exposure with 150 nm bandwidth around λ = 540 nm, we need a flux of 10^6 photons/cm^2/s to achieve SNR = 100
- Corresponds to apparent magnitude ~1.5-1.8

$$SNR = \frac{N}{N_{RON} + N_{poisson}}$$

$$N_{poisson} = \sqrt{N}$$

$$N = FT_{int}\eta\left(\frac{A_{mirror}}{n_{lenslets}}\right)$$

$$\eta = \eta_{mirror} \times (\eta_{lens})^4 \times (QE) = 0.52e^-/photon$$

$$T_{int} = 50ms$$

$$A_{mirror} = \pi(4.5cm)^2$$

$$n_{lenslets} = 177$$

$$N_{RON} = n_{pixels} \times 13e^-/pixel = 169.3e^-$$

$$F = 3.4 \times 10^6 photons/cm^2/s$$

Camera Mass Budget

Part	Mass (g)
Collimator barrel assembly	750
Imaging barrel assembly	754
Metrology plate	683
Mask mechanism	77
SHWS	136 × 2
Front Baffle	26
Electronics	188
Radiation shielding	126
Beamsplitter assembly	71
Boom inspection camera	53
Total	**3000**
+ Margin (10.0%)	**3300**

< 4000 g requirement

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Camera Power Budget

Part	Peak (W)	Standby (W)	WF Sensing Mode (W)	Imaging Mode (W)	Reconfiguration Mode (W)
Telescope CPU	0.60	0.45	0.60	0.60	0.60
Imaging Detector	0.74	0.30		0.74	
SHWS	2.40 × 2	1.80 × 2	2.40 + 1.80		
BIC	0.22	0.15			
ZigBee	0.14		0.14	0.14	0.14
Mask	0.60				0.60
Total	**7.10**	**4.50**	**4.94**	**1.48**	**1.34**
+ Margin (10%)	**7.81**	**4.95**	**5.43**	**1.63**	**1.47**

- Requirement: < 5 W
- Using existing prototypes to estimate power; SHWS prototype camera has unnecessary features (e.g. high framerate output)
- Further power reduction through having only one SHWS active during WF sensing

Camera Open Issues

- SHWS detector readout electronics and software
  - Reduce power consumption
  - Challenging to design FPGA for readout
- SHWS alignment and calibration
  - Need to decouple piston from tip/tilt positioners

Camera Future Work

- Mature prototype
  - Metrology plate + lens barrel mounts
  - Pupil mask
  - SHWS
  - B/S mounts
  - Frangibolt interface
  - Integrate electronics and software prototypes
- Test stray light control strategies
  - Build front baffle
  - Select optical black coatings
  - Test mask optical properties

Review Outline

1. Mission Overview (15 mins)
   - Telescope overview
2. Spacecraft Design (150 mins)

   < Coffee Break>
3. Telescope Design (150 mins)
   a) Telescope Concept of Operation (Melanie)
   b) Camera (Manan)
   c) Mirrors (John)
   d) Electronics (Yamuna)
   e) Boom (Lee)
   f) Telescope System Modelling (Lee / Marie)
   g) Telescope Breadboard/Test (Marie)
4. Summary & wrap up (15 mins)

Please send comments to Dr. Greg Davis (Gregory.L.Davis@jpl.nasa.gov)

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Deformable Mirrors

John Steeves
Erin Evans, Marie Laslandes

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Problem Description

- Develop & design a deformable mirror assembly
  - Key Characteristics
    - Thin, flexible, low areal density
    - Identical manufacturing process
    - Actively controlled
  - Key Challenges
    - Large strokes (10 – 100 µm) required in order to perform figure correction
    - Nanometer precision required for visible wavelength imaging
    - Volume, power constraints
    - Accommodate thermal variations
    - Launch survival

Deformable Mirror Requirements

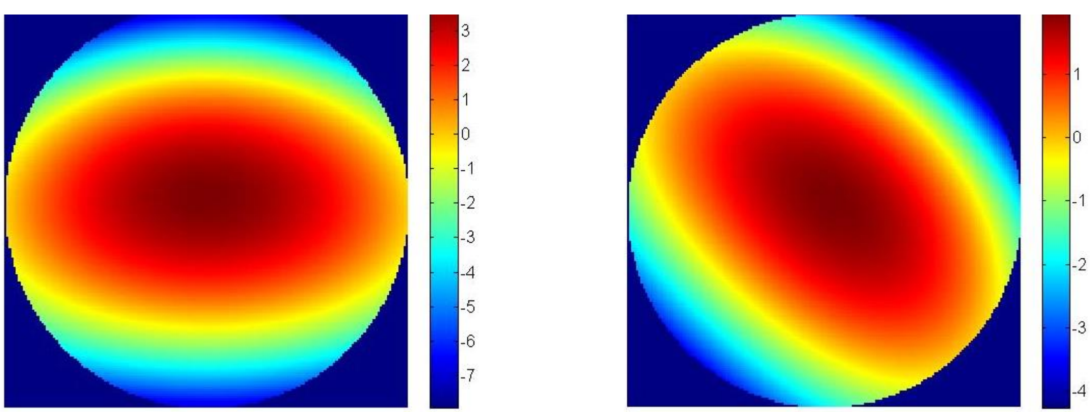
- Physical:
  - Mirror diameter: 100 mm
  - Nominal ROC: 2.326 m
  - Total hardware volume: ~1U (10 x 10 x 10 cm)
  - Manufacturing tolerances:
    - 3 µm RMS aspheric figure error
- Actuation:
  - Capable of achieving λ/10 (50 nm) RMS figure accuracy
    - Accommodate both wide and compact telescope configurations (2.7 µm RMS)
    - Correction of manufactured shape errors (3 µm RMS)
    - Correction of deformations due to thermal imbalance (3µm RMS focus)
  - Stable shape deformation over exposure time (~50 ms)
- Environment:
  - Vibration:
    - Survival of launch loads (Delta IV Heavy test case)
    - Low excitation from S/C during imaging
  - Thermal:
    - Survival: -40 to +80 °C
    - Operational: -20 to +20 °C

Actuation Specifications

- Rigid body actuation (required for launch stowage, initial calibration, reconfiguration)
  - Piston: ± 10 mm
  - Tip/tilt: ± 0.1 rad
- Figure correction
  - Off axis shape generation
  - Manufacturing error correction
  - Thermal imbalance

=> Set of Zernike errors to be corrected (Z4 to Z66)

WFE measured by the Shack-Hartmann for a spherical mirror
Narrow segment (1.4 µm RMS) - Wide segment (2.7 µm RMS)



Total actuation requirements

Zernike	[µm RMS]
Focus	±6
Astigmatism3	±3
Coma3	±1
Spherical3	±1
Trefoil5	±1
Tetrafoil7	±0.5
Astigmatism5	±0.5
Higher order	±0.1

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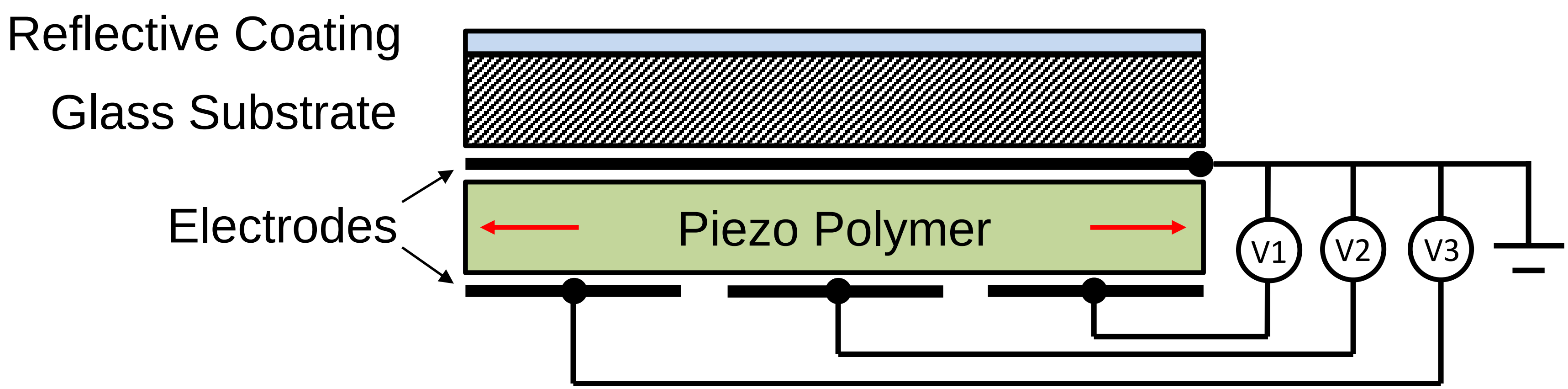
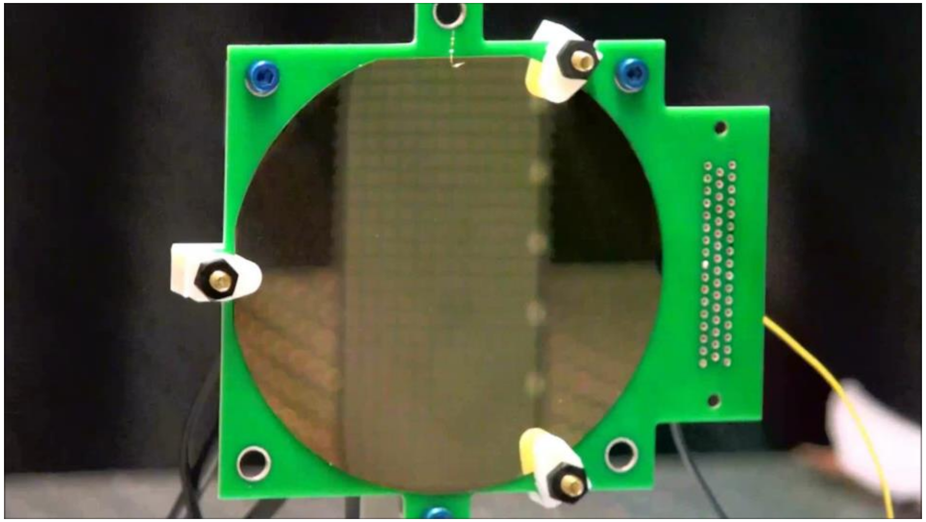
Deformable Mirror Overview

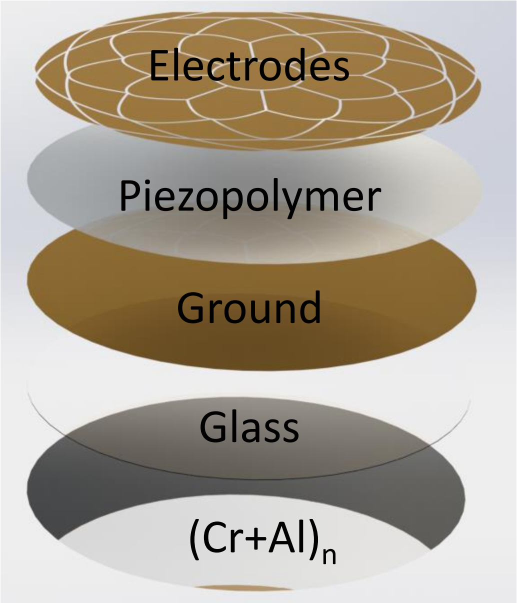


- Thin active laminate
  - Polished glass wafer
  - Piezoelectric polymer backside
  - Reflective front surface
- Surface-parallel actuation scheme
- Custom electrode pattern

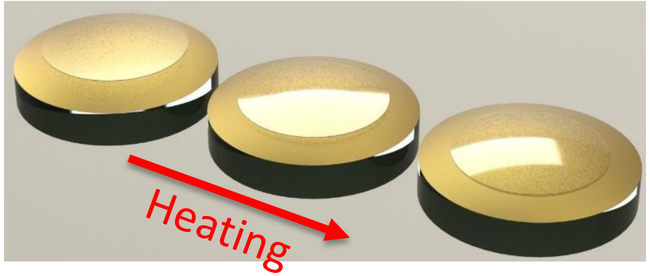


Mirror Fabrication Process

1. Polished glass wafer (~225um)
2. Slump at ~650C over quartz mold*
3. Coat Cr+Al laminate (~3um total)*
4. Roughen mirror backside with HF vapor
5. Sputter ground layer (Ti+Au+Ti, 10+50+10nm)
6. Spin coat + bake piezo layers 140C (20um)
7. Sputter blanket electrode (Ti+Au, 10+10nm)
8. Evaporate electrode pattern (Au, 100nm)
9. Pole active material layer to 100 V/um
10. Ion mill etch back blanket electrode
11. Wirebond electrodes and mount mirror onto PCB

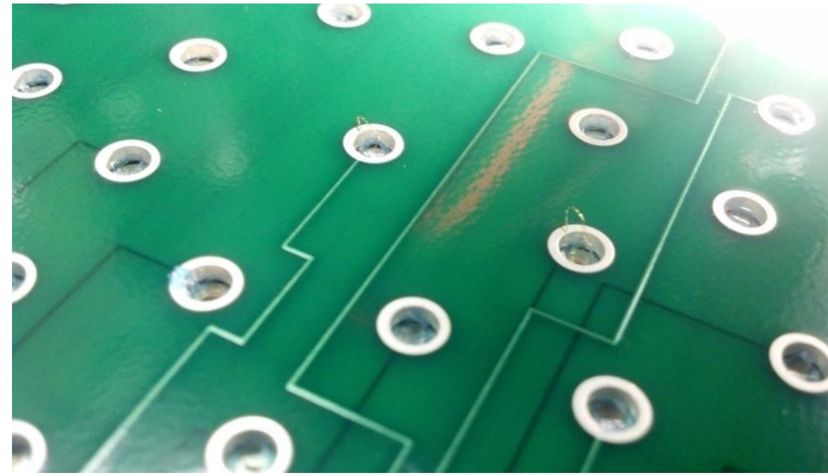


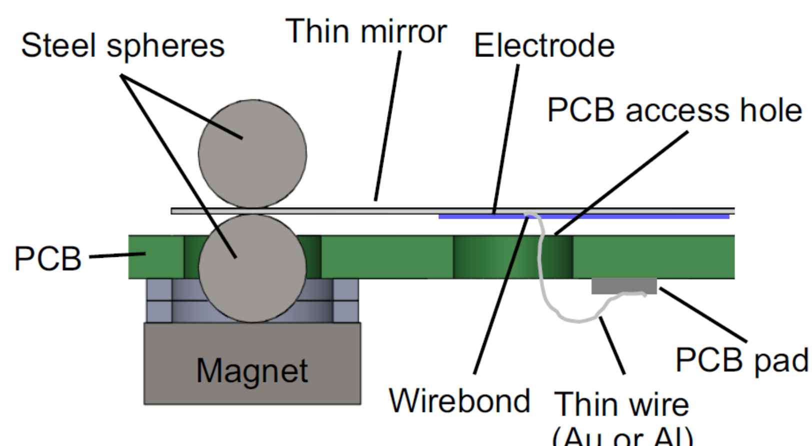
Slumping process (ongoing)



Mirror Mounting

- Low-stiffness Au wire-bonds connect mirror electrodes to PCB pads (via holes)
- Kinematic mounting to PCB
  - Spheres pinch mirror in 3 places
  - Preloaded and aligned using magnetic field





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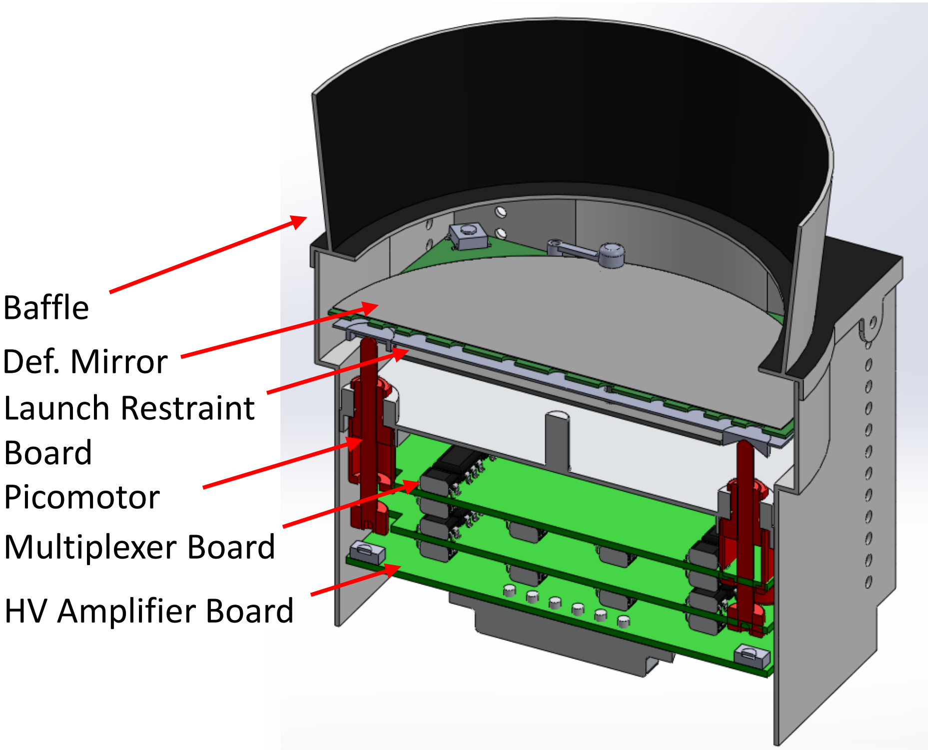
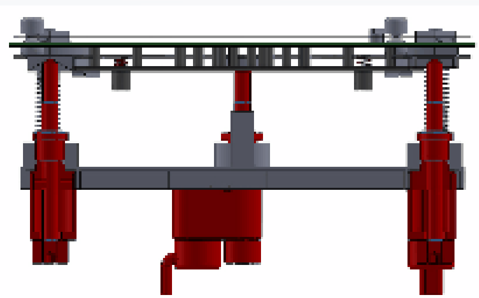
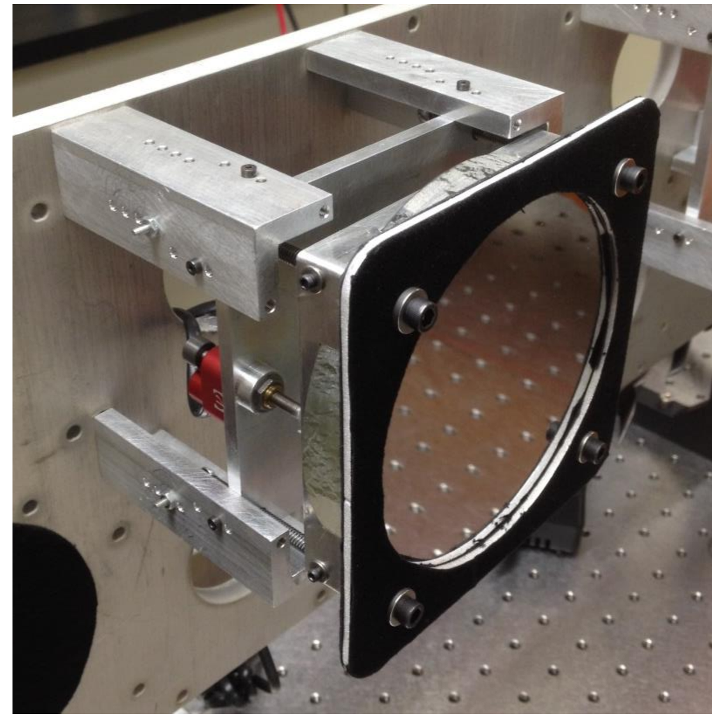
Flight Packaging





Rigid body actuation scheme



Mirror box prototype with rigid glass mirror

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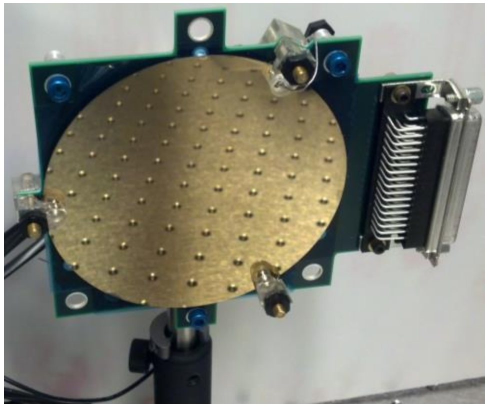
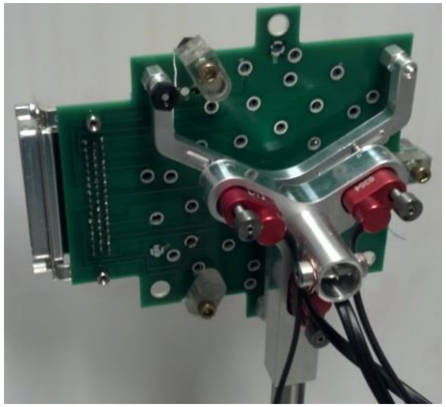
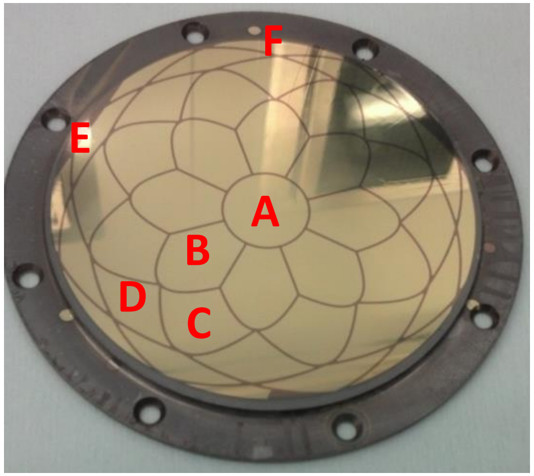
Current Mirror Prototype

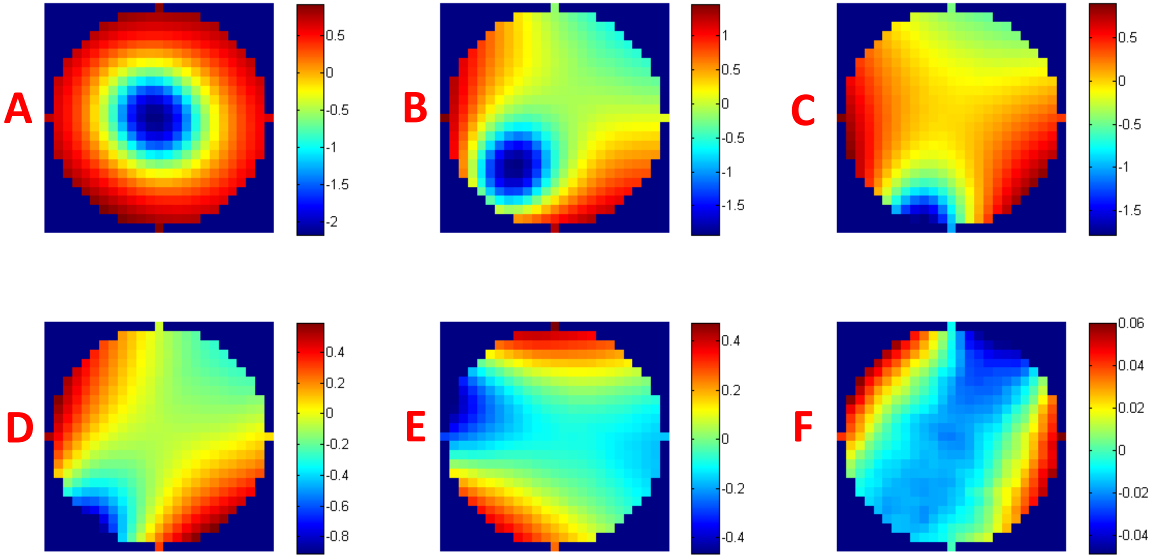
- Optimized “Notre Dame” actuation pattern
  - 41 independent channels
- Developed on flat glass substrates
- Optical characterization performed







Example influence function measurements



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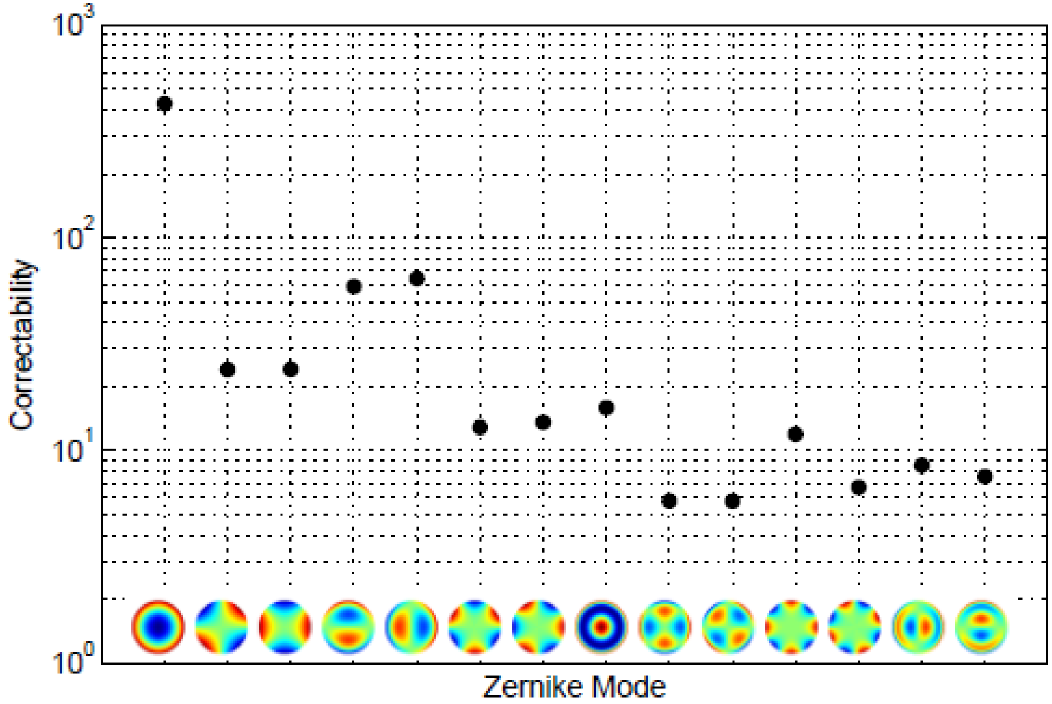
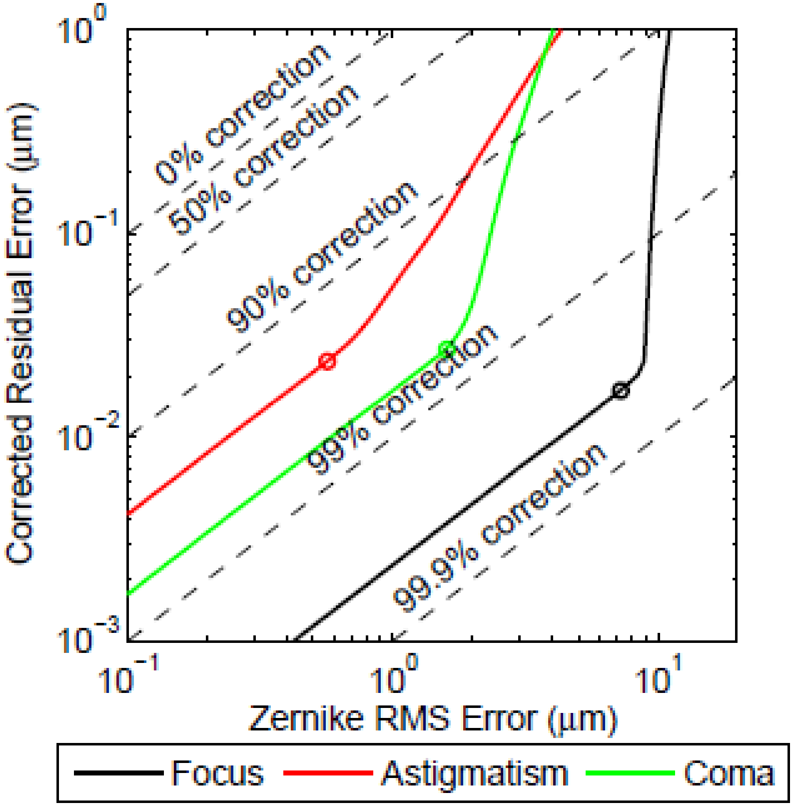
Performance Modelling





- High correctability for low-order Zernike Modes
- Large actuator strokes before saturation

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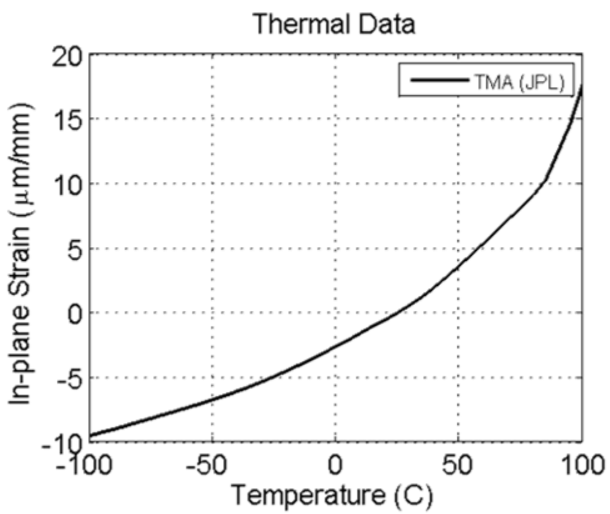
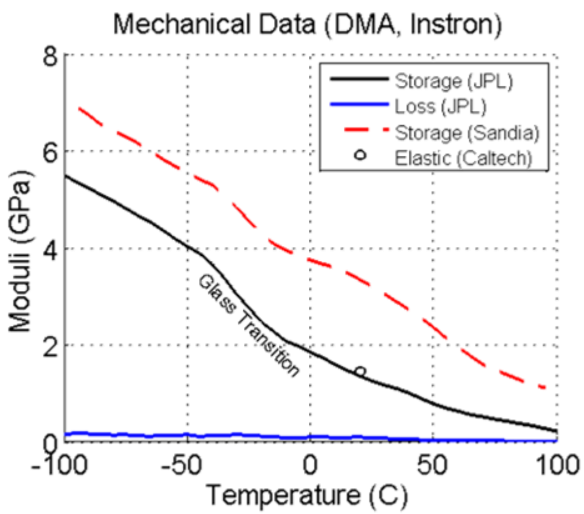
Flight Qualification

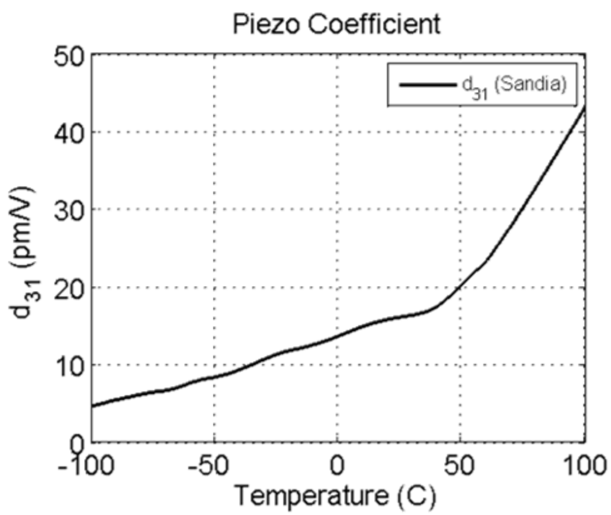
- Material Characterization
  - Piezopolymer material data
- Thermal Analysis & Testing
  - Quantification of survival and operating temperature limits
  - Thermal-vac testing of mirror laminates
- Vibrational Tests
  - Survival of launch loads
  - Mirror vibrations during imaging

P(VDF-TrFE) Material Characterization

- Data obtained from
  - JPL polymer lab (TMA, DMA, DSC, TGA)
  - Caltech material testing (Instron, optical measurements)
  - Sandia report on PVDF in space (DMA, piezo measurement)
- Large variation in properties across temperatures







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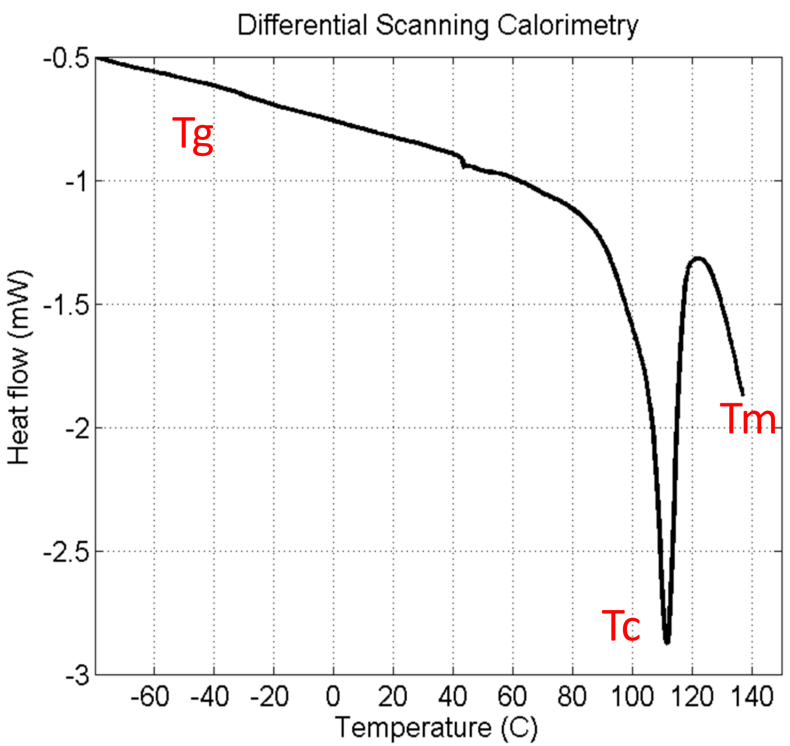
P(VDF-TrFE) Material Characterization

- Critical temperatures
  - Tg: -40C , glass transition (ill-defined)
  - Tc: +110C, Curie
  - Tm: >140C, melting
  - Td: >400C, decomposition
- Very low moisture absorption (<0.01%)
- Viscoelasticity
  - Stiff for a polymer but still viscoelastic
  - Creep master curve to be measured
  - Good news: glass substrate will dominate shape over time and maintain molded shape



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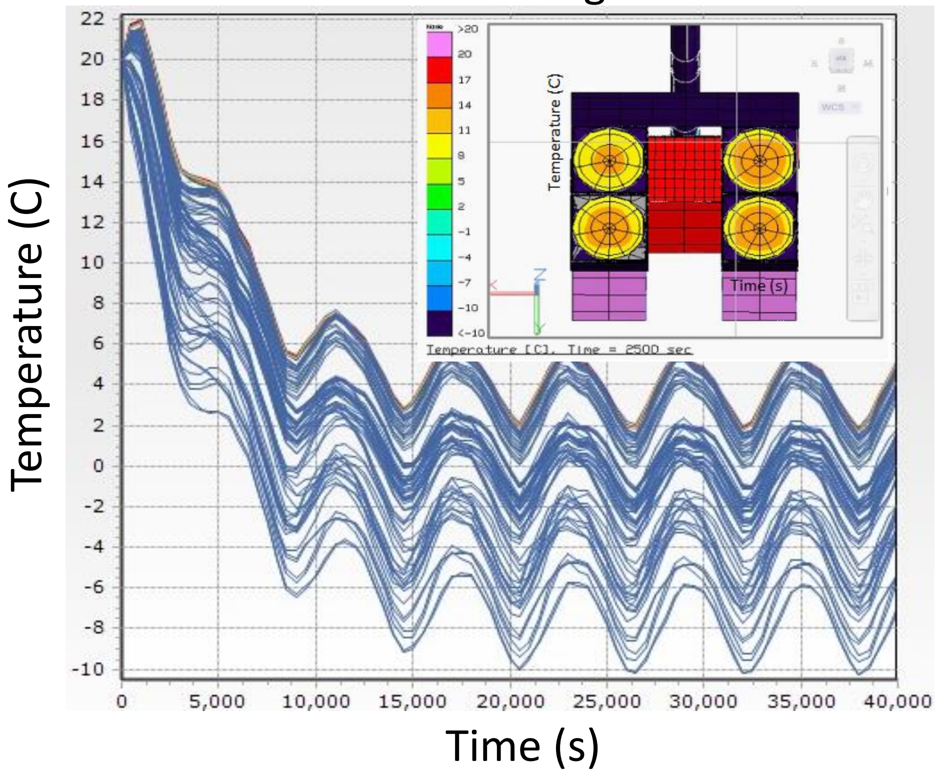
Thermal Environment

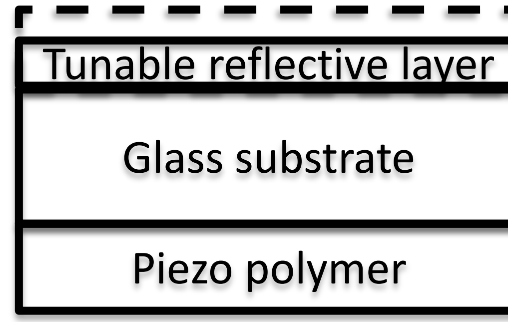
- Thermal modelling:
  - Thermal Desktop used to model on-orbit temperature profiles
  - Assumed 11am/11pm SSO
- Operating:
  - Mirror electronics on
    - **-10 to +6ºC**
- Survival:
  - Cold (Mirror electronics off)
    - **Down to -60ºC**
    - Mirror functionality proven to be retained down to -70ºC in lab setting
  - Hot (Sun facing (ie. loss of S/C control)
    - **Up to 50ºC**

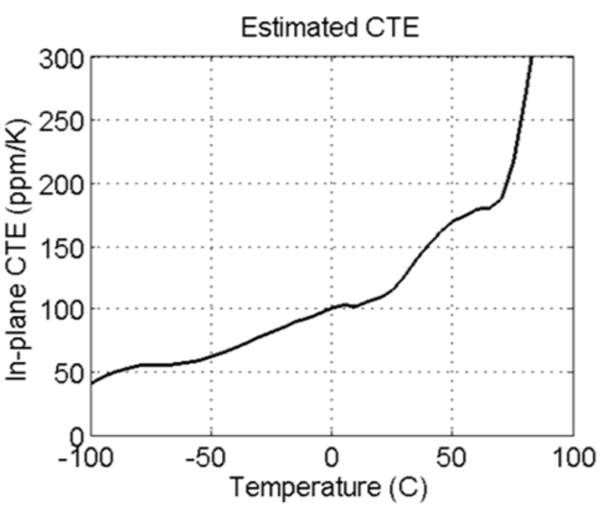
Operating thermal profile for the mirror segments

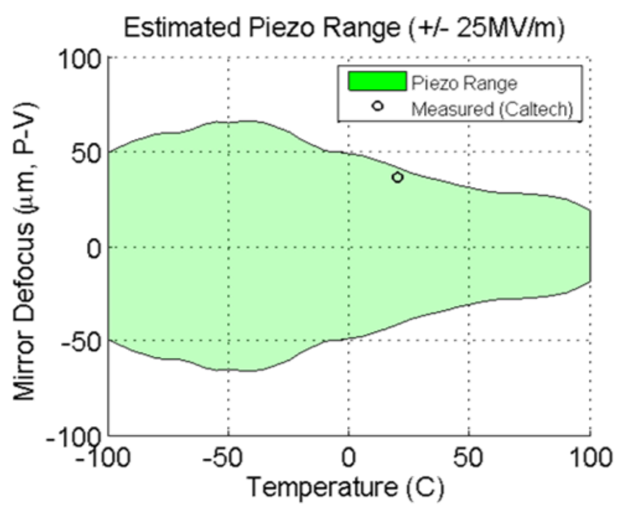


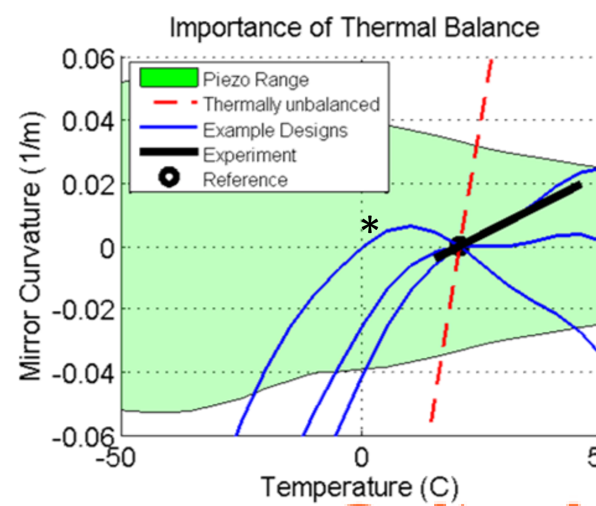
Thermal Balancing

- CTE varies from 50 ppm/K to >200 ppm/K
- When cold, stiffness increases, but piezo coeff decreases
- Actuation stress fairly flat, optimal peak ~-40C
- Mirror stroke (defocus mode)
  - +/- 40 µm at 20C
  - +/- 60 µm at -40C
- Thermal balancing
  - Balancing CTEs of mirror materials can extend operational range









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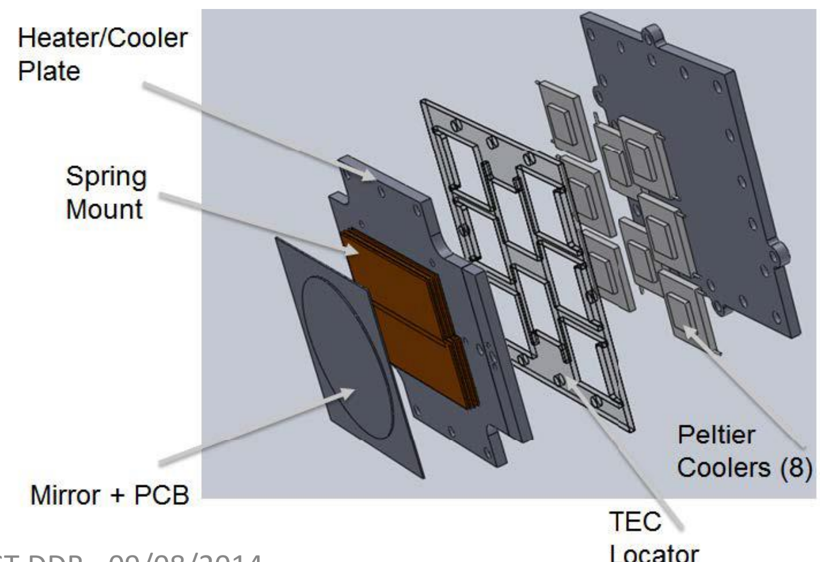
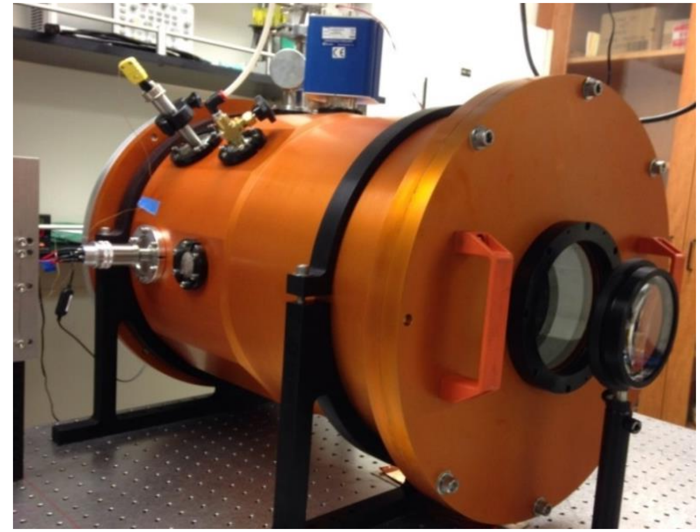
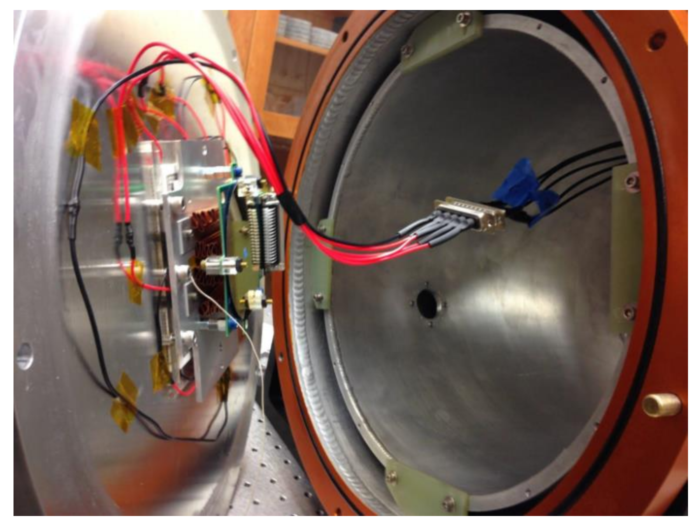
Thermal-Vac Test Apparatus

- Thermal-vac chamber developed in order to test mirrors in a representative thermal environment
- Chamber performance:
  - Vacuum: 10^{-5} torr
  - Temperature:
    - -35°C in open air
    - Expecting -50°C in vacuum (TBD)







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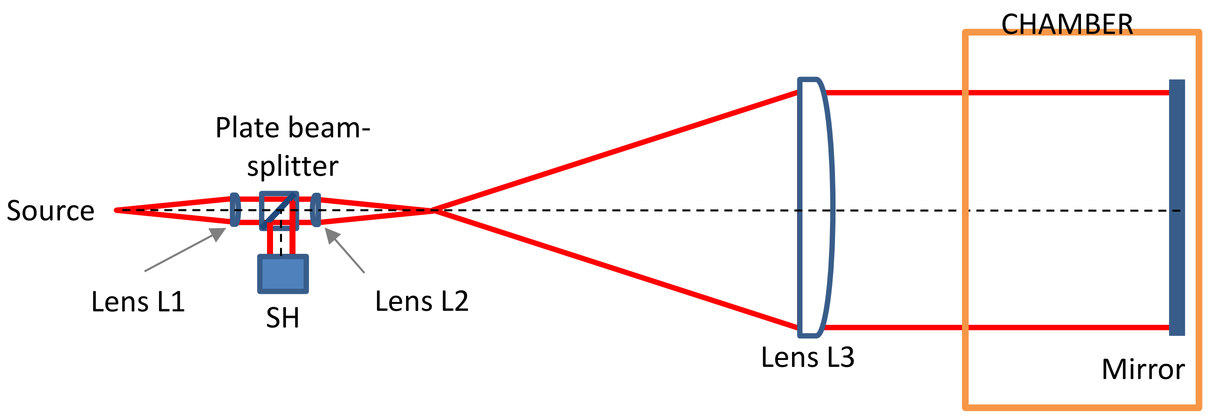
Thermal-Vac Test Apparatus

- Optical system developed to characterize mirror figure as a function of temperature
  - SHWFS to monitor WFE
  - Currently configured to test flat mirrors
    - Preliminary data obtained, but tests are currently under development



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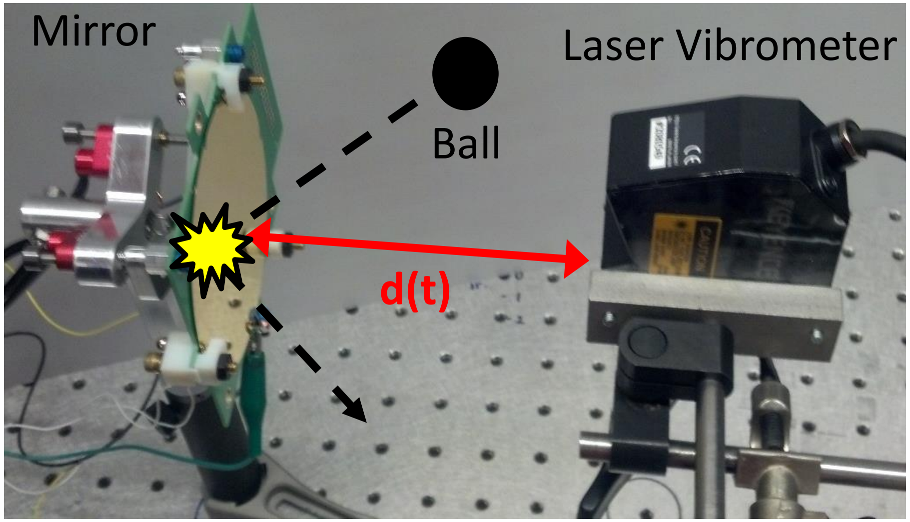
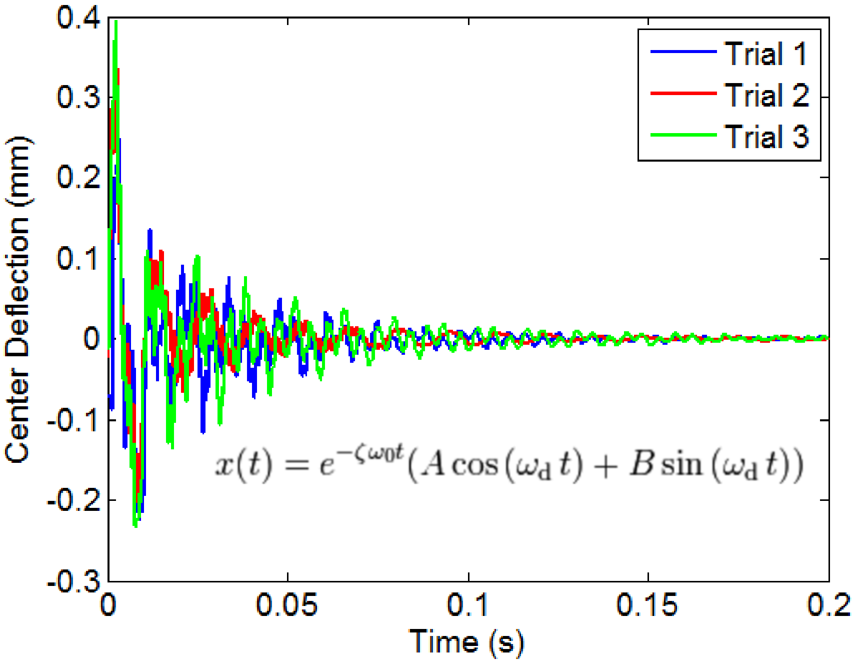
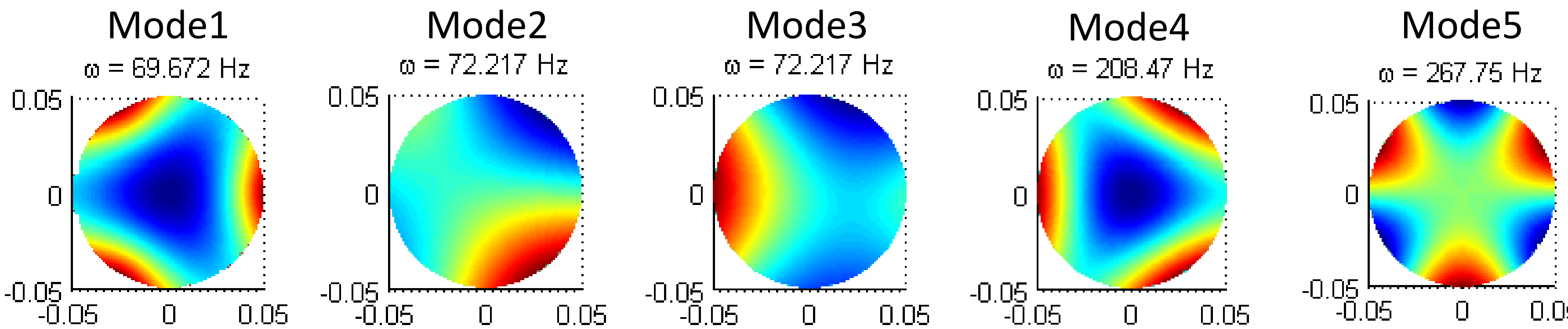
Vibrational Behavior

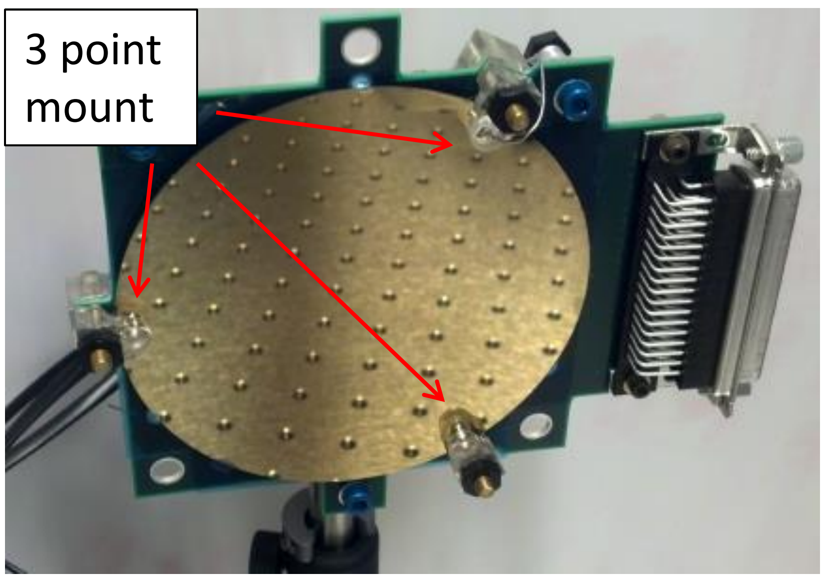


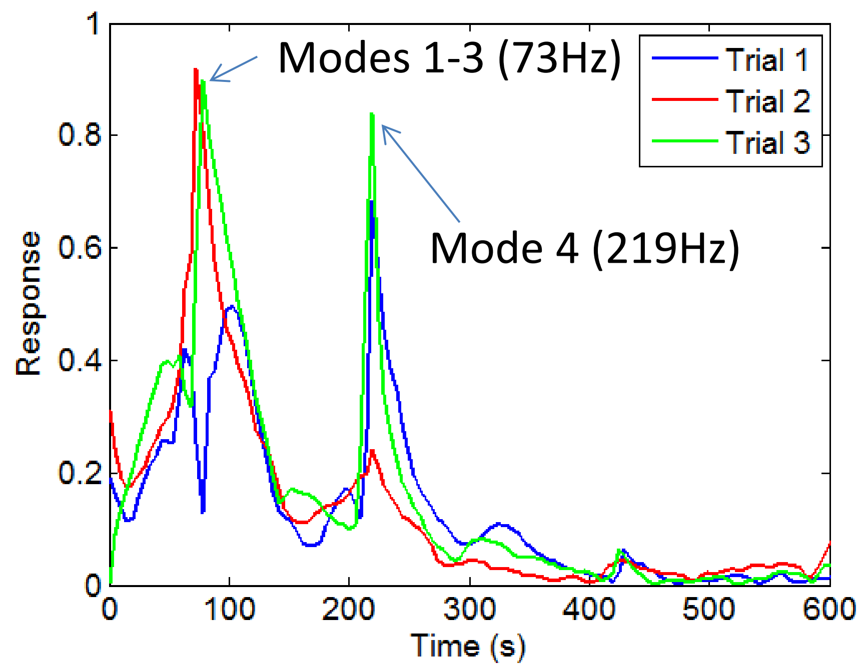


- Impulse response of mirror measured experimentally
  - Steel ball used to excite mirror
  - Center deflection measured as a function of time
- Damping coefficient determined by monitoring decay and fitting exponential
  - Average value: 0.068

Vibrational Behavior







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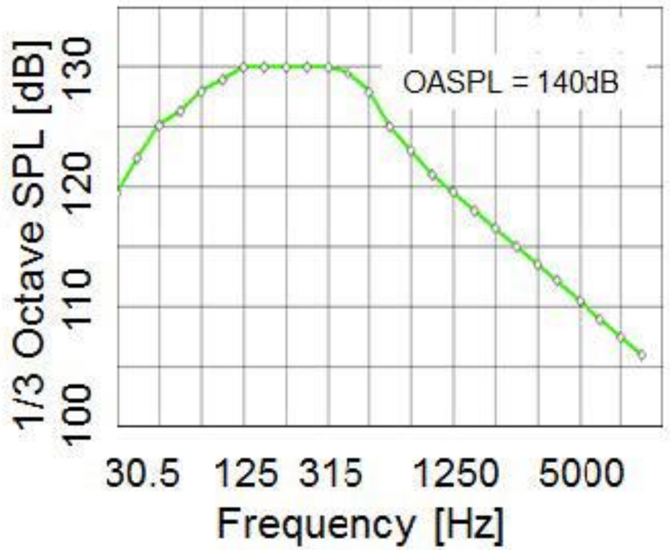
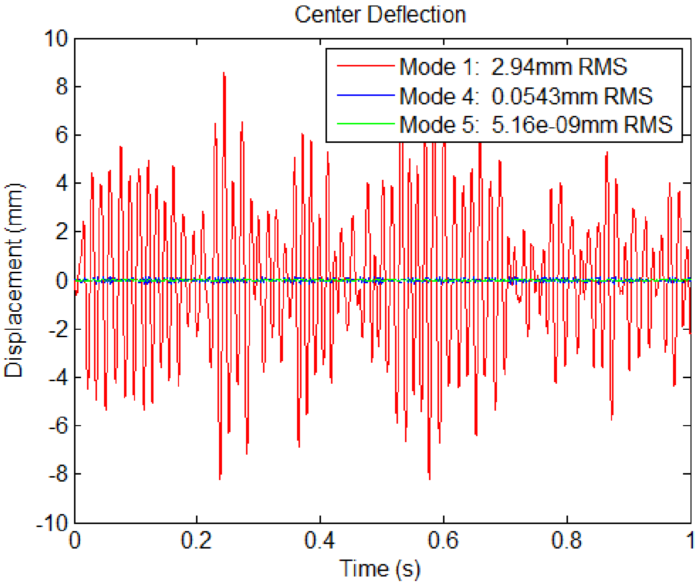
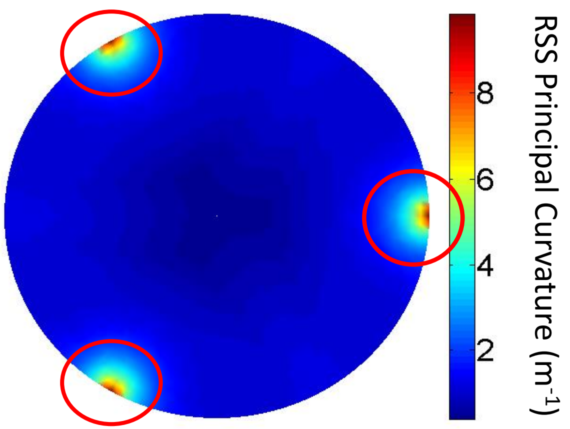
Launch Survival

Delta IV-Heavy Acoustic Profile





- Large acoustic loads during launch
  - Delta IV-Heavy (conservative case)
  - Mounting points are points of stress concentrations
- **Mirror launch restraint required**



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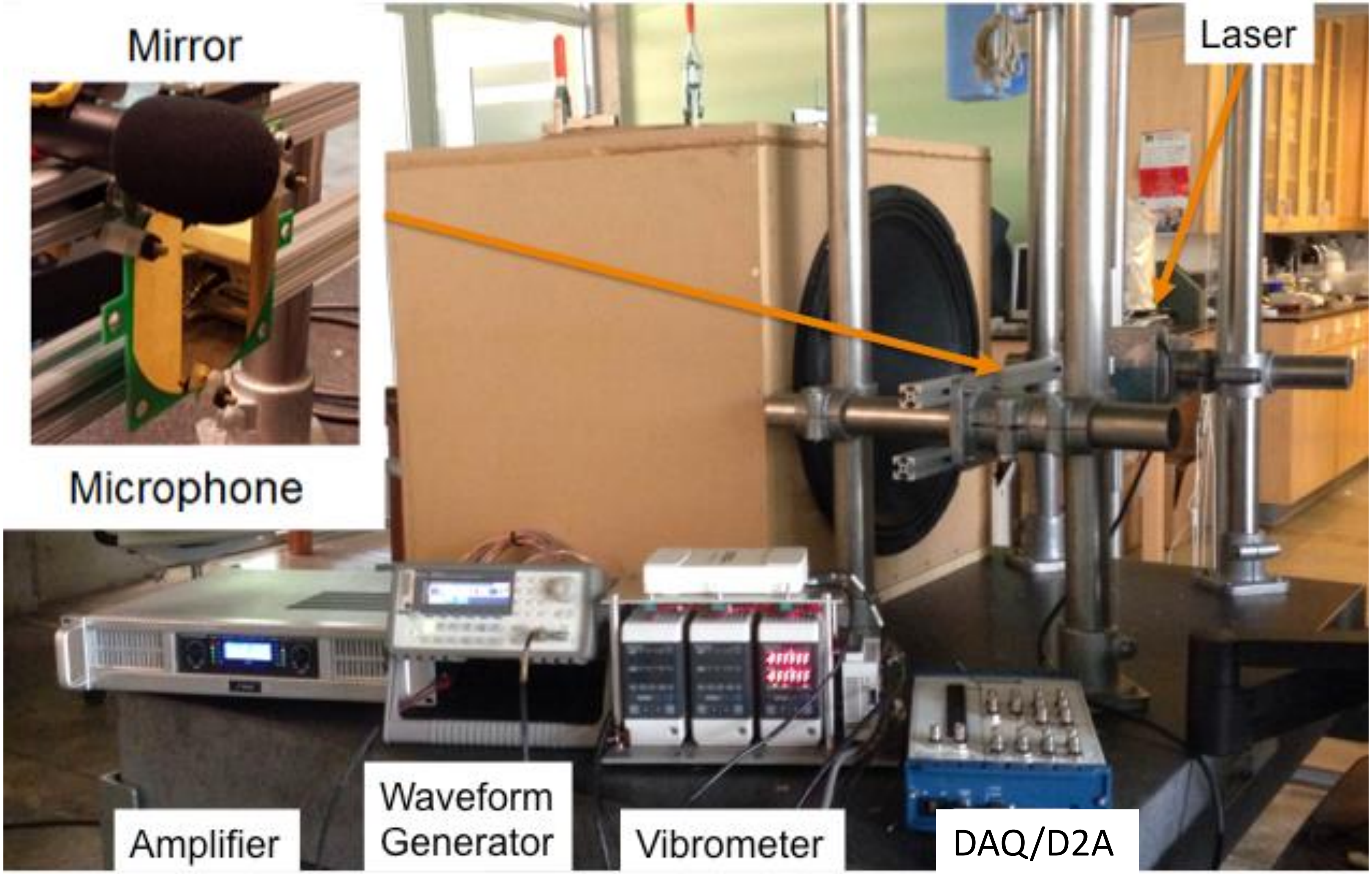
Acoustic Test Apparatus



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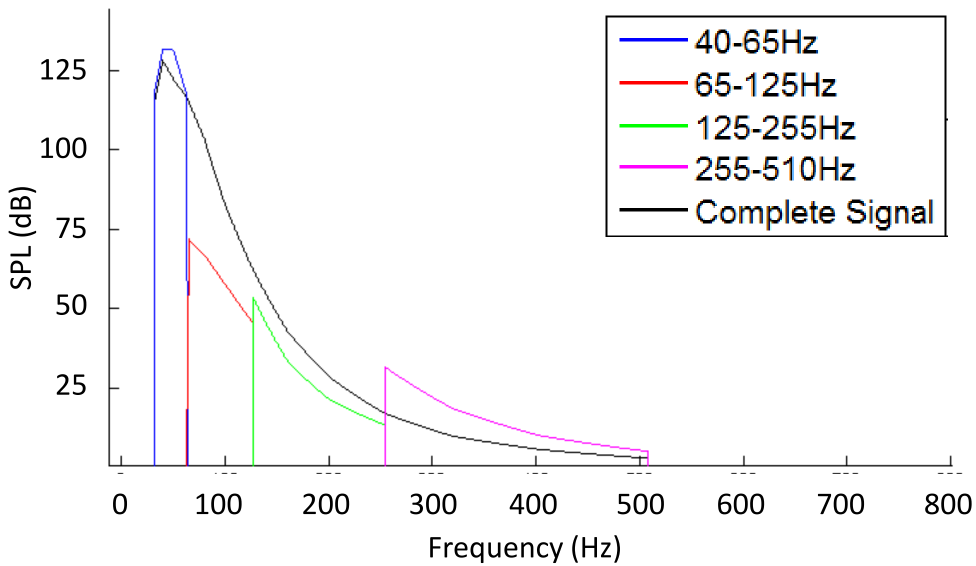
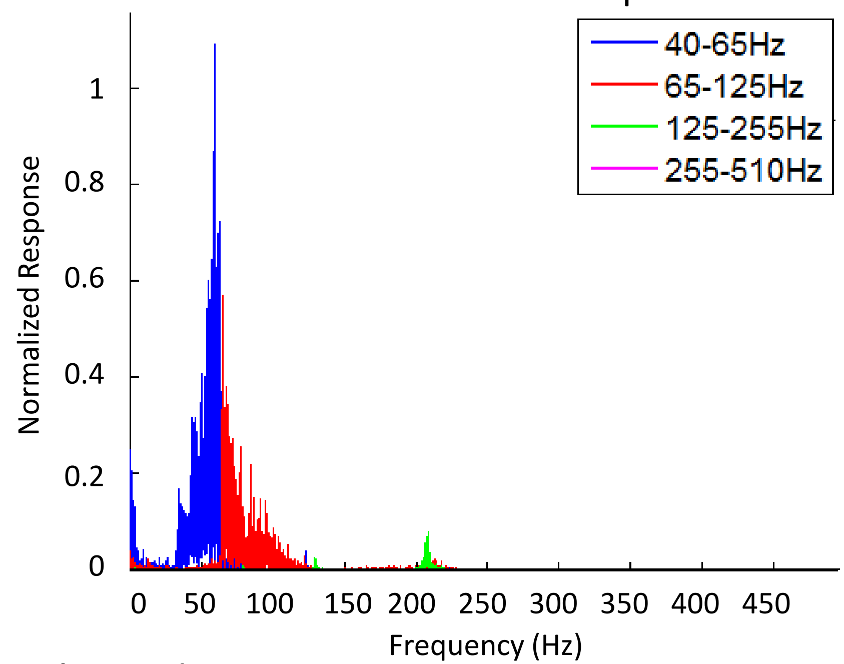
Signal Generation





- 125dB overall sound pressure level (OASPL) achieved
- Signal broken into sections in order to deliver proper SPL across all frequencies
- > 300 μm RMS center deflection measured at 125dB
  - Good agreement with model predictions (< 10 %)
  - Restraint system required

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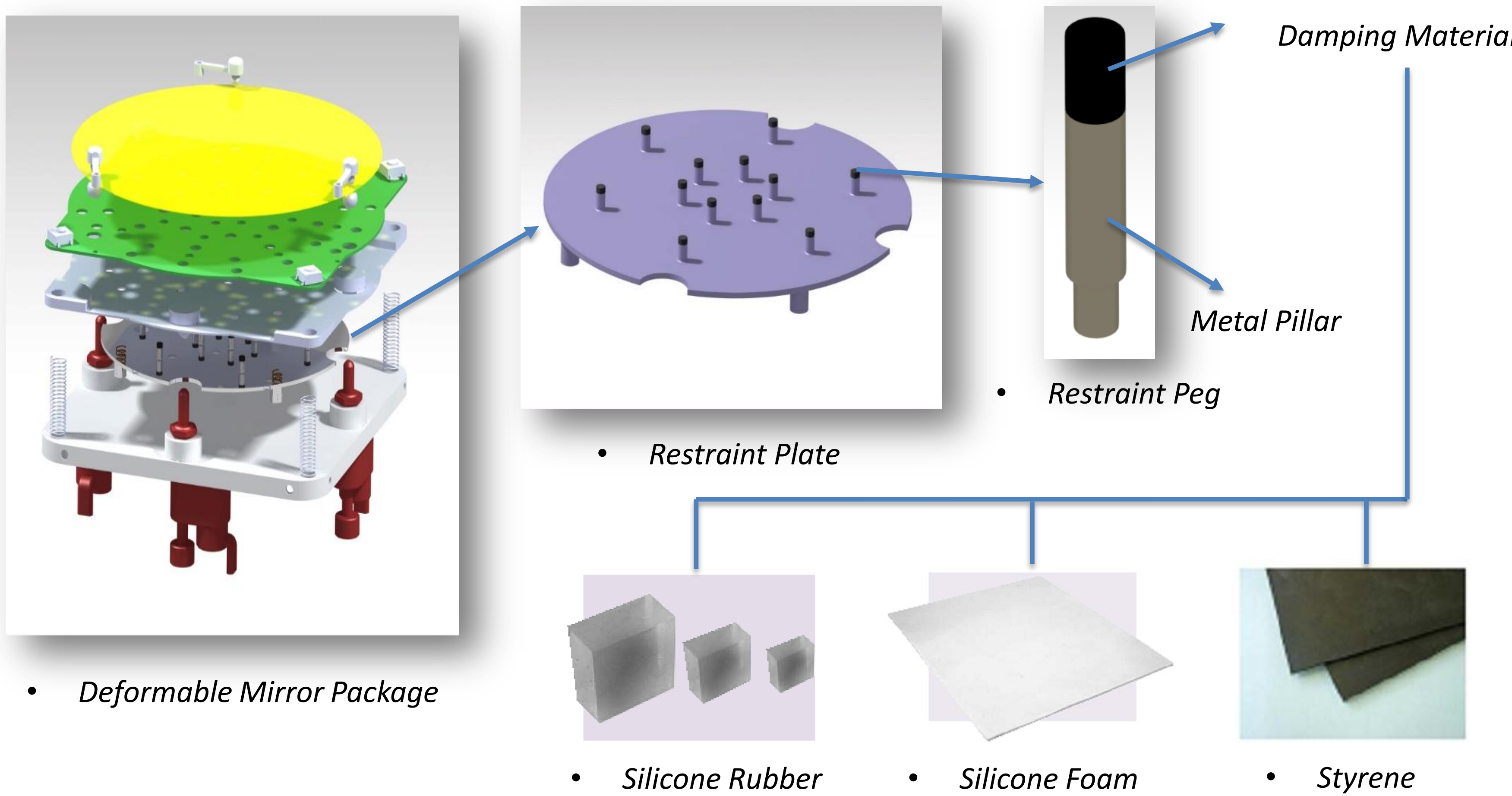
Restraint System



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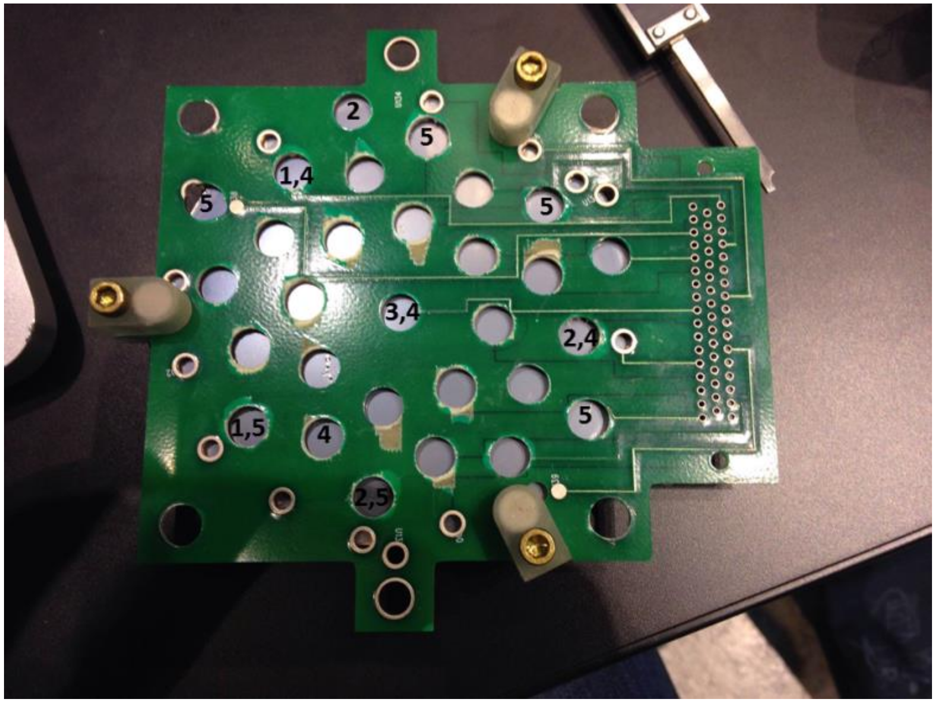
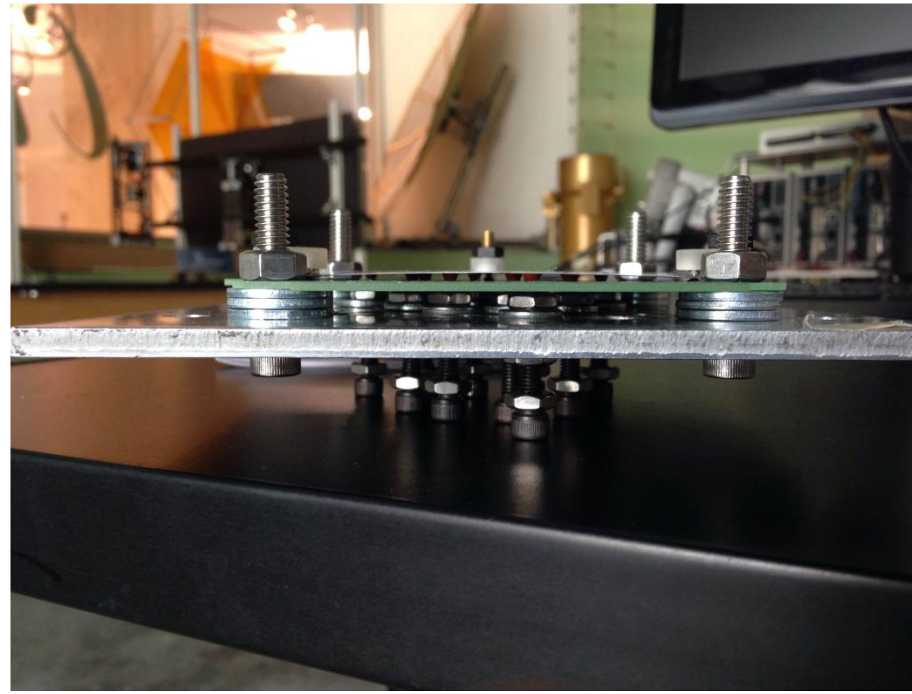
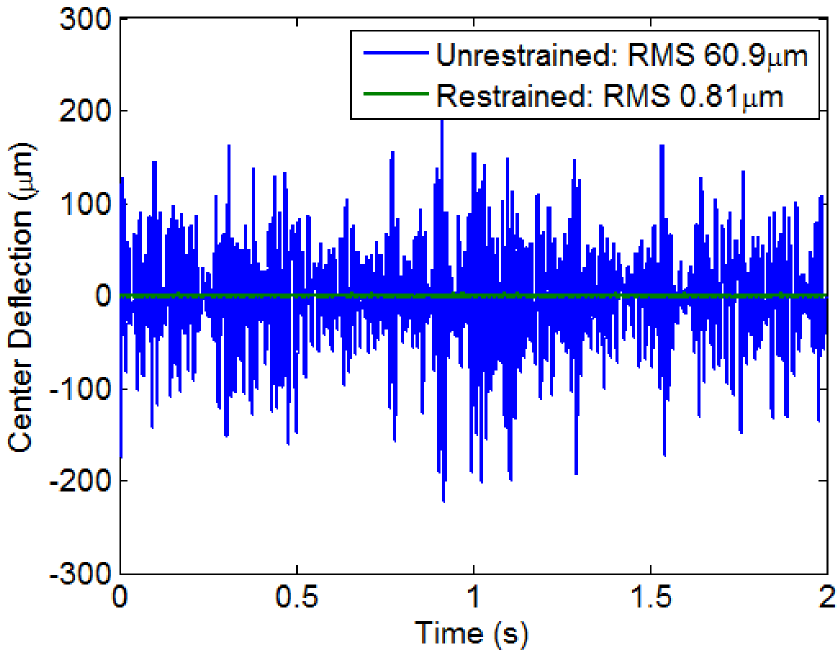
Restraint System

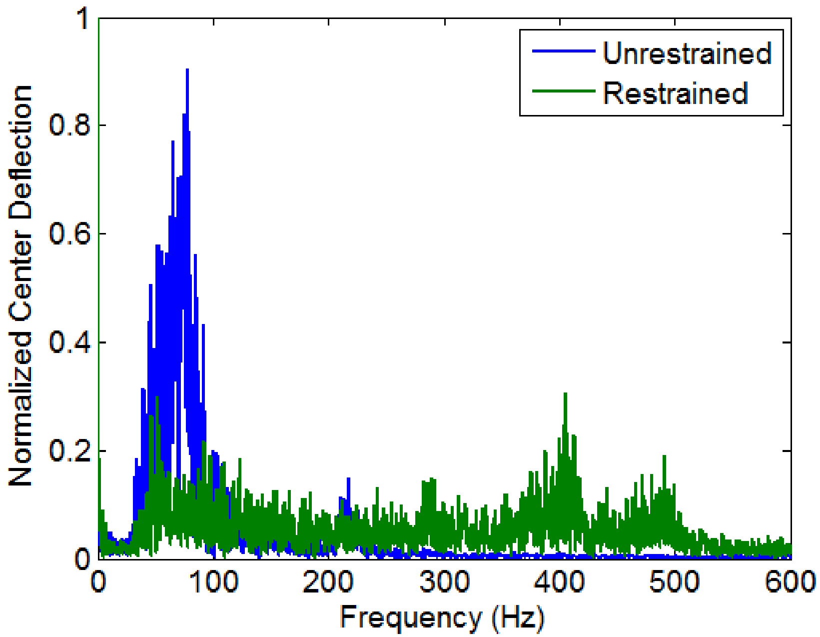




- Lab implementation:
  - Holes drilled through mirror PCB in order to accommodate various restraint configurations
  - Mirror seated against silicone pads atop shoulder bolts

Vibration Suppression





- 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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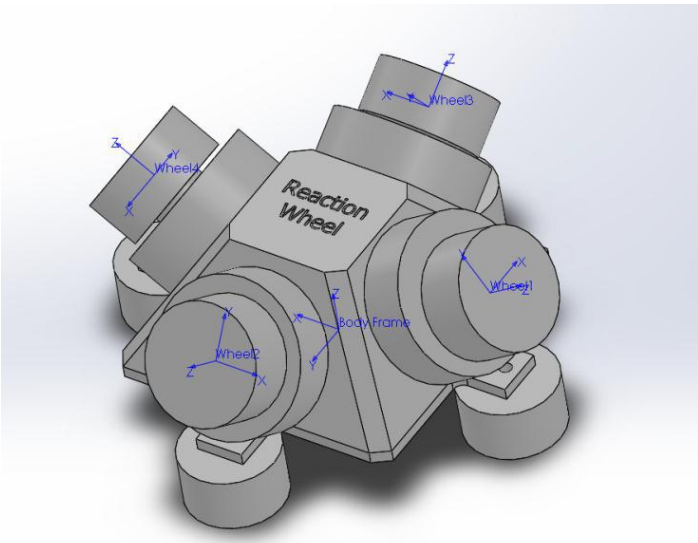
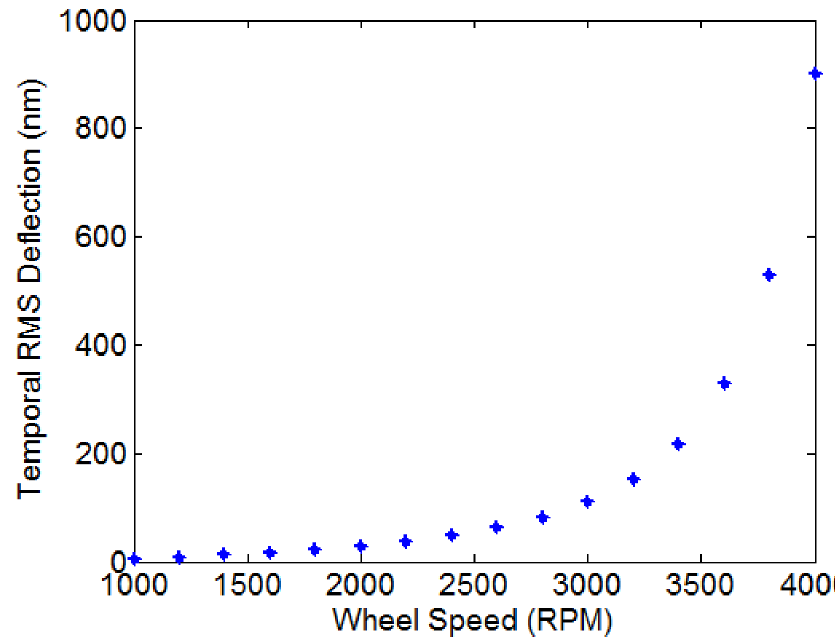
Vibration During Imaging





- Mirror jitter calculated as a function of reaction wheel imbalances
  - Imbalances measured using sample wheel from Surrey
- Large deflections predicted towards resonant frequencies, however wheels will operate at much lower speeds during imaging (< 650 rpm)
  - No significant concerns for imaging

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Conclusions

- Design of deformable mirrors complete
  - Fabrication process (almost) finalized
    - Still working on obtaining slumped glass substrates
  - Design of flight package complete
  - Flat prototypes constructed
- Flight qualification of mirrors
  - Extensive material data gathered for piezoelectric polymer
  - Thermal-vac chamber commissioned
    - Thermal balancing of mirror laminates (TBD)
    - Optical performance during thermal cycling (TBD with figured mirrors)
  - Launch survival
    - Data gathered for reduced SPL inputs
    - Restraint system constructed in order to mitigate mirror vibrations

Review Outline

1. Mission Overview (15 mins)
   – Telescope overview
2. Spacecraft Design (150 mins)

   < Coffee Break>
3. Telescope Design (150 mins)
   a) Telescope Concept of Operation (Melanie)
   b) Camera (Manan)
   c) Mirrors (John)
   d) Electronics (Yamuna)
   e) Boom (Lee)
   f) Telescope System Modelling (Lee / Marie)
   g) Telescope Breadboard/Test (Marie)
4. Summary & wrap up (15 mins)

Please send comments to Dr. Greg Davis (Gregory.L.Davis@jpl.nasa.gov)

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Mirror Electronics

Yamuna Phal,
Melanie Delapierre, Eric Grohn

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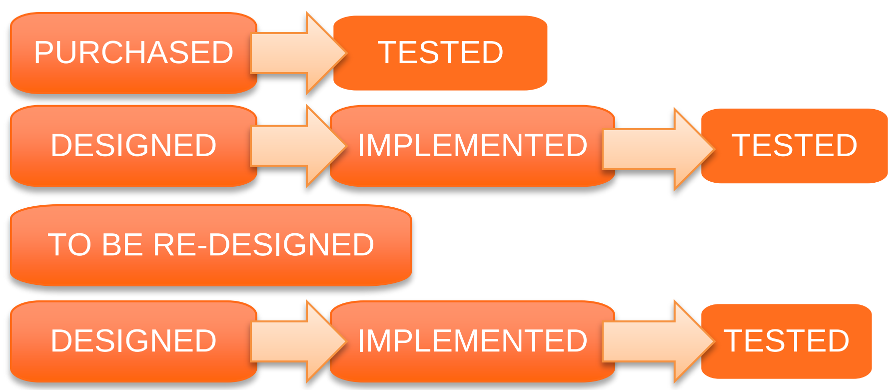
Mirror Electronics - Overview

- Requirements
- Block diagram
- Lab-prototype design decisions
- Lab-prototype design
  - Controller board
  - HV board *(Mirror actuators)*
  - HV board *(Picomotors)*
  - MUX board
  - Power budget
  - Components used
- Plan Forward



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Mirror Electronics - Requirements

- Constraints
  - USB interface to mirrorcraft
  - ZigBee wireless interface to camera
  - Volume : Contained within a 10 cm x 10 cm x 5 cm box
  - Power constraints : < 2 W

- Performance
  - HV DC output for driving mirror actuators *(Wavefront correction)*
    - +/-500V range for driving 41 modes
    - 0.1 V resolution at the output (corresponds to λ/10 wavelength)

  - HV DC output for driving picomotors *(Translation)*
    - 0-110V range for driving 3 modes
    - Required SR – 0.6 V/µs*(transient)*

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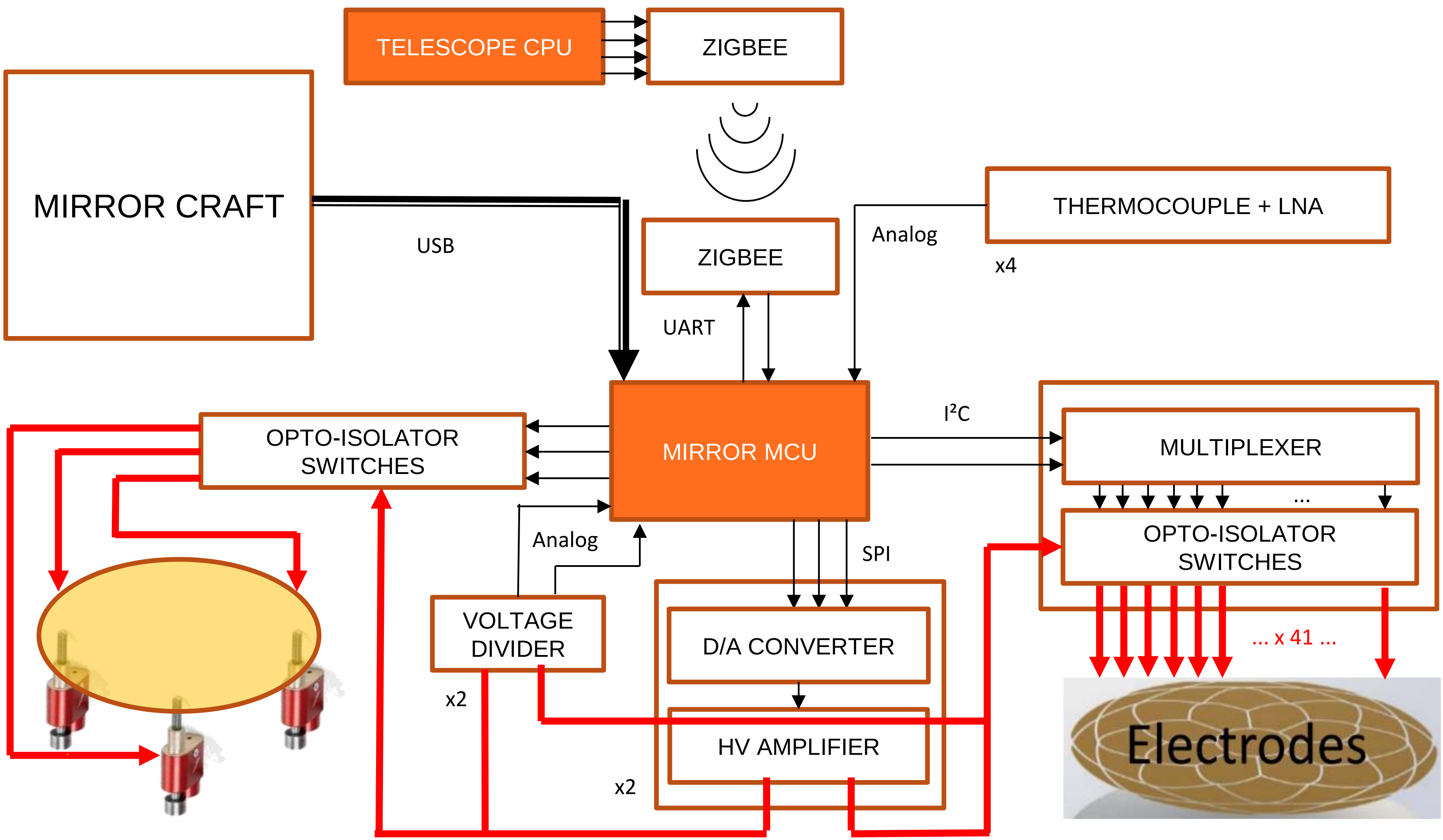
Mirror Electronics - Block Diagram



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Lab-prototype - Design Decisions

- ATMEL MCU
  - RAD tolerant – used in INSPIRE mission
- DAC needed
  - 16-bit DAC for a resolution of 61 mV
  - I^2C or SPI – SPI Interface
  - Could be interfaced for bipolar output range
- Power Amplifier selection - HV board *(Picomotors)*
  - Gain of X100
  - Output swing of +/-500 V DC as required
- Power Amplifier selection - HV board *(Mirror actuators)*
  - 10KHz capacity and swing 0-110 V (SR ~0.6 V/µs)
  - Output current of 120 mA rms max
- HV DC-DC converter selection
  - 1 W dissipation each with 1.67 mA input current
- Temperature sensors + Telemetry channels

Lab-prototype - Controller board

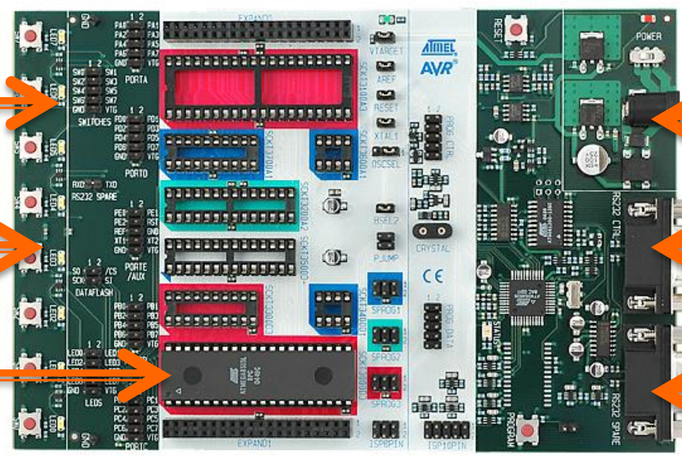
- Summary
  - 12 V power supply for board operation *(3.3-5 V desired)*
  - UART interface (RS232) for sending program and feedback *(needed)*
  - I^2C/SPI interfaces *(needed)*
  - ANALOG INPUT *(present)*/ANALOG OUTPUT interfaces *(absent)*
  - On-board switches and other interfaces *(not needed)*

PURCHASED → TESTED

Manual Switches

LED

Microchip ATmega 1284



Power (12V)

UART interface for sending program

UART interface for feedback

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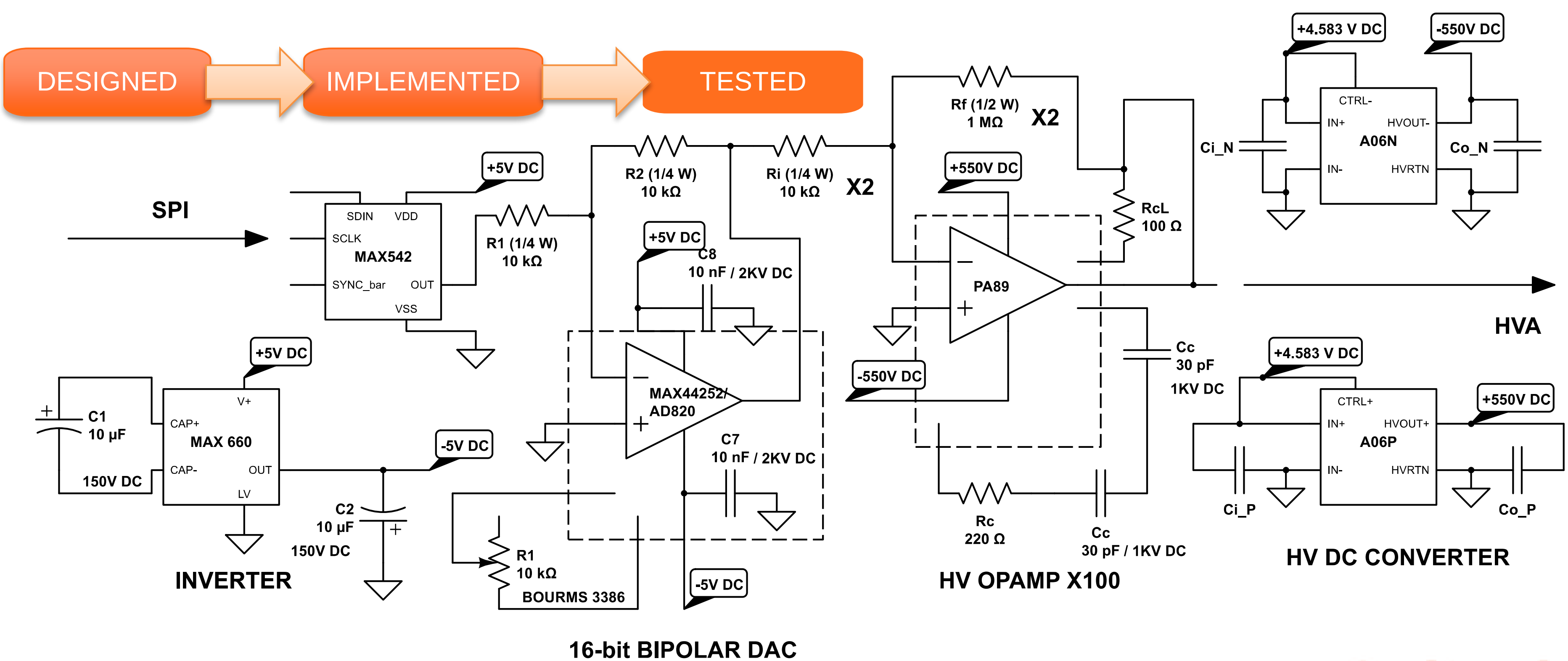
Lab-prototype - HV board *(Mirror actuators)*

- Design Summary
  - Provides Digital/Analog interfacing with the Controller board
  - Provides an amplification factor of x100 for HV output (-500 V to +500 V)
  - Target value of the HV output line with resolution of 0.1 V



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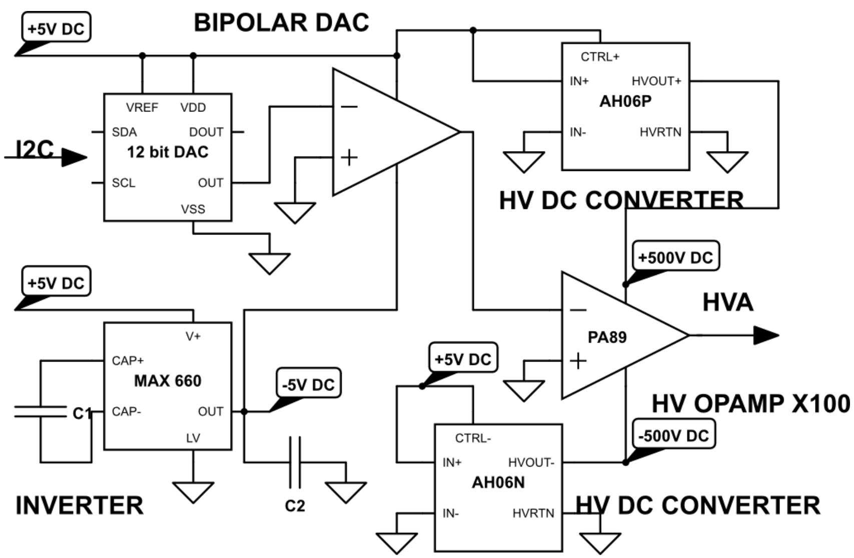
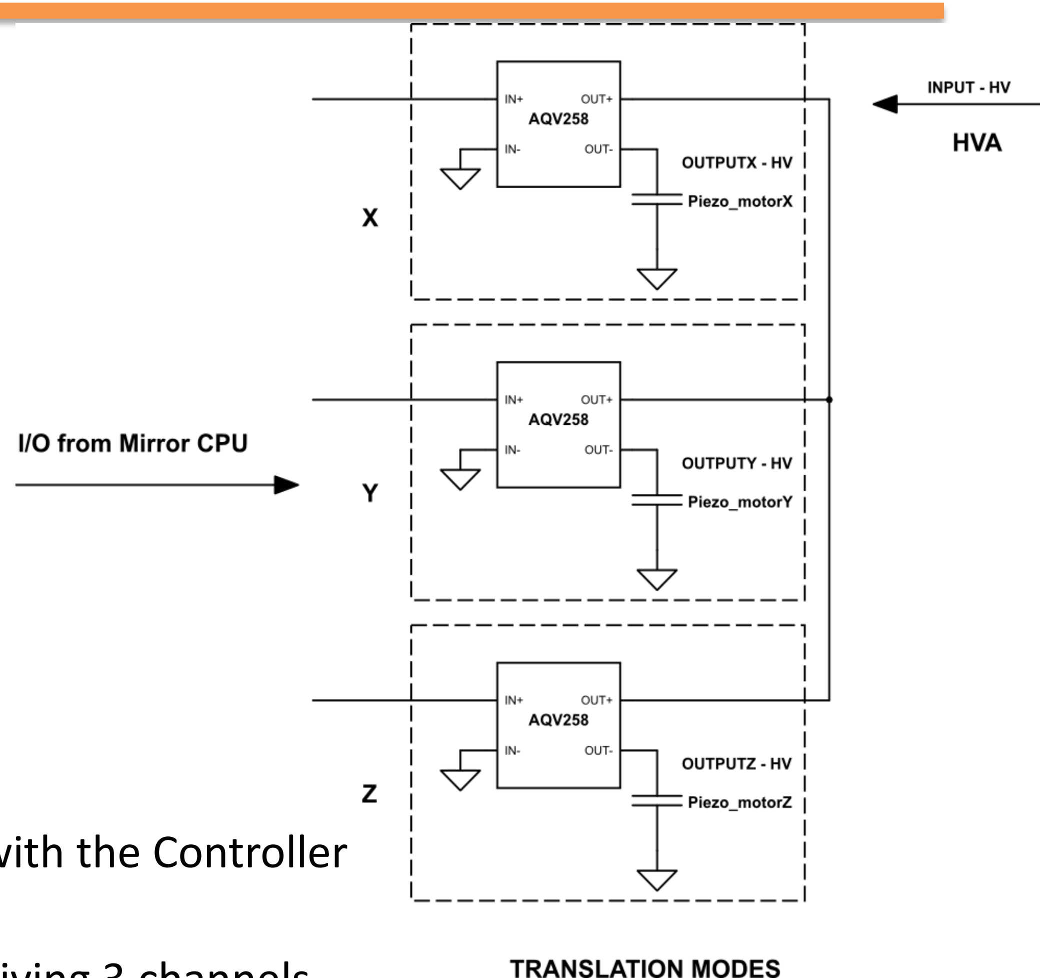
Lab-prototype - HV board *(Picomotors)*



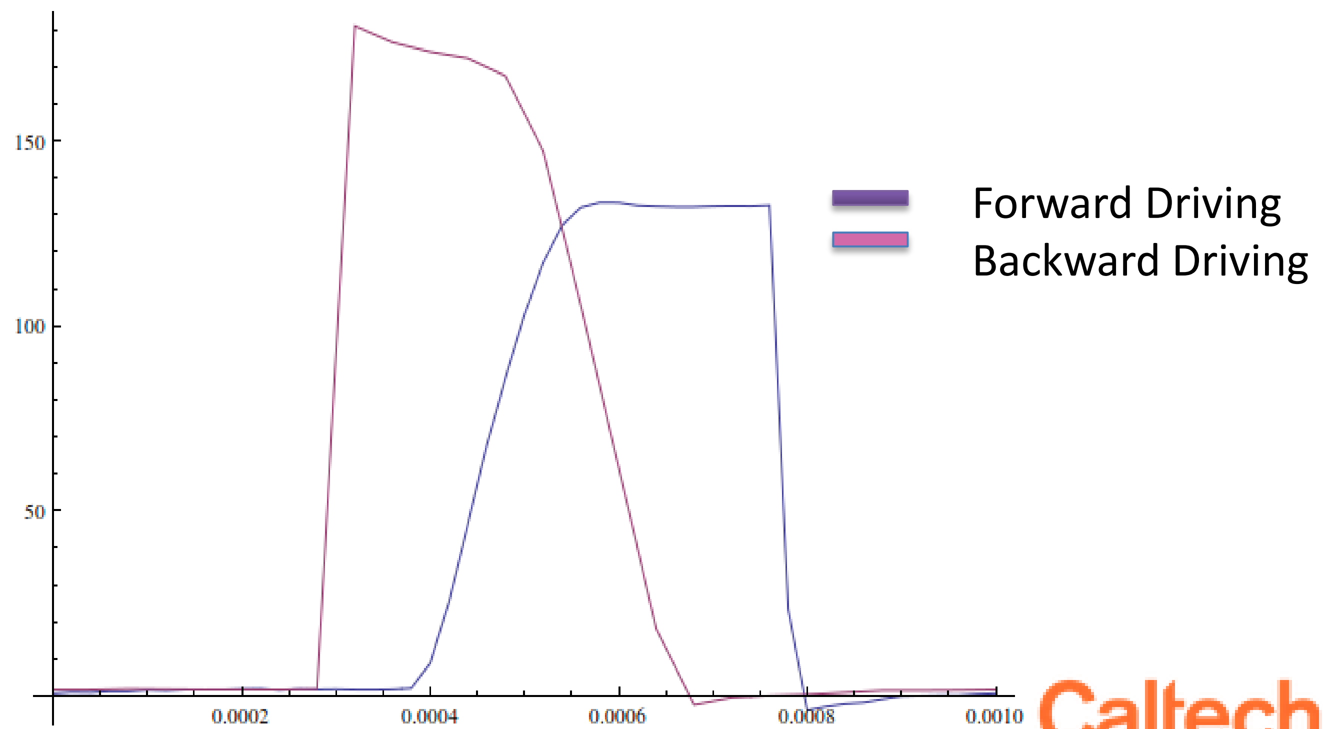


TO BE RE-DESIGNED

- Design Summary
  - Provides Digital/Analog interfacing with the Controller board
  - A single HV line could be used for driving 3 channels

HV board *(Picomotors)* - Open Issues

- Designing appropriate driver for picomotors
  - 10KHz capacity and swing 0-110 V (SR ~0.6 V/µs)
  - Output current of 120 mA rms max
  - Corresponds to ~3-4 W (FULL LOAD)



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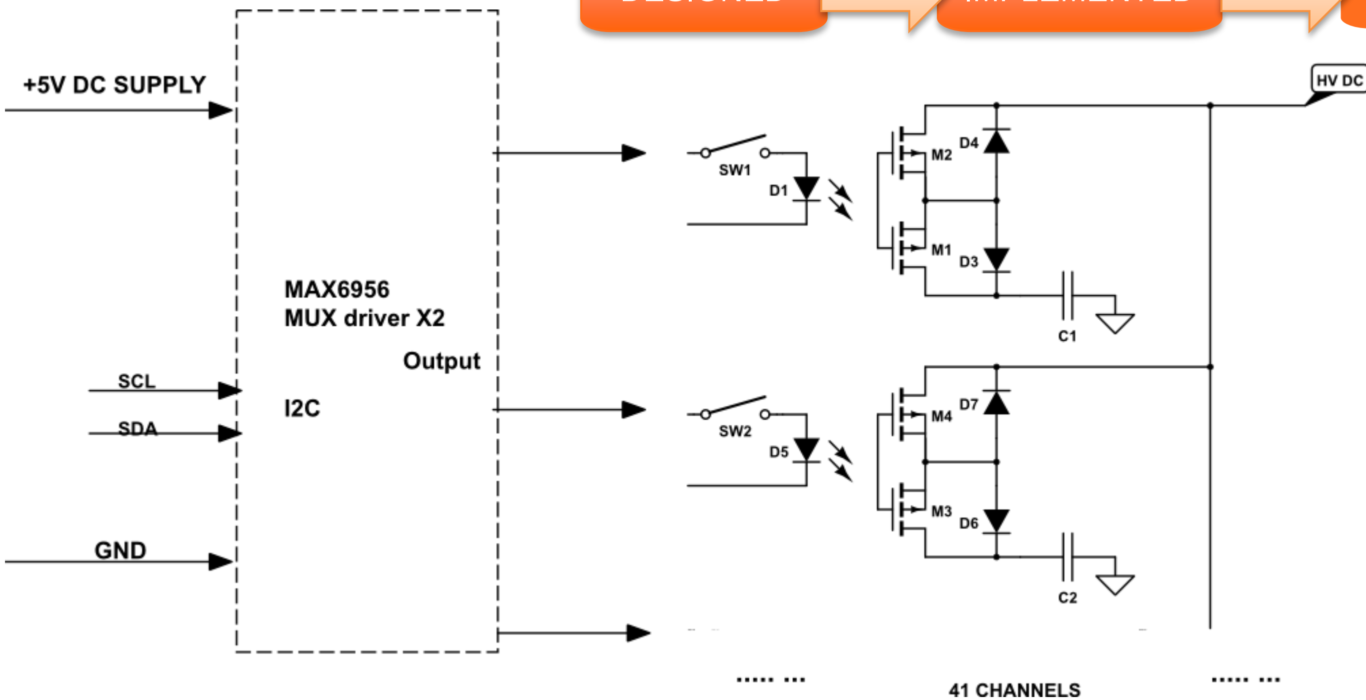
Lab-prototype - MUX board

- Design Summary
  - I^{2}C interfacing with the Controller board
  - Provides optical isolation between LV-HV signals
  - A single HV line could be used for driving 41 channels

DESIGNED → IMPLEMENTED → TESTED



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Mirror Electronics - Power Budget

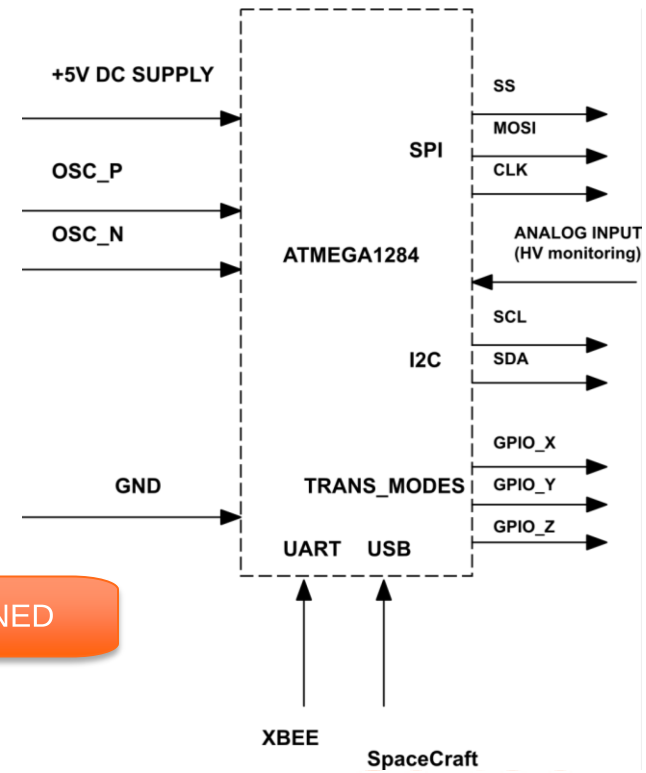
LAB PROTOTYPE *(TESTED)*	**POWER RATING (*NO LOAD)***	**POWER RATING (*FULL LOAD)***
CONTROLLER BOARD	0.1 W	2.76 W
HV BOARD *(Mirror actuators)*	0.4 W	TBD
HV BOARD *(Picomotors)*	0.4 W	TBD
MUX BOARD	0.1 W	0.8 W
TOTAL	1 W	TBD

Lab-prototype - Components used

- Controller board
  - MCU - ATMEGA 1284
  - DAC - Maxim MAX542
  - Zigbee
    - XBEE-ZB – XBP24BZ7SIT-004J (63mW RPSMA Router/End Device)
    - Antenna – A24HASM450 (2.4 GHz RPSMA)
- HV board *(Mirror actuators)*
    - Power Amplifier - Apex PA79
    - HV DC-DC converter - EMCO FS10-CT
- HV board *(Picomotors)*
    - Power Amplifier - Apex PA78
    - HV DC-DC converter - EMCO FS02-CT
- MUX board
  - PhotoMOS relay - Panasonic AQV258
  - LED driver IC - Maxim MAX6956
- Temperature sensor
  - TI TMP006

Plan Forward

- Designing appropriate driver board for picomotors
- Validate the use of HV board (mirror actuators) and MUX board for in-flight operation
- Design a customized controller board for in-flight operation with a new controller
  - 5 V (3.3 V) power supply
  - UART interface (RS232)
  - I^2C/SPI/ANALOG INPUT-OUTPUT interfaces



TO BE DESIGNED

Camera Electronics

Manan Arya,
Melanie Delapierre, Yamuna Phal, Eric Grohn

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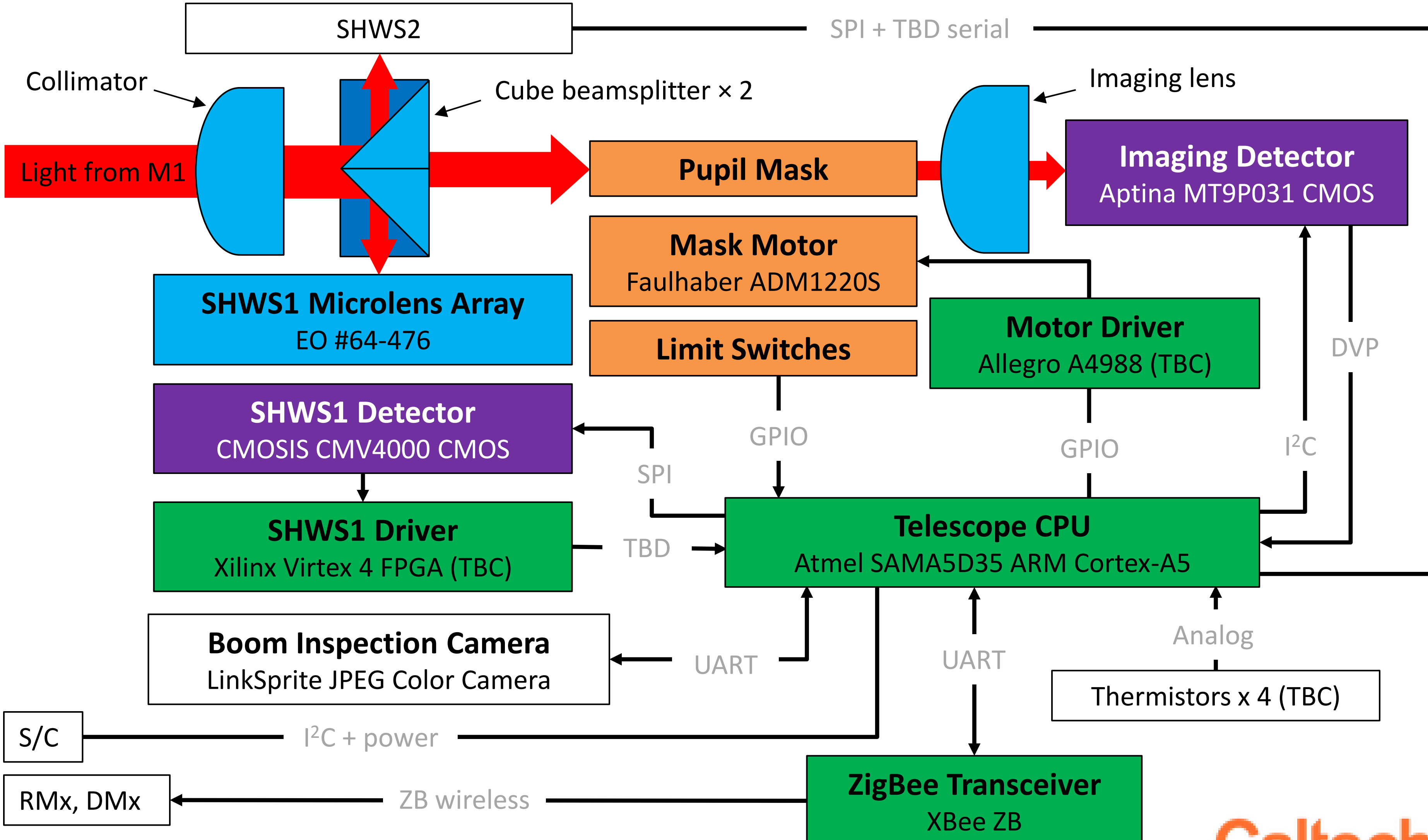
Camera Electronics - Overview

- Requirements
- Lab-prototype block diagram
- Lab-prototype design
  - Power budget
  - Components used
- Open Issues
- Plan Forward

Camera Electronics - Requirements

- Constraints
  - USB interface
  - ZigBee wireless interface with mirror electronics
  - Volume < 10 cm x 10 cm x 35 cm box (must fit between the two MirrorCraft – stowed configuration)
  - Power < 5 W
  - Mass < 4kg

Camera Block Diagram



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Camera Power Budget

Part	Peak (W)	Standby (W)	WF Sensing Mode (W)	Imaging Mode (W)	Reconfiguration Mode (W)
Telescope CPU	0.60	0.45	0.60	0.60	0.60
Imaging Detector	0.74	0.30		0.74	
SHWS	2.40 × 2	1.80 × 2	2.40 + 1.80		
BIC	0.22	0.15			
ZigBee	0.14		0.14	0.14	0.14
Mask	0.60				0.60
Total	**7.10**	**4.50**	**4.94**	**1.48**	**1.34**
+ Margin (10%)	**7.81**	**4.95**	**5.43**	**1.63**	**1.47**

- Requirement: < 5 W
- Using existing prototypes to estimate power; SHWS prototype camera has unnecessary features (e.g. high framerate output)
- Further power reduction through having only one SHWS active during WF sensing

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Components used

- Telescope MPU : Atmel SAMA5D35 ARM Cortex-A5
- Imaging Detector : Aptina MT9P031 CMOS sensor
- Boom-Inspection Camera : OV7670
- SHWS
  - MicroLens Array : EO #64-476
  - Image Sensor : CMOSIS CMV4000
- SHWS driver : Xilinx Virtex 4 FPGA (TBC)
- Motor driver : Allegro A4988 (TBC)
- Zigbee
  - XBEE-ZB – XBP24BZ7SIT-004J (63mW RPSMA Router/End Device)
  - Antenna – A24HASM450 (2.4 GHz RPSMA)

Open Issues

- SHWS detector readout electronics and software
  - Reduce power consumption
  - Challenging to design FPGA for readout
- SHWS alignment and calibration
  - Need to decouple piston from tip/tilt positioners

Plan forward

- Validate the use of components for in-flight operation
- Design a customized controller board for in-flight operation
- Reduce power consumption by reducing the interfacing electronics on the Atmel SAMA5D35 evaluation board

Review Outline

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Please send comments to Dr. Greg Davis
(Gregory.L.Davis@jpl.nasa.gov)

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Boom

Lee Wilson,
John Steeves, Erin Evans

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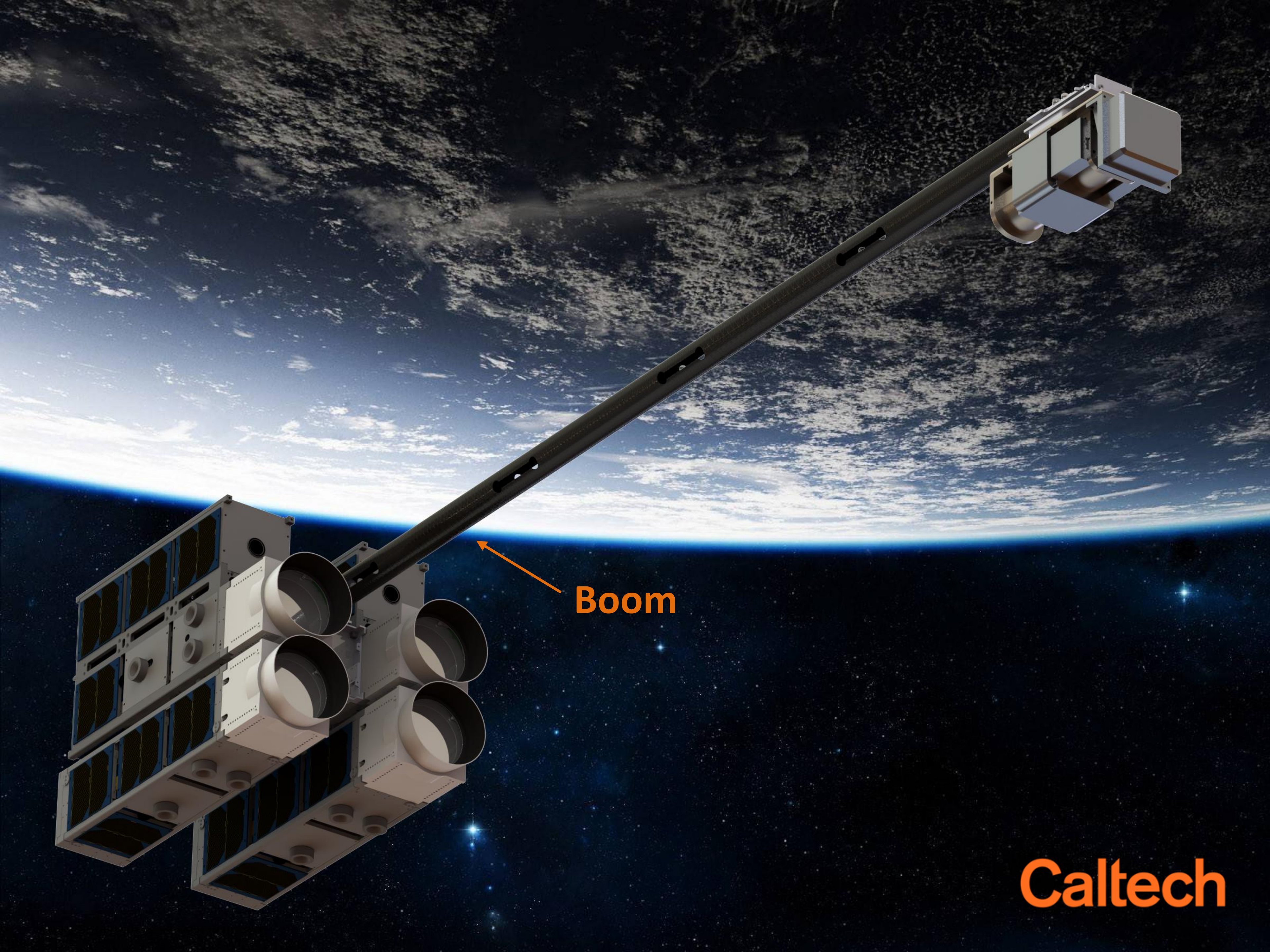
Boom
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Boom Requirements

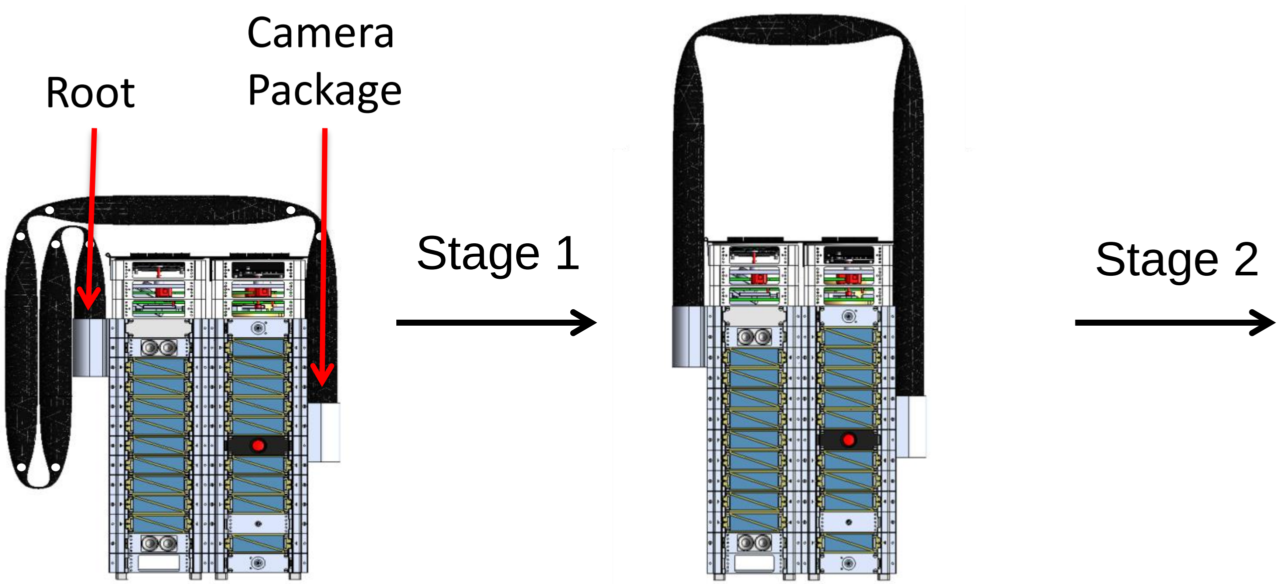
✓ = Requirement Completed

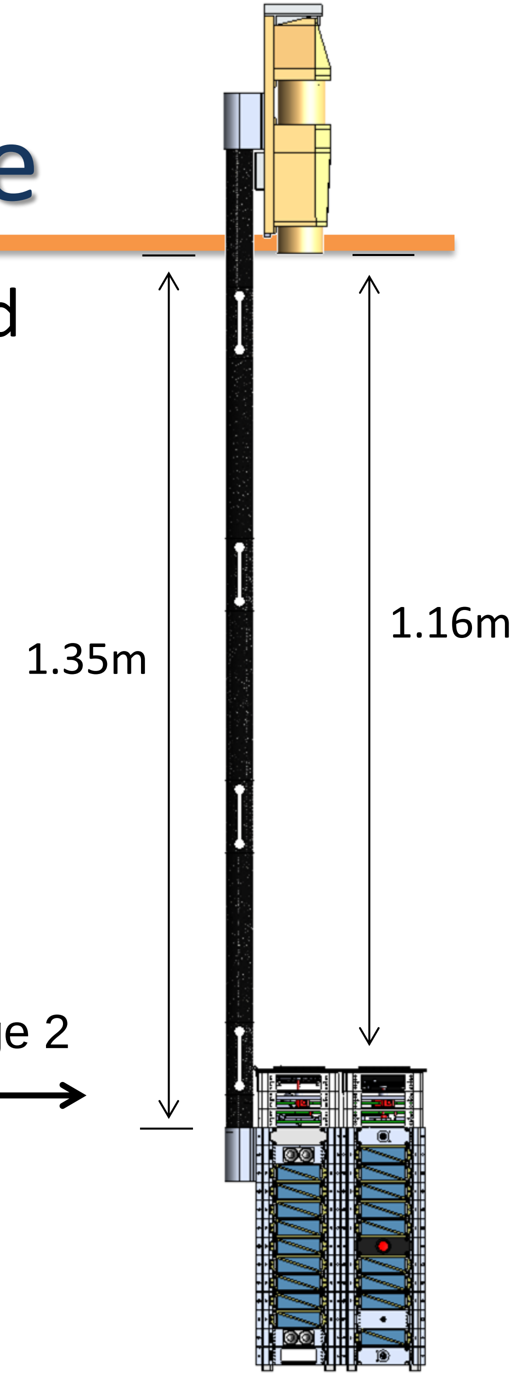
? = Additional testing required

- Functional
  - Enable 1.16m telescope focal length ✓
  - Compact launch configuration ✓
  - Can self deploy ✓
- Performance
  - Boom elongation
    - Static: < 500µm (can handle with rigid body mirror actuators) ✓
    - During imaging: < 50 µm ✓
  - Boom lateral deflection
    - Static: < 2mm (keep image on detector) ?
    - During imaging: < 200 µm/s (avoid image smearing) ✓
  - ACS
    - Boom deployment within ACS control authority ✓
    - Avoid coupling between S/C and ACS system ?

Boom Architecture

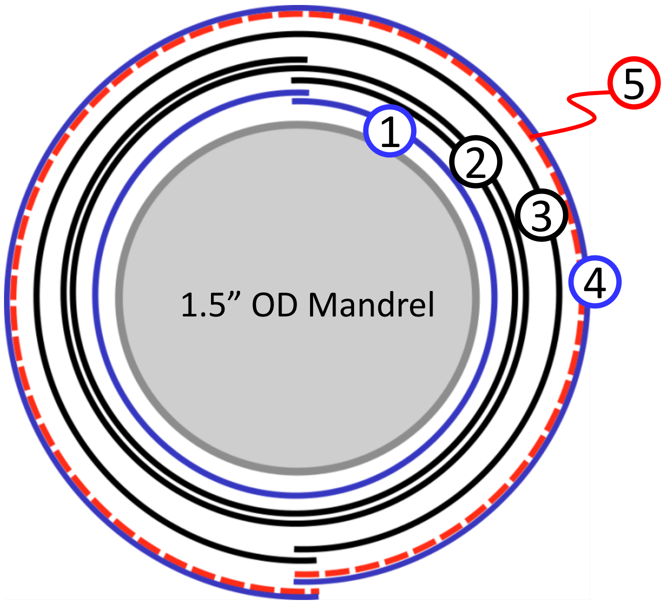
- Hollow cylindrical boom wrapped around S/C via folding-tape-spring hinges
  - 4 hinges total
  - Bonded to S/C and Camera
- Two stage unconstrained deployment process



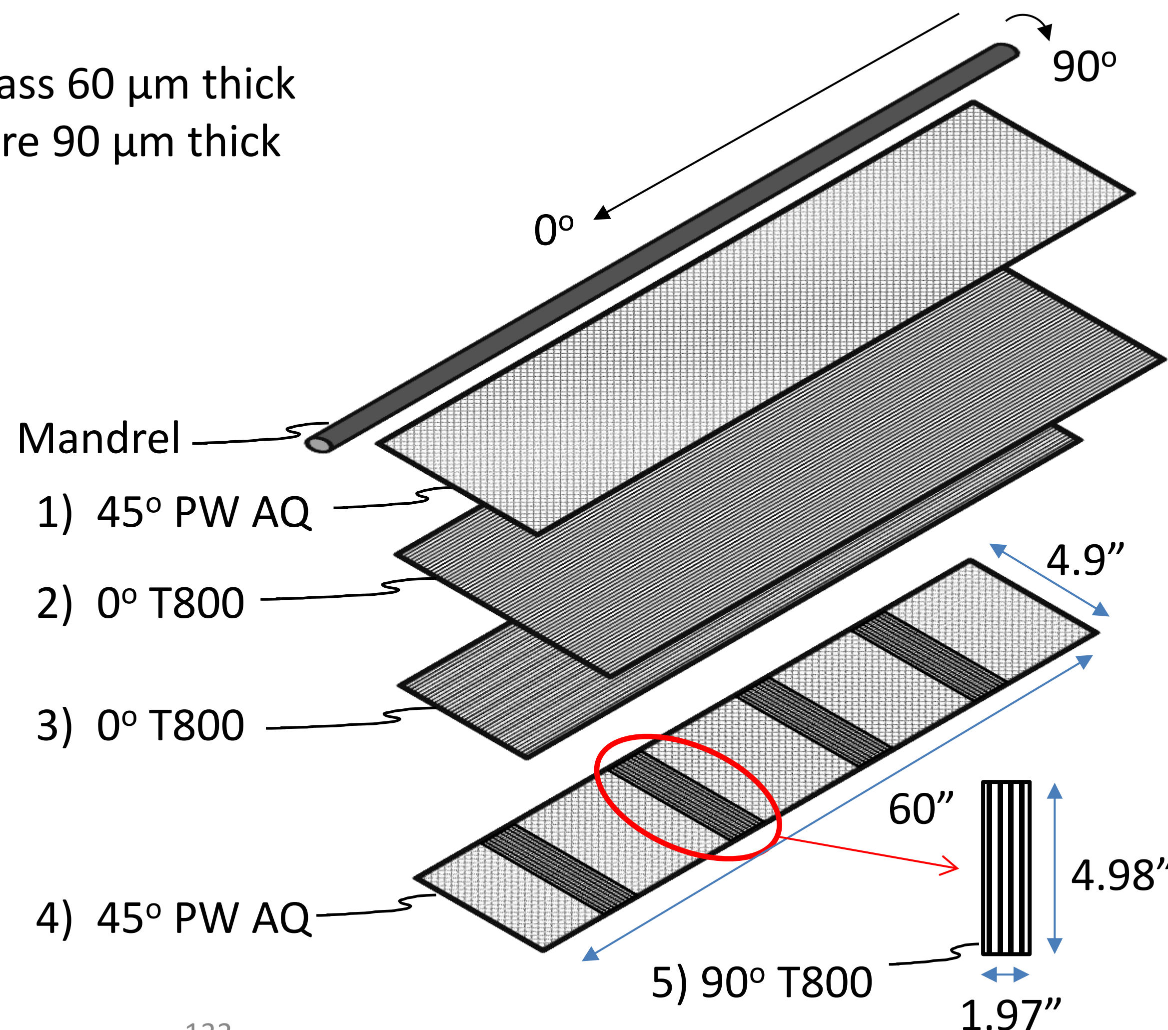


Boom Lay-up

- Now manufactured by AFRL in Albuquerque for improved quality
- Combination of
  - Plain-weave (PW) fibreglass 60 µm thick
  - Unidirectional carbon fibre 90 µm thick
- Mass = 80 g

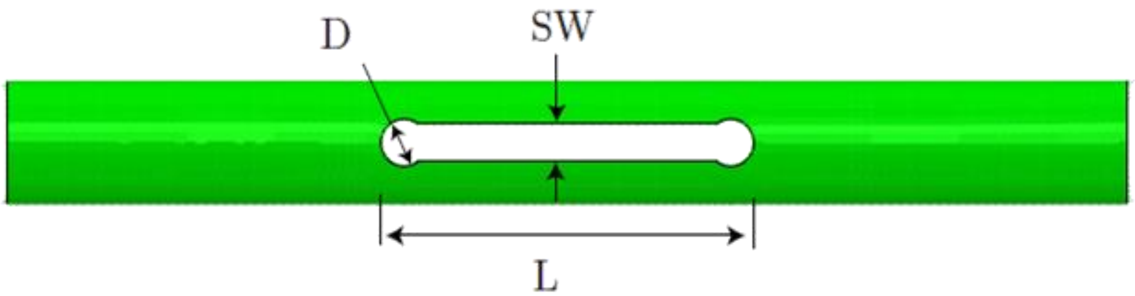


Boom Cross Section

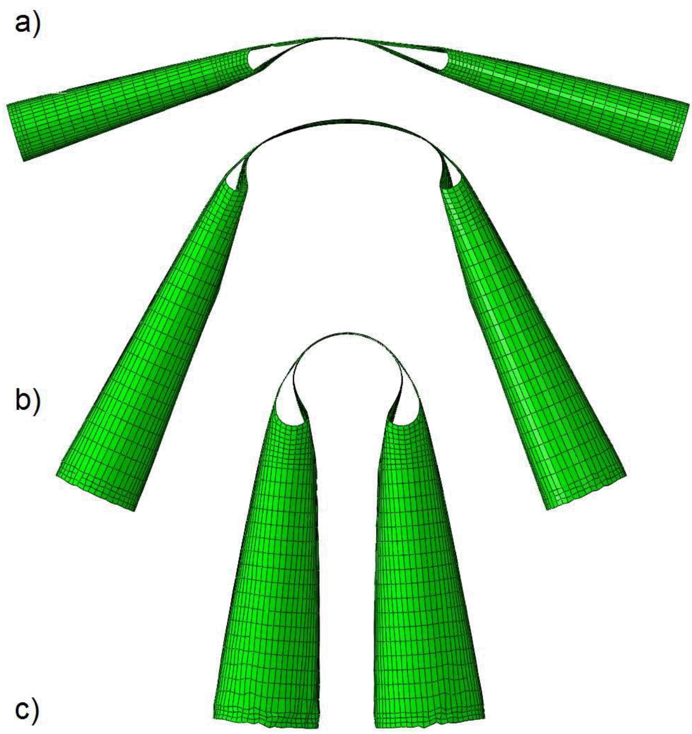


Hinge Design

- Extra 90° layup on outer side of hinge regions
- Dimensions
  - 210 µm total thickness
  - 38 mm diameter



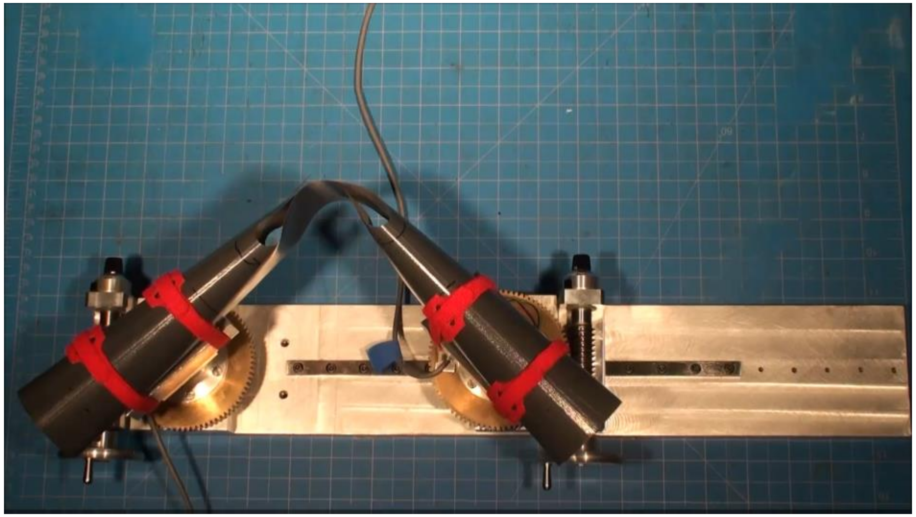
- Cutting pattern
  - "Dog-bone" hinge cutting pattern
  - D = 15mm, L=90mm, SW = 8mm
- Structural optimisation techniques used to develop design



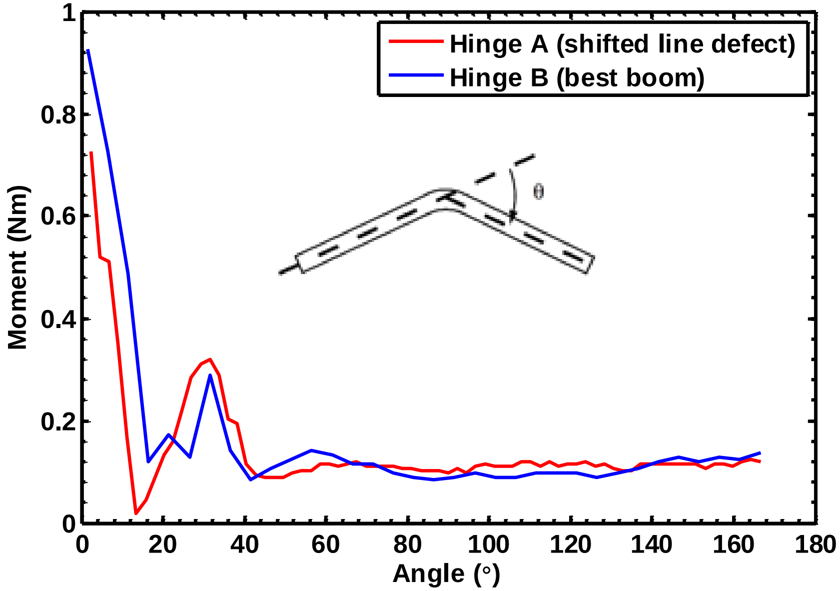
Based off of Mallikarachchi, H.M.Y.C. and Pellegrino, S. (2008-2012)

Hinge Characterization

- Characterized moment vs angle for individual hinges
  - Torque for each angle determined with strain gauges on mounts
  - Steady moment (~0.1 Nm) at large-fold angles
  - Moment less stable near snap-through



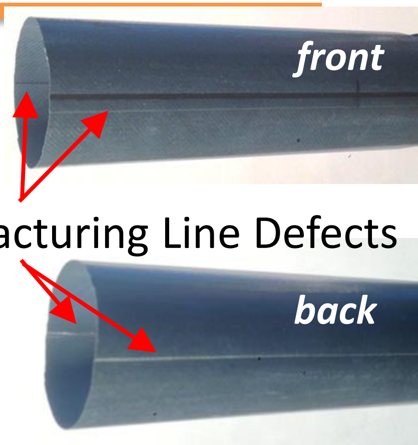
Hinge Test
[32x speed]



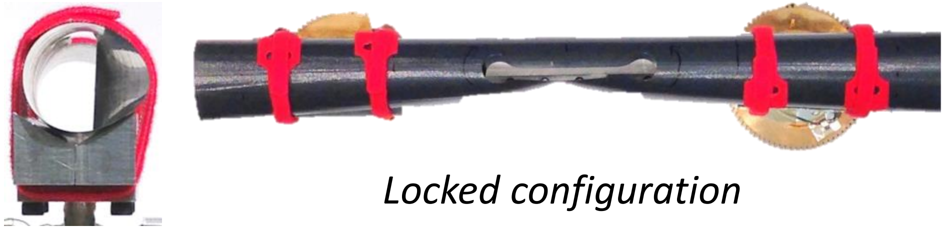
Moment-Angle Relation

Hinge Characterization

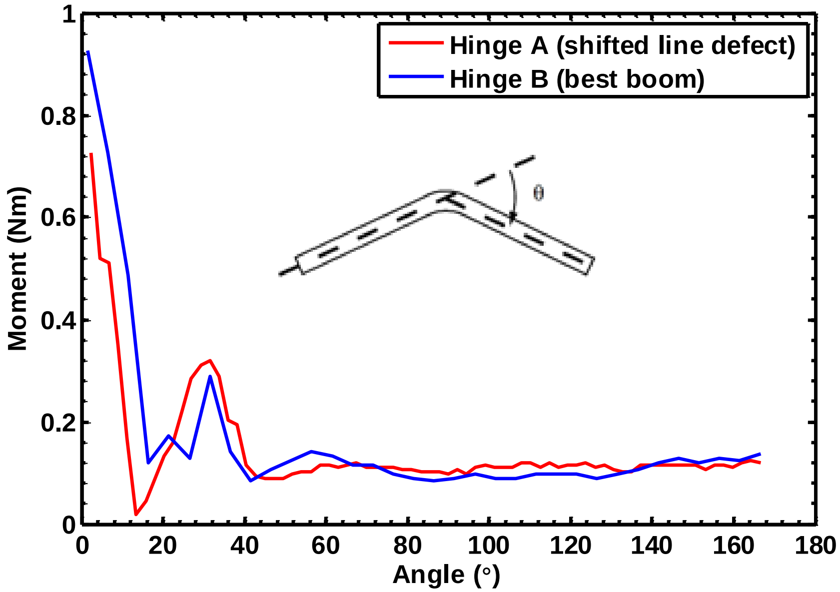
- Hinges locked before reaching deployed configuration
  - Quasi-static test
  - Some manufacturing defects in hinges tested – process now improved



Deployed configuration



Locked configuration



Moment-Angle Relation

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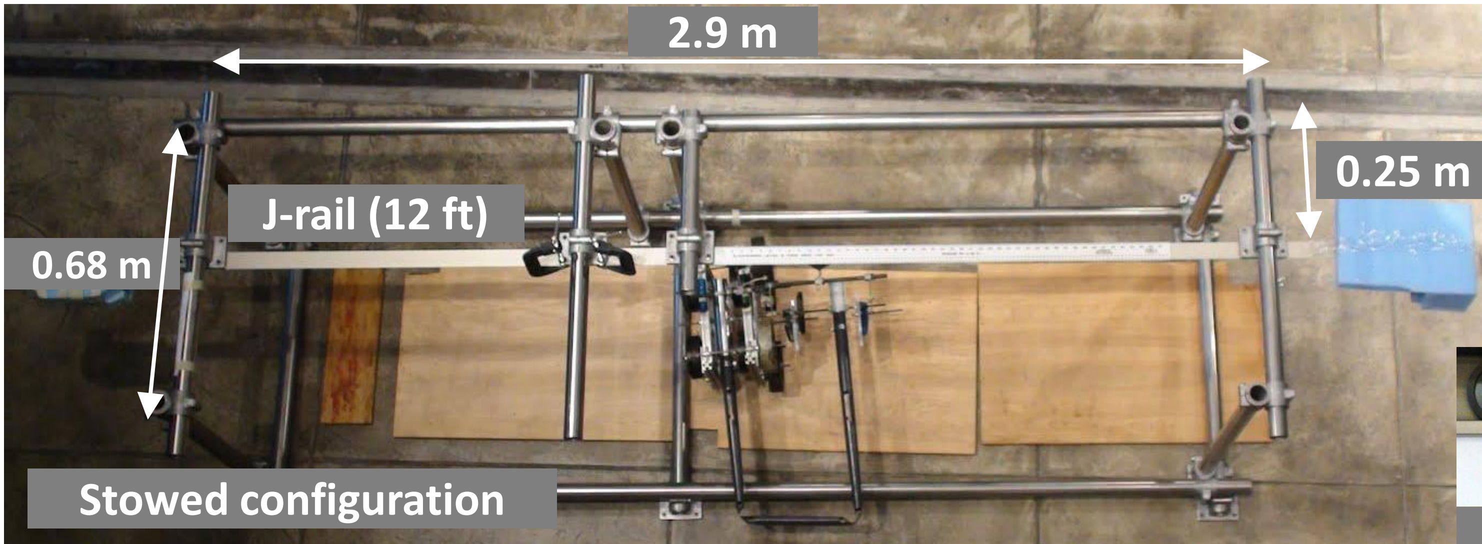
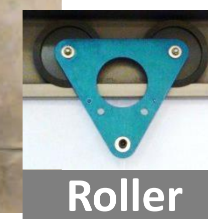
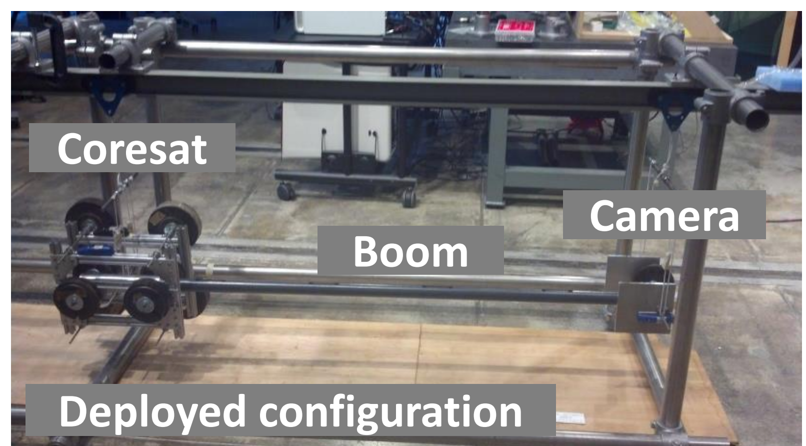
Dynamic Stage 2 Deployment Test

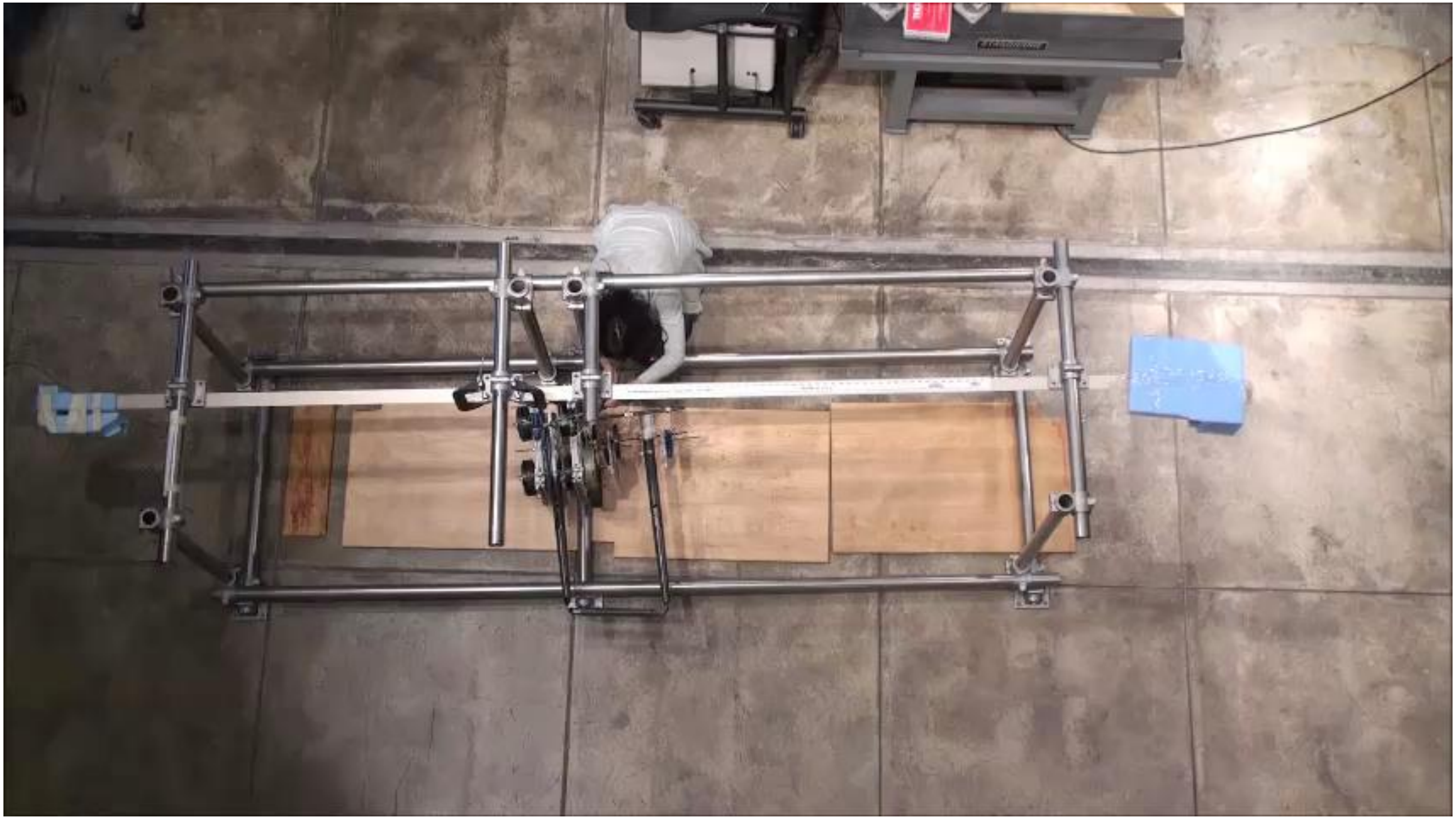




- Gravity offload setup used to test stage 2 deployment
  - Determine if deployment needs to be controlled
- Representative masses (4kg & 30kg) suspended from J-rail – can rotate freely
- Accelerometers attached to masses measure shocks



Dynamic Stage 2 Deployment Test



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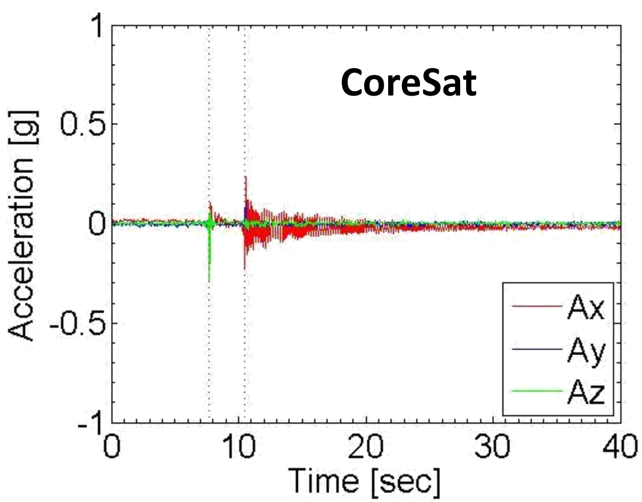
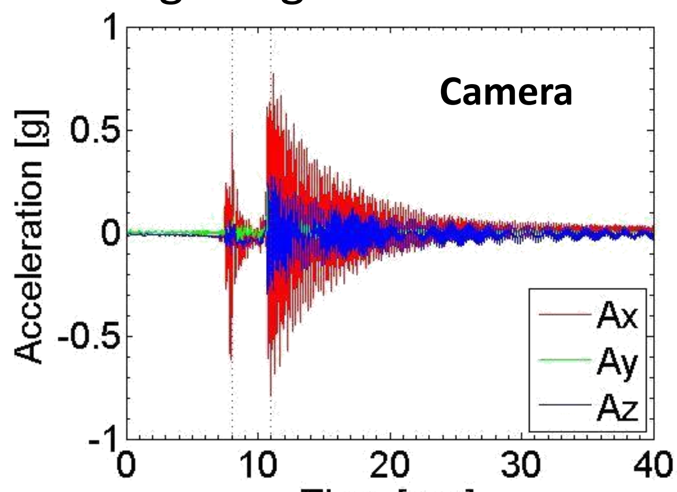
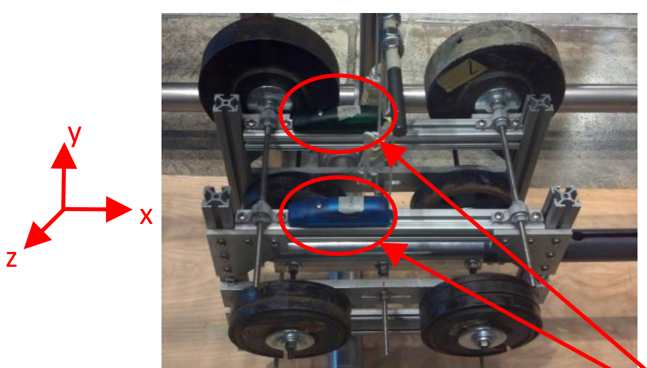
Stage 2 Deployment Test Results

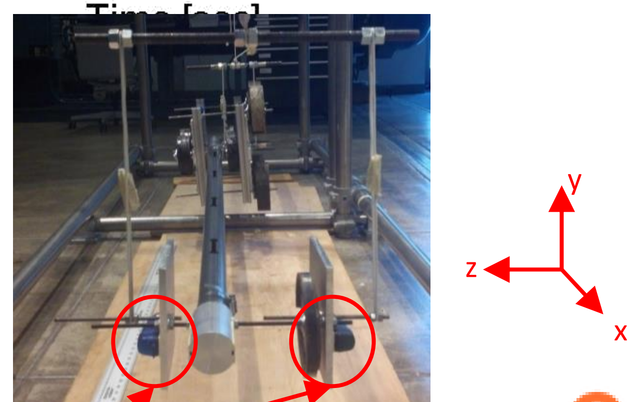
- Low accelerations compared to those experienced during launch
  - Boom had axial line defects – may reduce accelerations slightly
  - Ie, Delta IV rocket load factors -2g to 6g





Stage 2 deployment lasts 7s





Accelerometers

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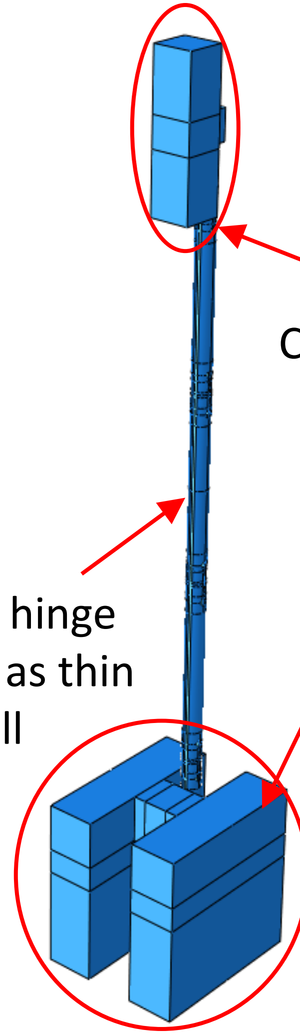
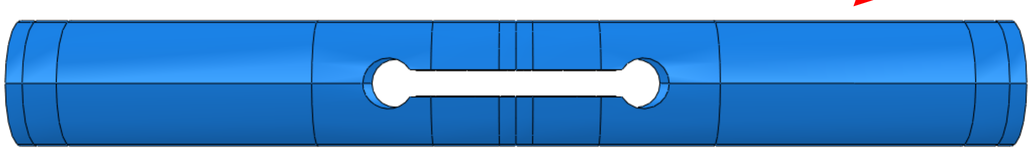
Stage 2 Finite Element Simulation

- Abaqus/Explicit used to model stage 2 deployment process
  - Reduces number of gravity offload tests needed
  - Used to estimate failure margins
- Simulation first folds boom then allows unconstrained deployment
- Work in progress





Single Hinge

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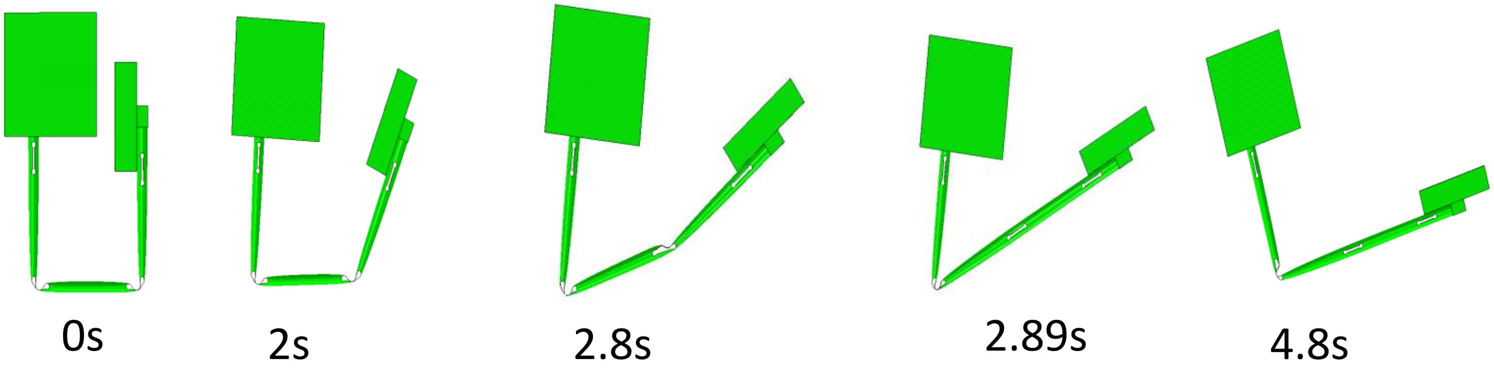
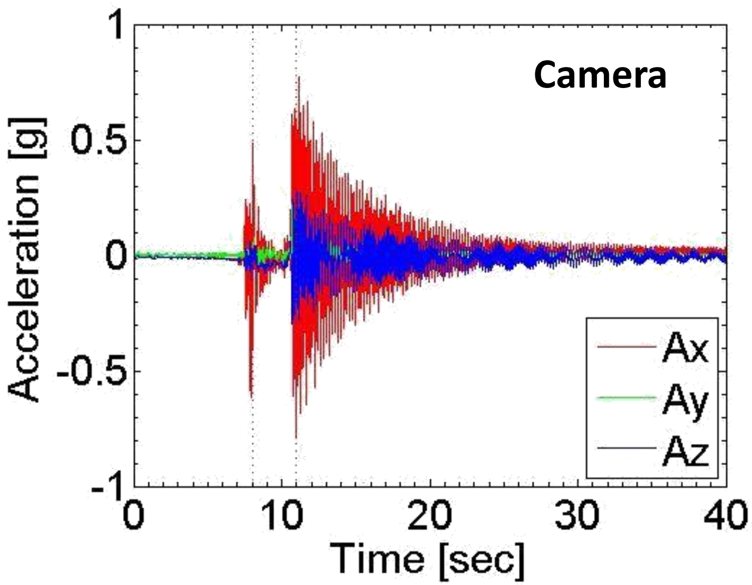
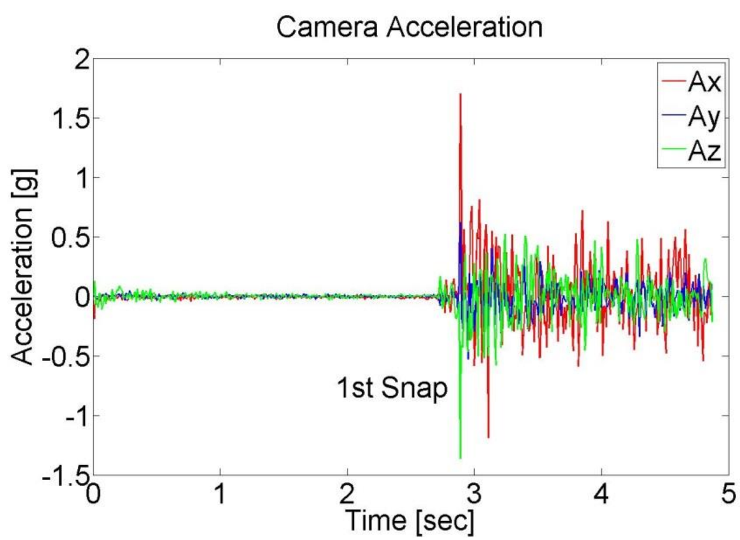
Preliminary FEA Results



Shock G's similar to experiment



Experiment - First latch at 2s



Simulation - First latch at 2.89s

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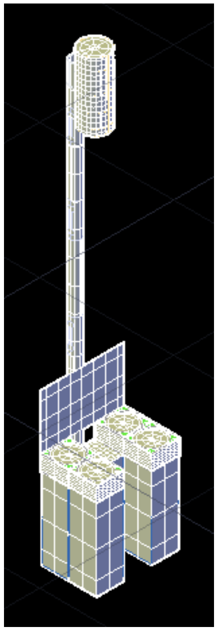
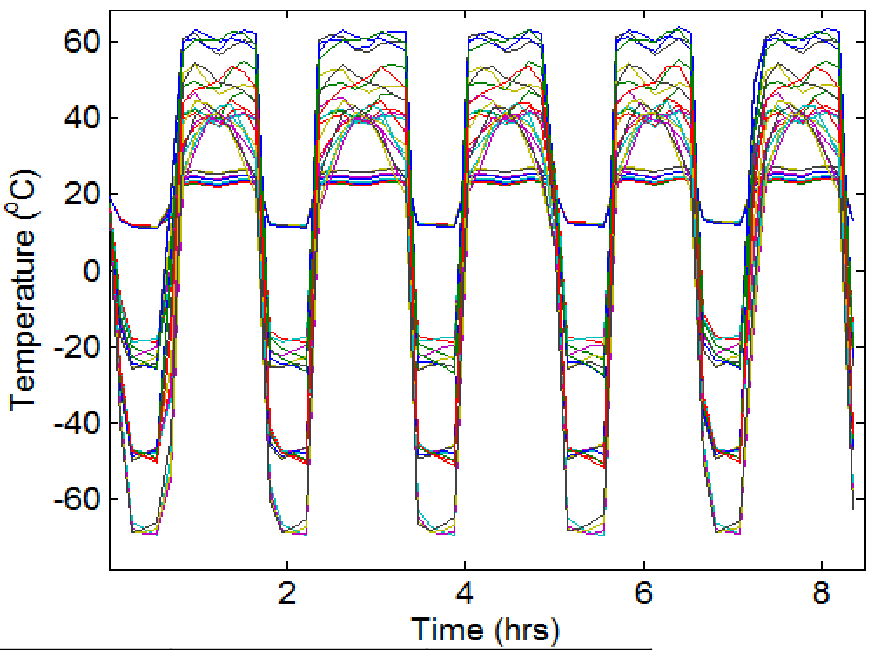
Simulated Thermal Profile Summary



Boom nodal temperatures over multiple orbits



- Assumed sun-sync orbit (11am – 11pm)
- Software: Thermal Desktop
- Nodes plotted are uniformly distributed across boom surface – boom painted black
- Deflections are stable for approximately half the orbit

Case	Axial Deflection	Lateral Deflection	Rotation
Hot	25 µm	625 µm	0.04°
Cold	-127 µm	97 µm	0.006°
	< 500 µm	< 2 mm	

Boom CTE	
Axial	~ 1.0 ppm/°C
Circum	21 ppm/°C

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Boom Interfaces

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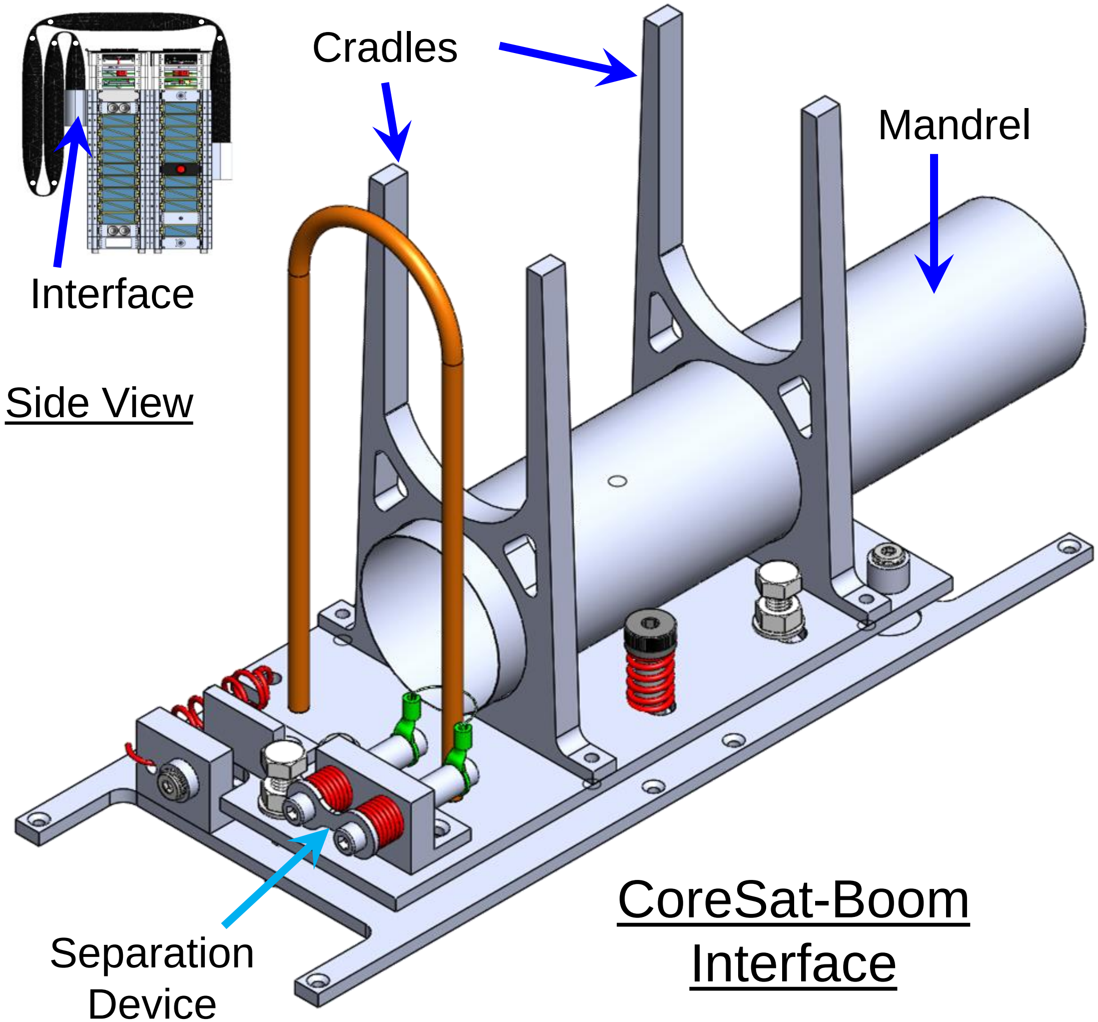
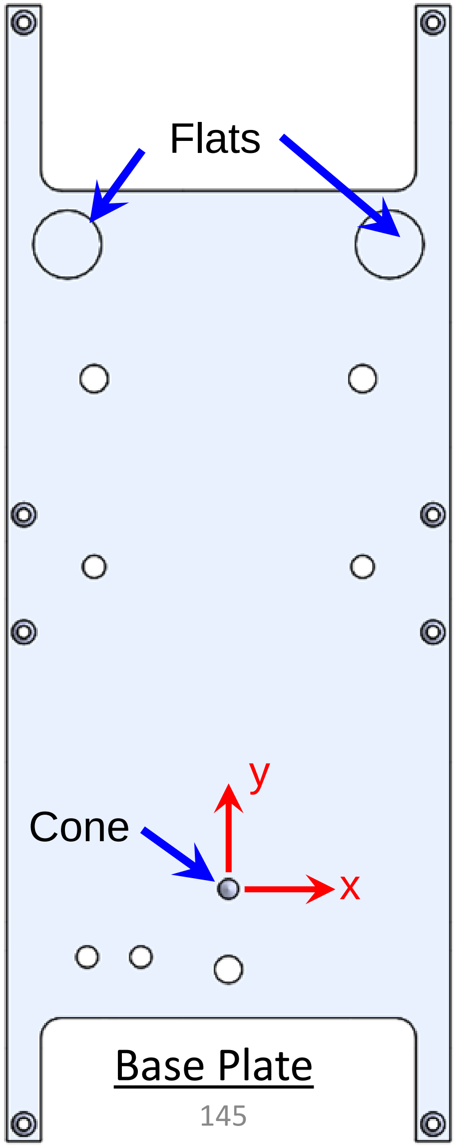
CoreSat-Boom Interface



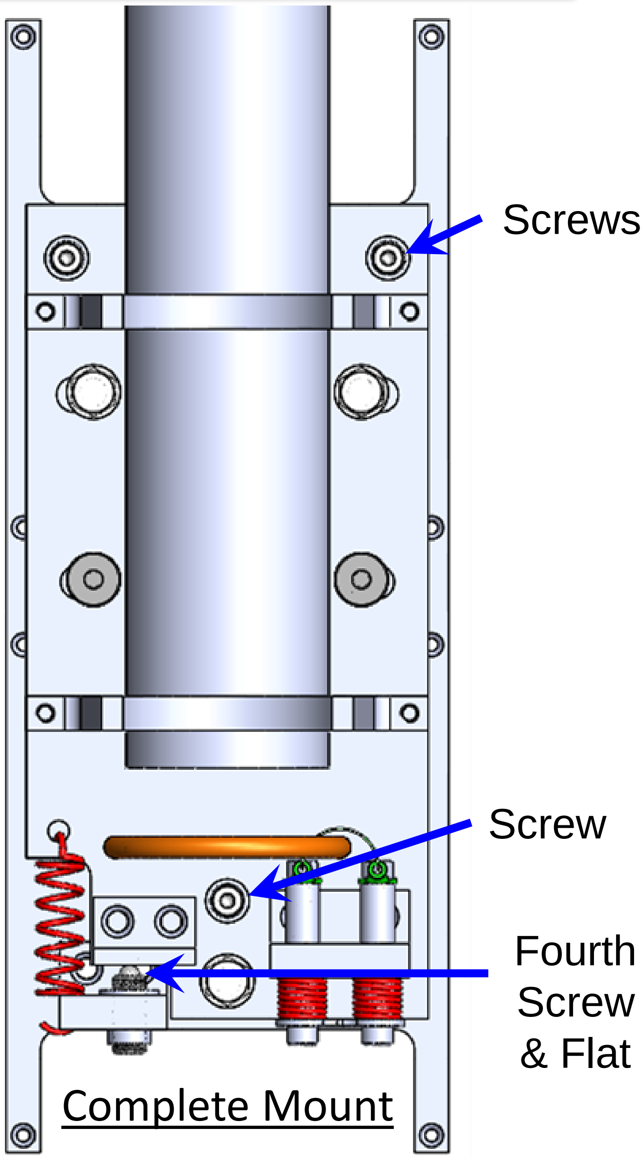
- Boom bonded on to mandrel
- Features
  - Cradles support boom during launch
  - Kinematic mount
    - For boom alignment during assembly
  - Stage 1 separation device
- Camera mount similar but more compact & no separation device

Kinematic Mount

- Components
  - 4 ball tipped screws
  - 3 flats
  - 1 cone
  - 3 screws on base plate control rotation about x, y
  - 4^{th} screw controls rotation about z
- Clamping Method
  - Two springs hold plates together during alignment
  - Three nuts hold plates together after alignment



Base Plate



Complete Mount

Kinematic Mount

- Components
  - 4 ball tipped screws
  - 3 flats
  - 1 cone
  - 3 screws on base plate control rotation about x, z
  - 4th screw controls rotation about y
- Clamping Method
  - Two springs hold plates together during alignment
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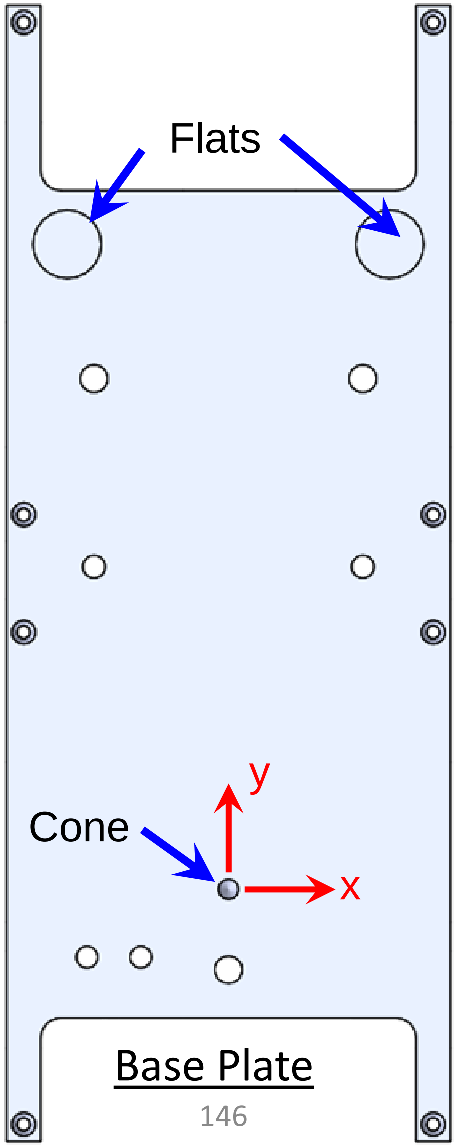
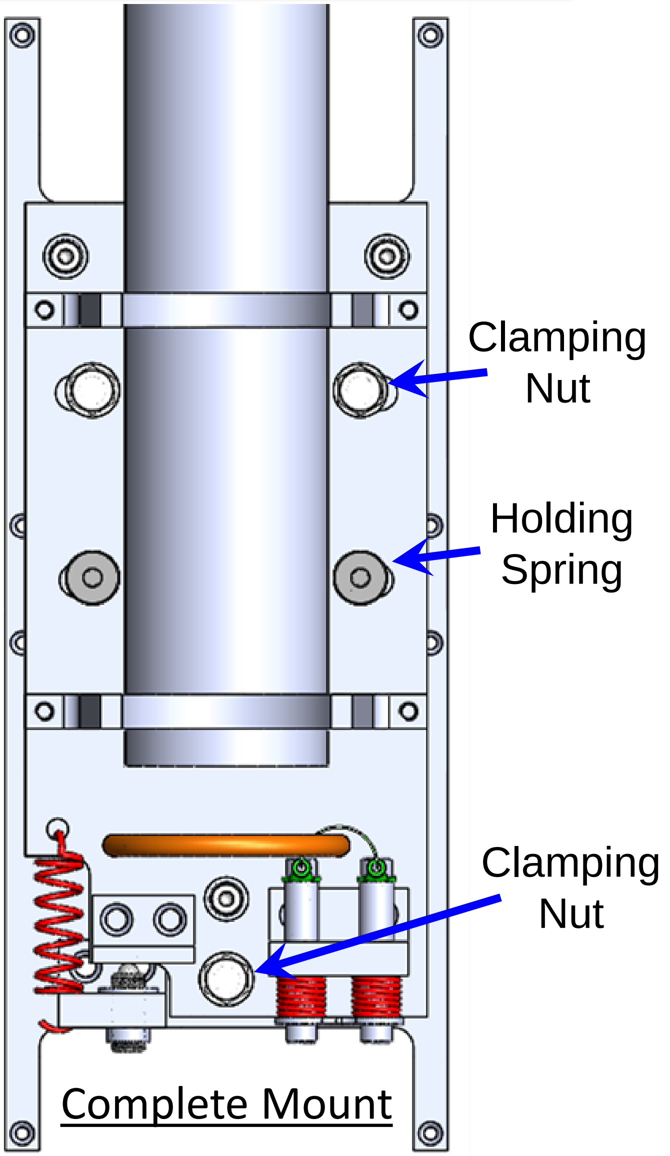


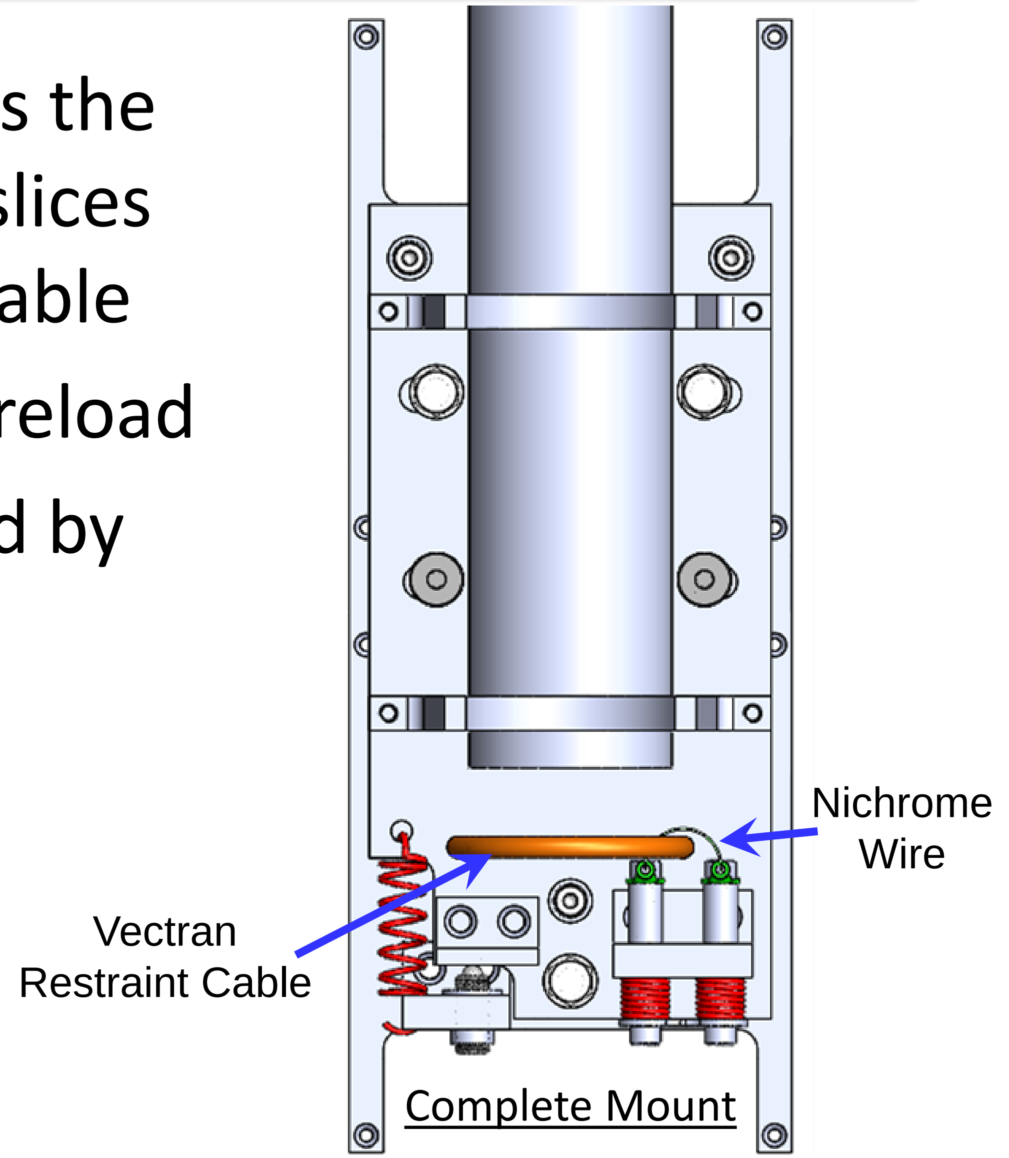
Base Plate



Complete Mount

Separation Device

- 1.60 ± 0.05 amps heats the nichrome wire which slices the vectran restraint cable
- Two springs provide preload
- Based on design tested by NRL*



**A Nichrome Burn Wire Release Mechanism for CubeSats* by Thurn et al.

Future Work

- Prototype testing is needed for:
  - Stage 1 burn wire cutting release mechanism
  - Shake test for boom alignment & survivability
    - Will determine if additional cradles / damping material is needed to support boom in launch configuration
    - Confirm dimensional accuracy needed from kinematic mount is attainable
- Redo stage 2 deployment tests with final boom layups
  - Integrate boom cabling into the tests

Future Work

- Utilize cyanate ester resin in boom
  - Improved thermal properties
  - Low outgassing
- Quantify viscoelasticity of boom material
- Monitor damage of hinges due to multiple folding/deployment processes

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   < Coffee Break>
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   g) Telescope Breadboard/Test (Marie)
4. Summary & wrap up (15 mins)

Please send comments to Dr. Greg Davis (Gregory.L.Davis@jpl.nasa.gov)

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Telescope System Modelling

Lee Wilson, Marie Laslandes

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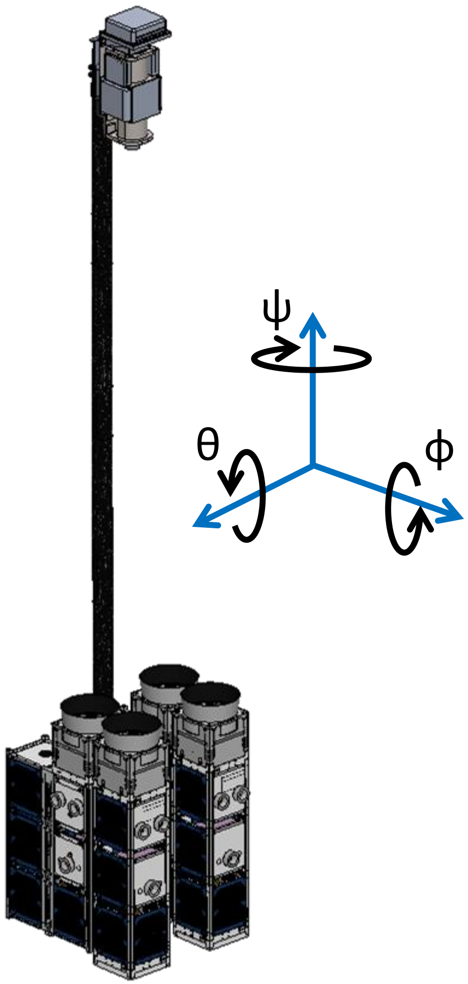
Dynamic Pointing Control

- MATLAB Simulink model of S/C control system was developed
  - Prove pointing requirements can be met with given reaction wheel disturbances
  - Only example control system – Surry with implement actual system
  - Assume optical axis = principle S/C inertia axes
- Requirements
  - Camera jitter from pixel size and exposure time: $d\theta/dt, d\phi/dt < 0.02\ ^\circ/s$
  - Image remains on detector during calibration: θ, ϕ constant to within 0.1° for 600s



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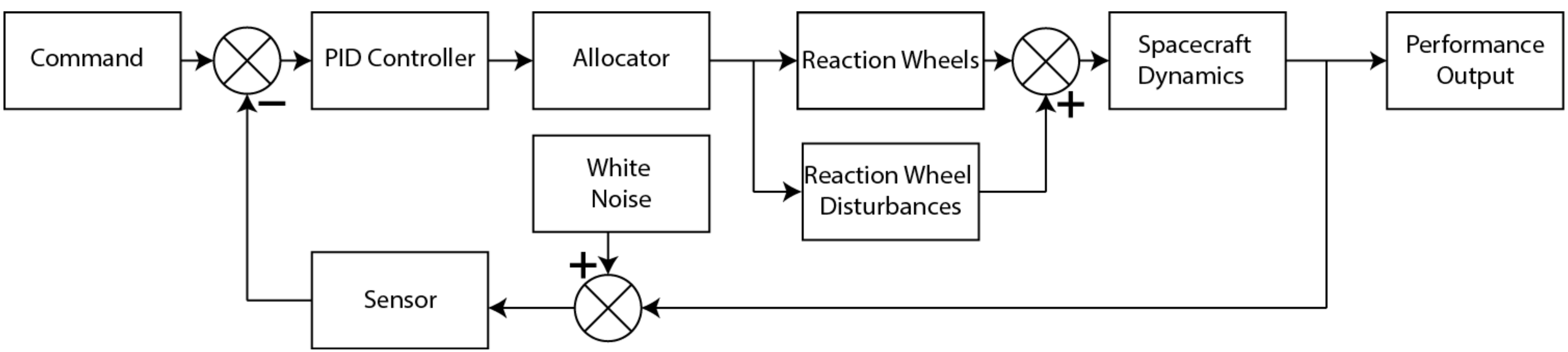
Control Loop

- PID Controllers – Determine required torque on S/C from orientation, angular velocity
- Allocator – Uses psudo-inverses to distribute torque to four RWs
- RW disturbance torque calculated from wheel speed
- Spacecraft Dynamics - Torques combined & new S/C and Camera positions, angular velocity calculated
- Sensor – White noise can be added to estimated position knowledge then fed back to the PID controllers



Block representation of evaluation tool

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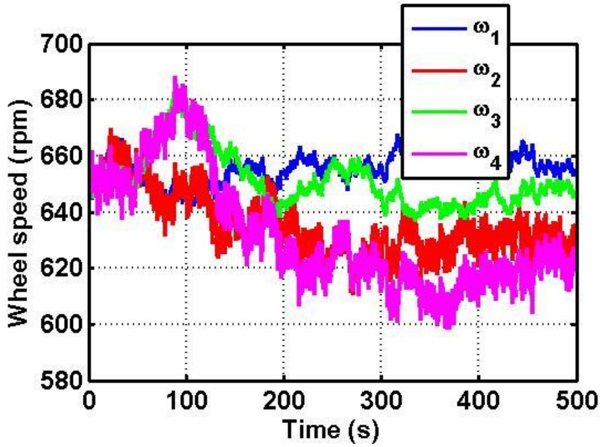
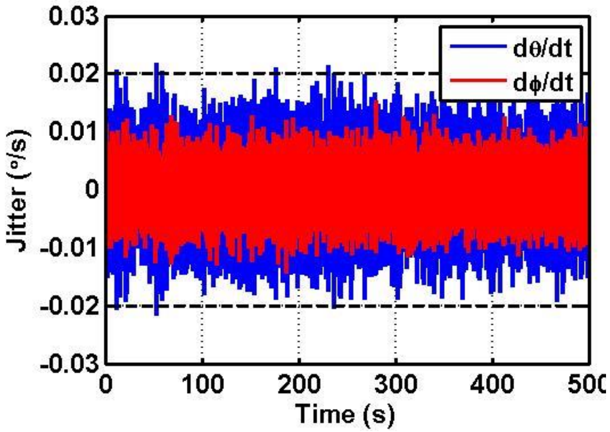
Dynamic Pointing Results

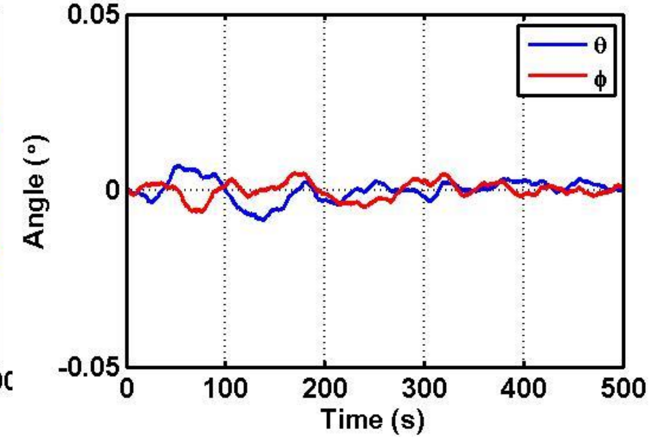
- Version 1 unbalanced RW prototype had disturbance amplitude of F = 11 μNm/Hz^2*ω^2
  - Assume here 1.1 μNm/Hz^2
  - Estimate wheels will operate at < 650 rpm during imaging
- Sensor (ie, MEMS gyro) noise – assume white noise with variance 3.5e-4 rad^2
- System meets requirements with these assumptions



RW Speeds



S/C Jitter (< |0.02| °/s)



S/C Orientation (< 0.1° for 600s)

Telescope closed loop modeling

- Objective: validate optical performance and control concept
- Modeling of a 1 segment telescope, on axis observation at 540 nm
- Code V + Matlab + Abaqus for an end to end simulation
  - Inject a set of perturbations into optical model (Monte Carlo)
  - Ray trace: degraded performance
  - Compute correction commands and inject into optical model (5 iterations)
  - Ray trace: corrected performance
- Statistics on 500 Monte Carlo trials give the expected performance of the telescope

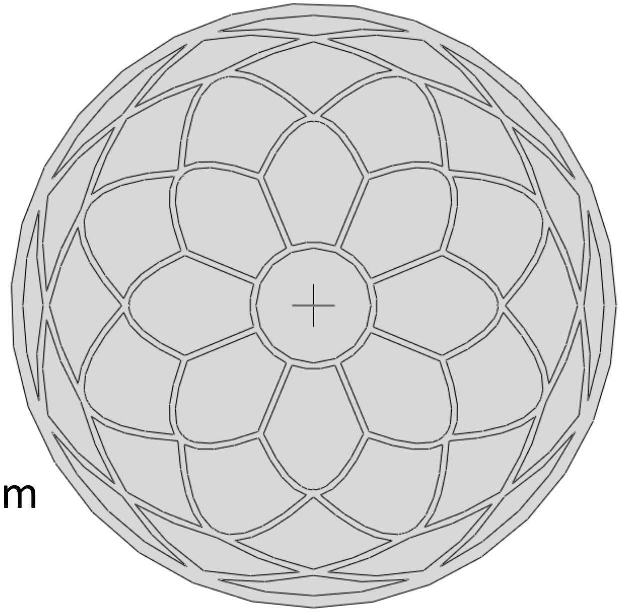
Injected errors

- Mirror initial shape error (< 4.5 µm RMS)
  - Off-axis shape generation + manufacturing errors correction
  - Defined by set of Zernike (Z4-66)
- Boom deflections (±0.04° / ±0.6mm)
  - Induce camera translation and rotation
- Thermal effects (±20°C)
  - Mirror curvature depends on temperature
  - Spacing between elements depends on temperature (CTE mismatch)

Correction loops

- Segment Rigid Body Motion
  - Segment Tip/Tilt (centering)
    - Control feedback: spot centroid position on focal plane
  - Segment Piston (focusing)
    - Control feedback: spot size on focal plane

- Deformable mirror shape (41 embedded actuators)
  - Control feedback: wavefront error on Shack Hartmann plane (177 measure points per segment)
  - Actuators influences from finite element model
  - Voltages computed with constrained least square algorithm (500 V limit) and applied with a 0.1 V resolution



AAReST deformable mirror Finite Element Model

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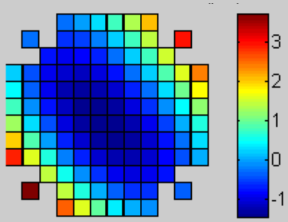
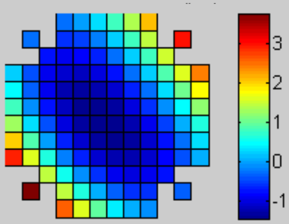
Example trial

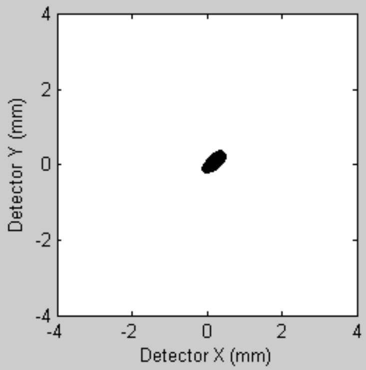
Initial error, measured on the Shack Hartmann



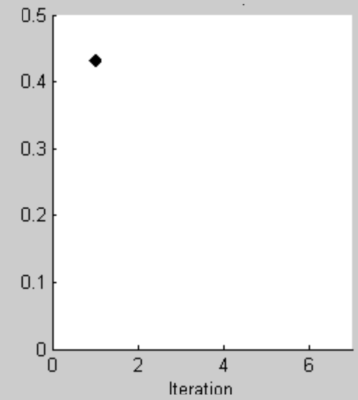
Error measured on the Shack Hartmann at each iteration



Spot on imaging detector

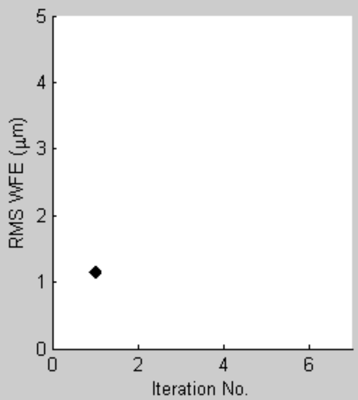


Spot size (µm)



Mirror voltages

WFE (µm RMS)



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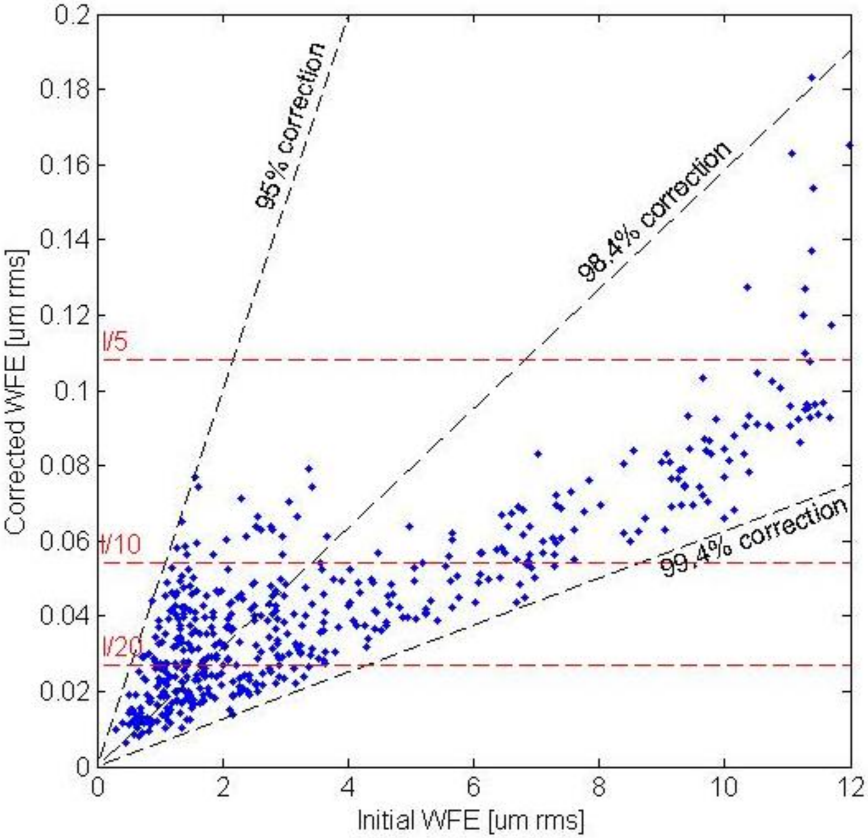
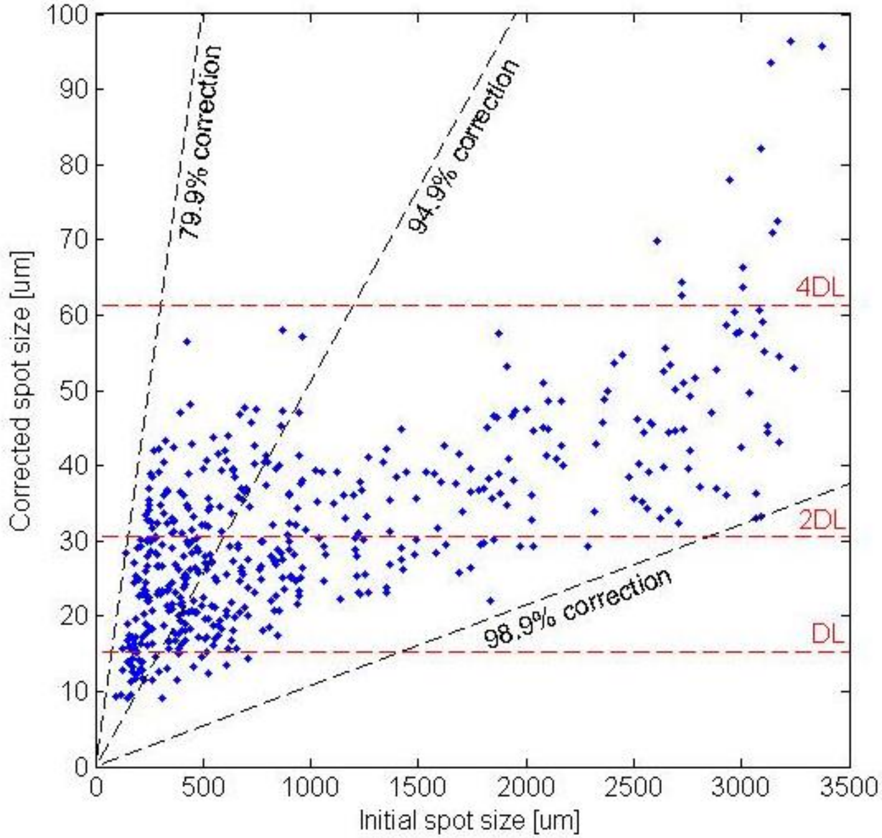
Telescope closed loop results

- Narrow configuration: performance meet requirements
  - Mean wave-front error: 43.5 nm rms ~ λ/10 RMS
  - Mean spot diameter (80% EE): 31.4 μm < 50 μm required





Telescope closed loop results

- Wide configuration: more challenging but acceptable
  - Mean wave-front error: 89.7 nm rms ~ λ/6 RMS
  - Mean spot diameter (80% EE): 69.0 µm slightly above requirement
- Conclusion
  - The system should be able to correct efficiently the expected errors
  - Validate optical design and control scheme
  - Validate chosen hardware
  - Validate requirements on the deformable mirror initial shape error

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Telescope system Breadboarding

Marie Laslandes, Manan Arya,
Eric Grohn

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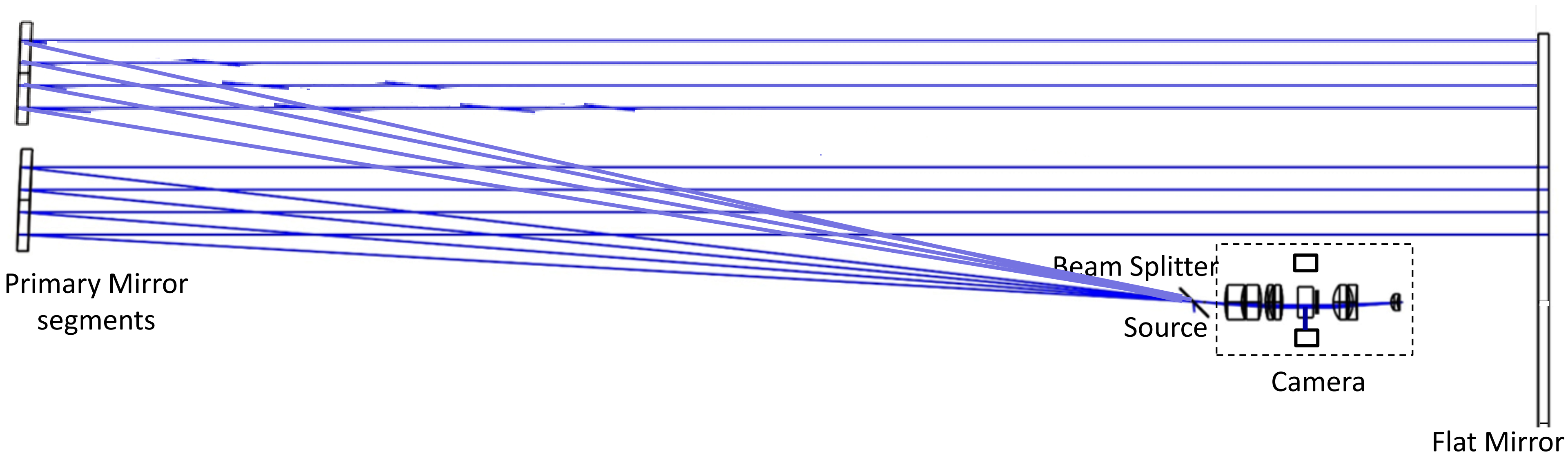
Objective

- Provide a set-up in which the different components of the telescope can be integrated and tested as a whole
  - Verify interfaces
  - Verify optical alignment
  - Verify calibration process
- Breadboard requirements
  - Simulate the interfaces between spacecraft and telescope
    - Mechanical, power supply, communication
  - Simulate the observation of a star
    - Feed the primary mirror segment with a large collimated beam

Optical design

- Auto-collimation technique to generate the collimated beam
  - Require a flat mirror of the size of the primary aperture
  - Pupil is divided in half in the Shack Hartmann plane
    => each half of the aperture can be tested independently
    => reduce the size of required flat mirror



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Implementation

Breadboard elements

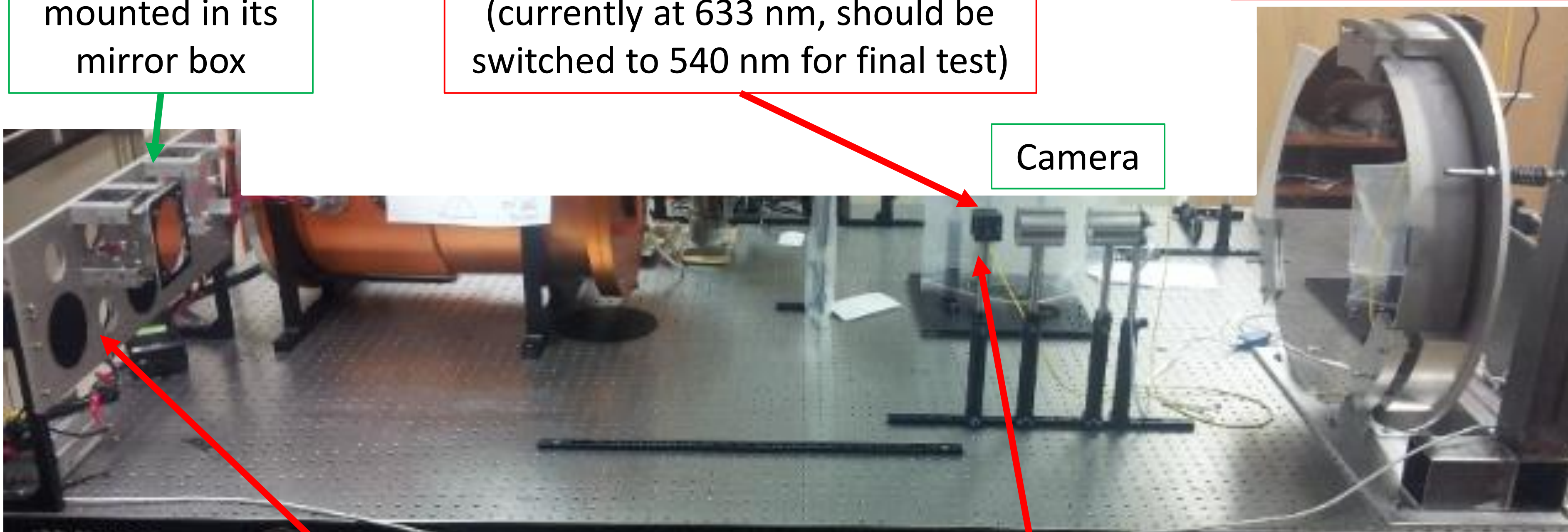
Telescope elements

Mirror Segment, mounted in its mirror box

Source (currently at 633 nm, should be switched to 540 nm for final test)

0.5 m diameter flat mirror, mounted on a tip/tilt plate

Camera

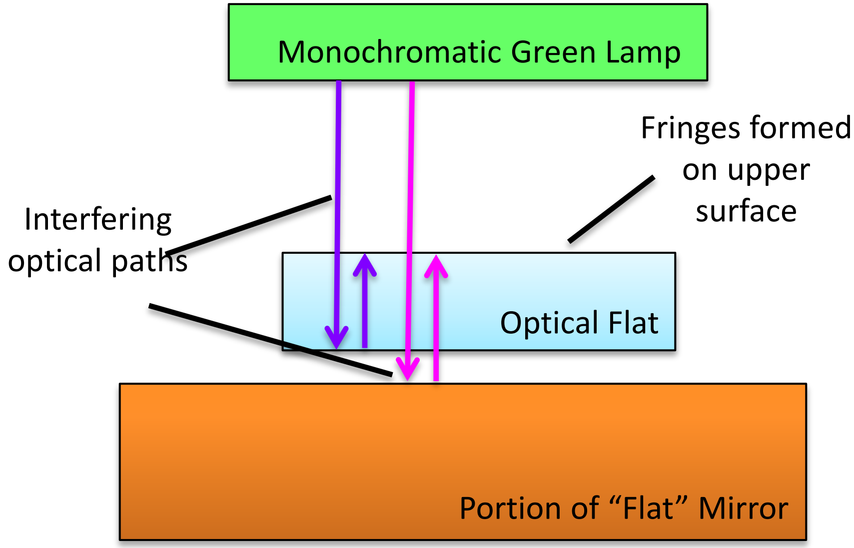


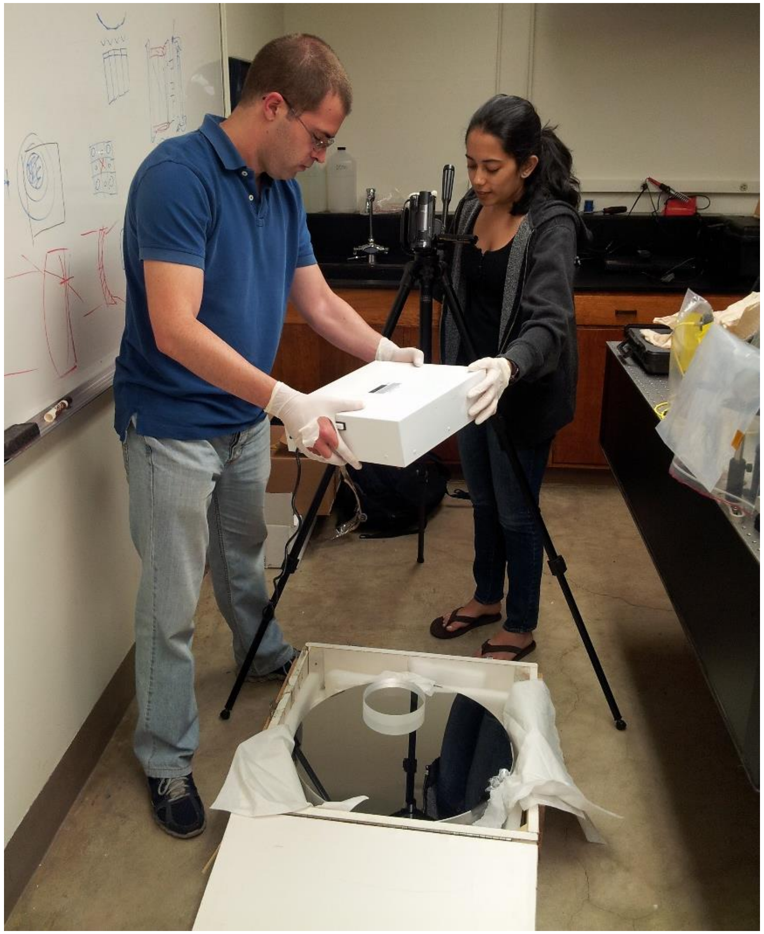
Spacecraft interface plate (representing mechanical interfaces between mirror boxes and spacecraft)

Pellicle Beam Splitter (minimizing aberrations)

Characterization

- Optical quality of flat mirror was unknown
  => Measurement through Newton fringes
- Fringes created between a 10 cm optical flat and the flat mirror surface
  - Distortion of the fringes compare to straight lines characterize flatness of the measured area





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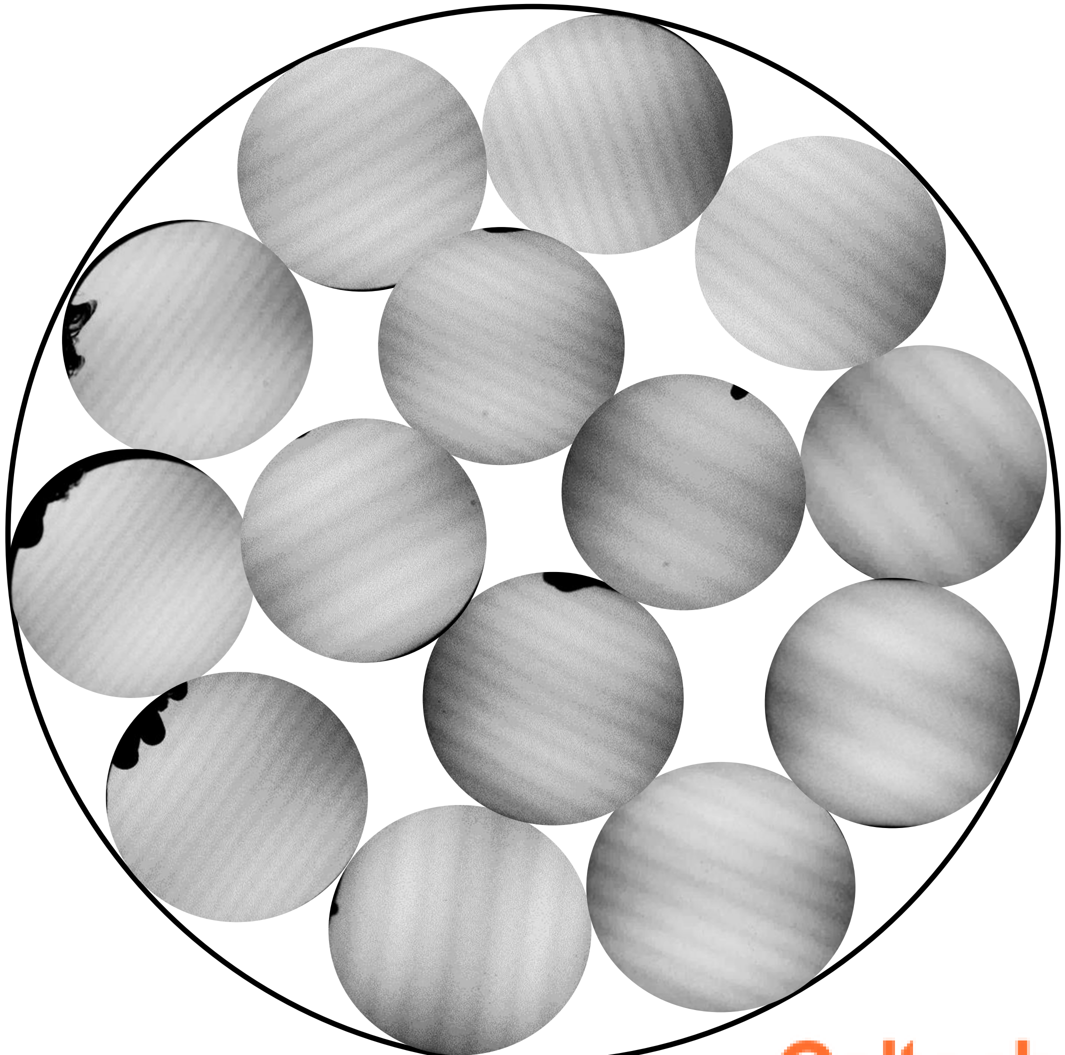
Characterization

- Measurements on different areas of the mirror
- Qualitative analysis: Fringes look straight everywhere => no obvious shape error
- Quantitative analysis with automatic image processing could be implemented if needed



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Breadboard Alignment

- Breadboard elements (Source, Beam Splitter and Flat Mirror) to be aligned first
- Alignment with a segment mirror in the reference position
  - Temporary segment : 100 mm diameter rigid spherical mirror mounted on mirror box

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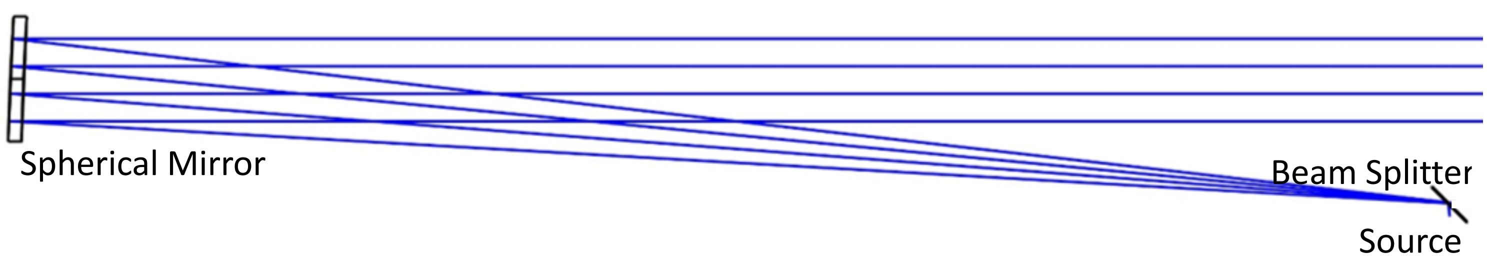
- Procedure
  - Set source and Beam Splitter on optical axis to illuminate segment
  - Set segment piston/tip/tilt to have a collimated beam with no tip or tilt



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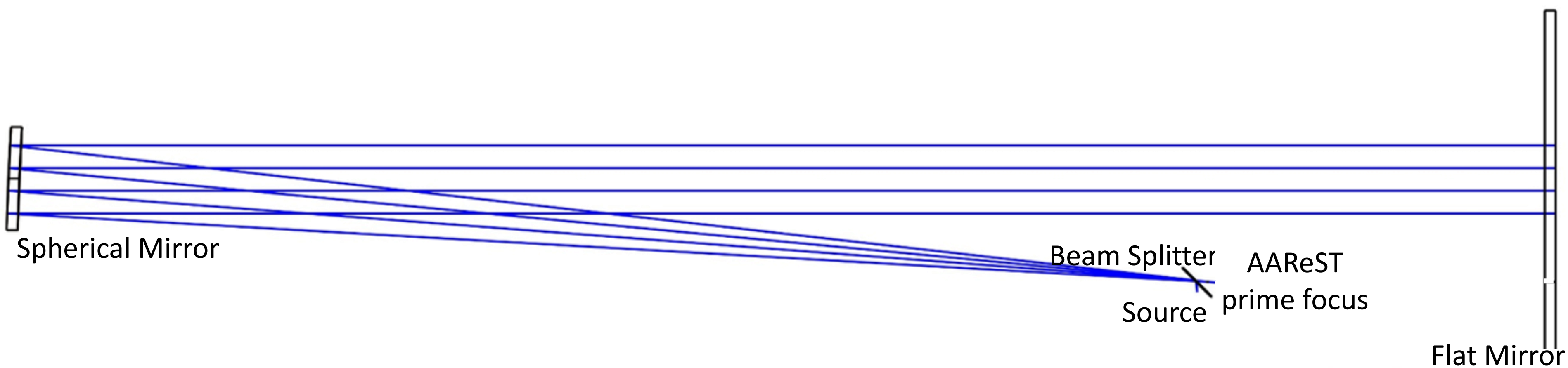
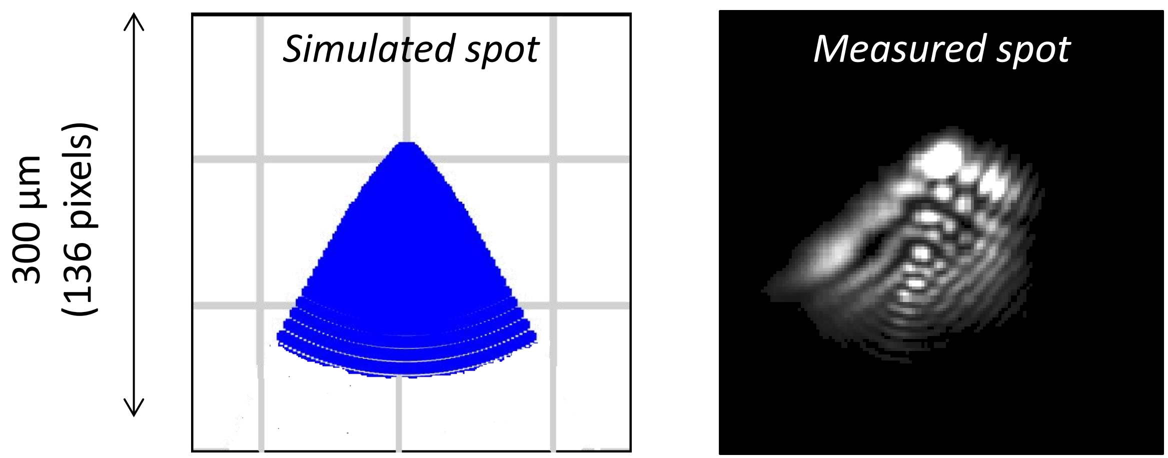
Breadboard Alignment

- Breadboard elements (Source, Beam Splitter and Flat Mirror) to be aligned first
- Alignment with a segment mirror in the reference position
  - Temporary segment : 100 mm diameter rigid spherical mirror mounted on mirror box
- Procedure
  - Set source and Beam Splitter on optical axis to illuminate segment
  - Set segment piston/tip/tilt to have a collimated beam with no tip or tilt
  - Set flat mirror tip/tilt to send back the beam onto the segment
  - Resulting focal point should be on the optical axis, at the camera entrance



Breadboard Alignment Validation

- Spot is measured at prime focus with the imaging detector and compared to optical model (ray tracing)
  - Expected spot size (80% EE): 90 μm
  - Measured spot size (80% EE): ~ 100 μm



=> Breadboard alignment is satisfactory for preliminary testing

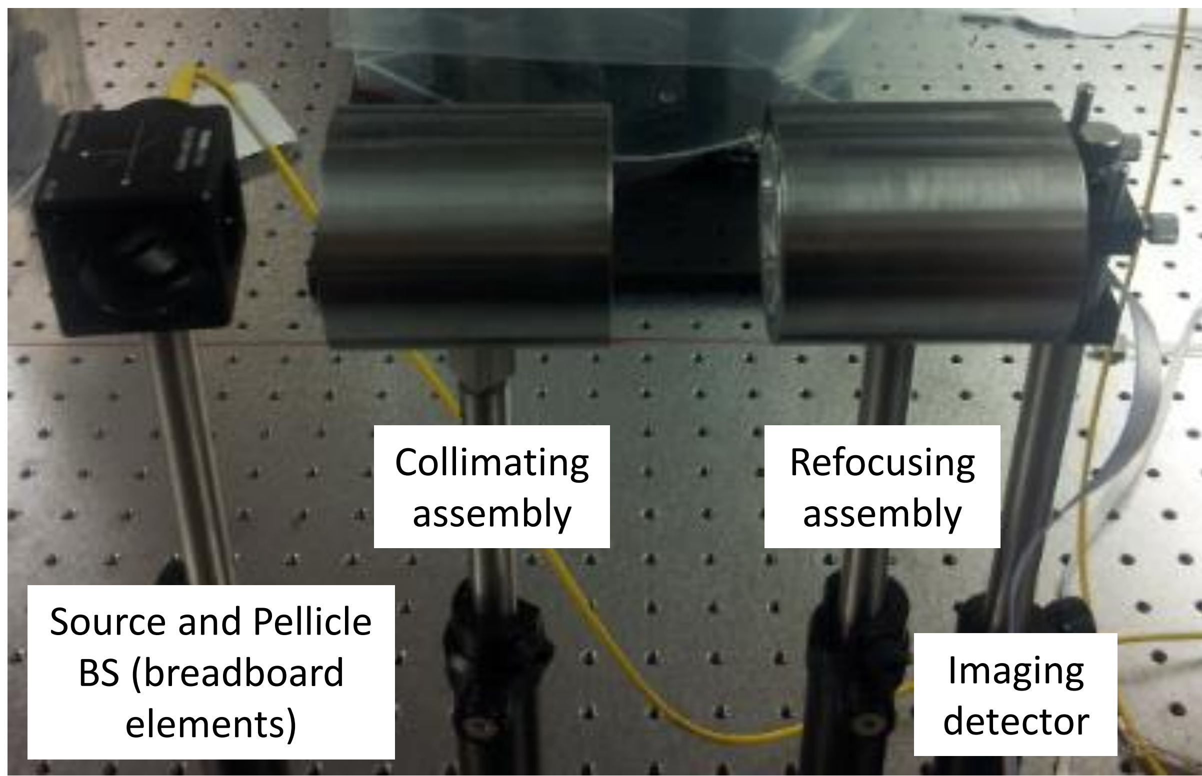
Telescope Integration & Tests

- Breadboard has been aligned with the 1st reference mirror
  - Once this is done, the breadboard elements should not be moved any more
  - The other AAReST elements are simply added

- Integration and Test plan
  - Breadboard alignment
  - Camera integration
  - Other segments integration
  - Optical performance validation
  - Functioning tests: inject error and run control loop
  - Boom integration
  - Check optical performance

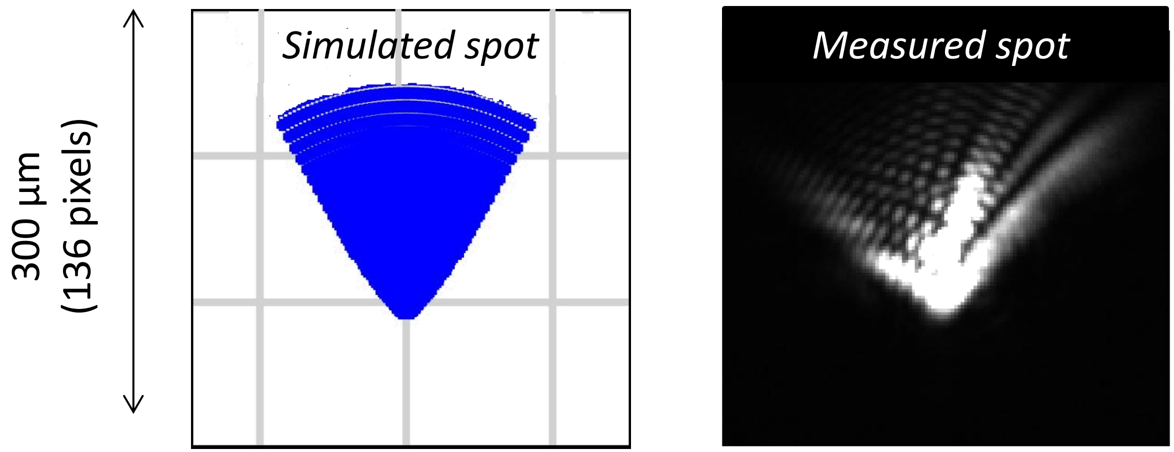
Camera on Breadboard

- Procedure
  - Insert collimating group according to prime focus
  - Insert refocusing group
  - Insert imaging detector
  - Insert cube beam splitter
  - Insert Shack Hartmann
- Degrees of freedom for each elements
  - Translation along optical axis
  - Height
  - Tip/Tilt
- Objectives
  - Minimize wave-front error on Shack Hartmann
  - Minimize spot size on imaging detector



Camera on Breadboard

- Validation with measured spot on imaging detector (compare to optical modelling)
  - Expected spot size (80% EE): 95 µm
  - Measured spot size (80% EE): ~ 110 µm



- When Shack-Hartmann implemented:
  measured and simulated wave-front error must be compared

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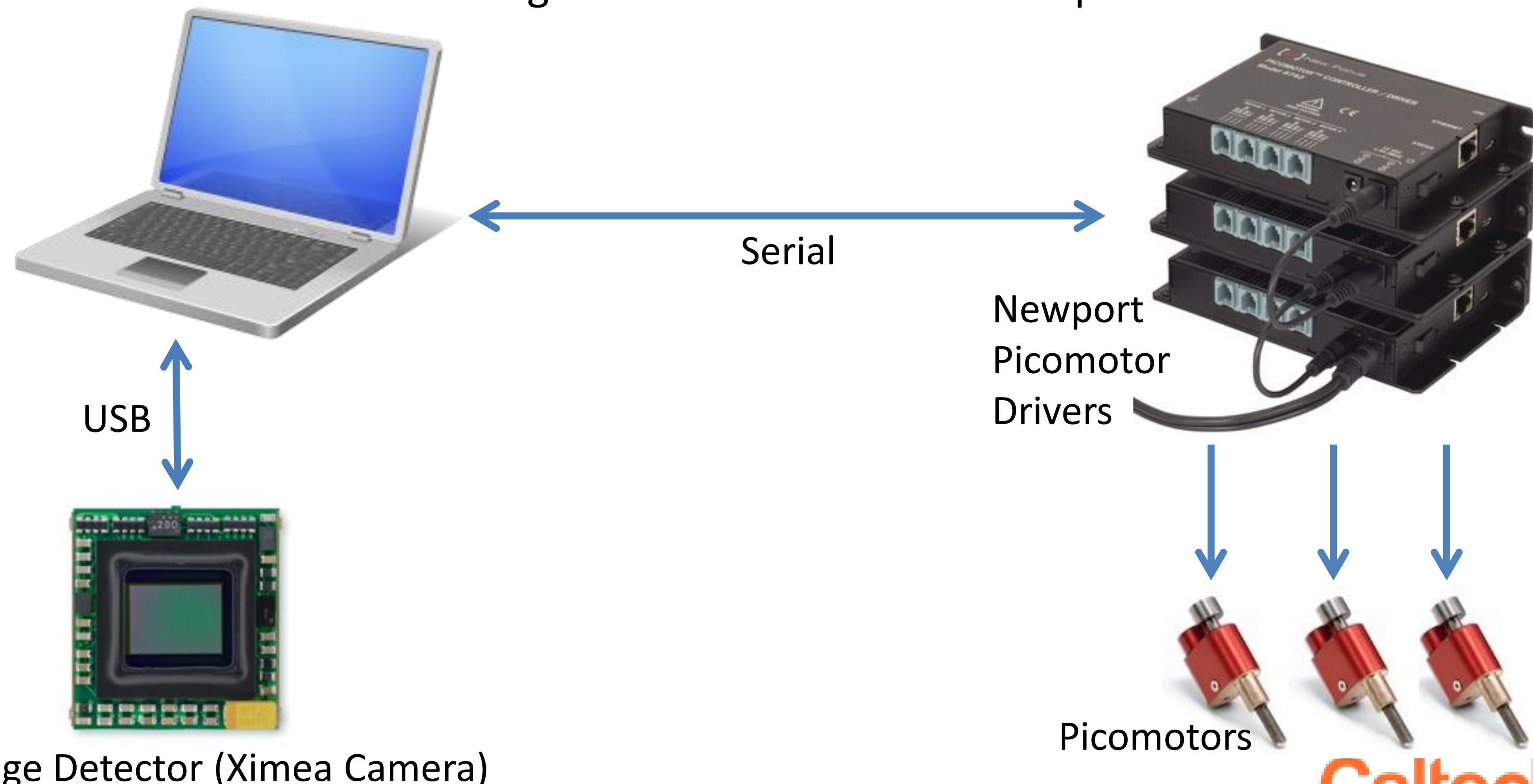
Other segments integration

- Only 2 segments can be tested in the same time (due to flat mirror size)
- Procedure
  - Mount segment on mirror box
  - Mount mirror box on interface plate
  - Set piston/tip/tilt using the imaging detector measurement (blind search, centering and focusing algorithms)
  - Set shape of deformable mirror using the Shack-Hartmann measurement (shape control algorithm)
- Validation: measurement vs breadboard optical modelling
  - Spot measured on imaging detector and wave-front error on Shack-Hartmann
  - Will validate both optical alignment and control functioning

Rigid Body Motion control

- Test of the blind search and centering algorithms on the breadboard
- Use of off-the-shelf hardware for communications between elements
- Current breadboard configuration for RBM control loop:



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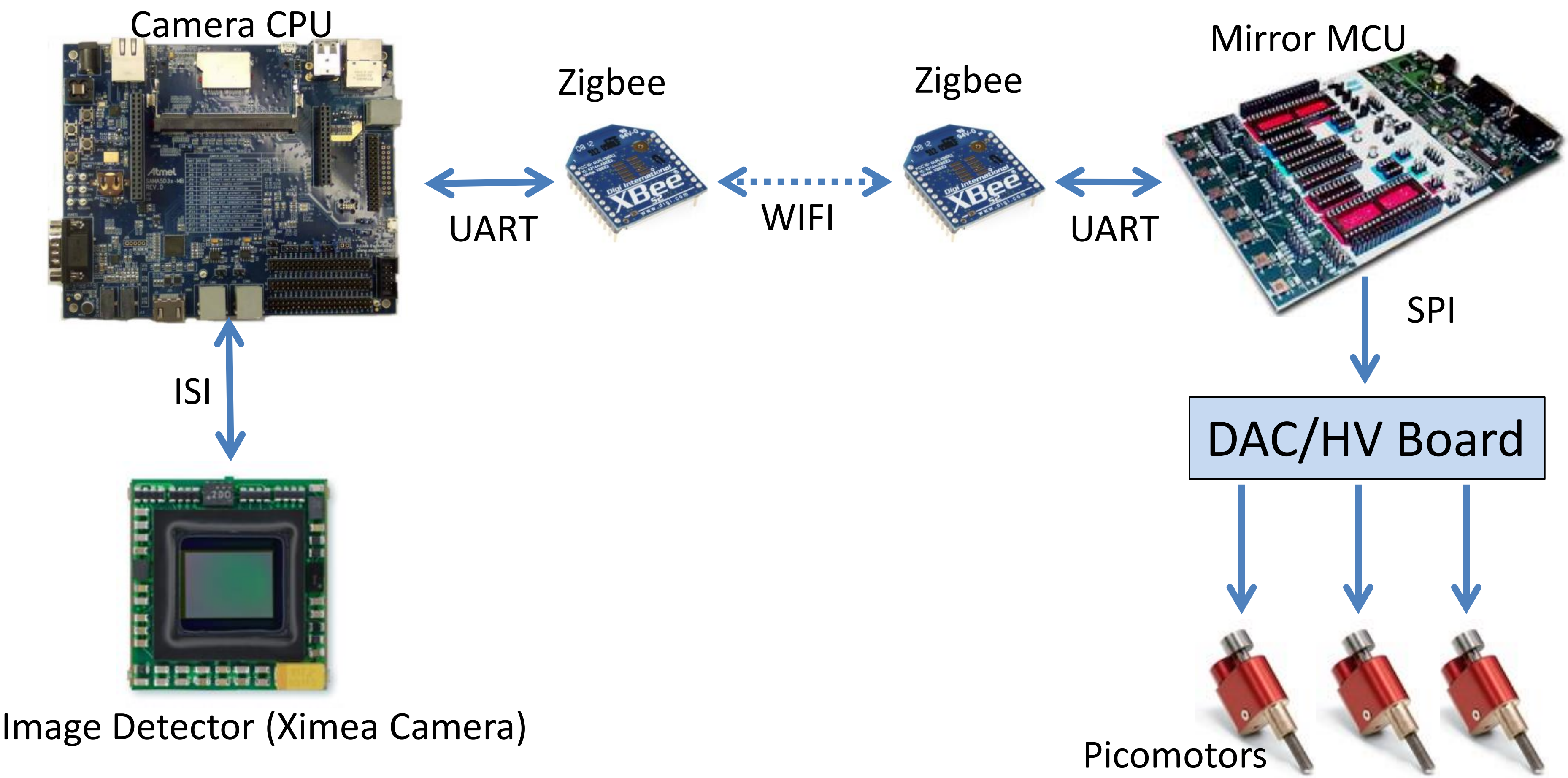
Rigid Body Motion control

- Hardware will gradually be switched to a flight-like configuration:



RBM control loop - results

- Test performed with one spherical segment on the aligned breadboard
- Introduce an error: manually piston, tip and tilt the segment
- Run the algorithms => spot come back at the same position with same optical performance
- Focusing algorithm still to be implemented

Conclusion

- Breadboard assembled and validated
  - Integration and test plans developed
  - Alignment procedure validated with a rigid spherical mirror
  - Algorithm for Rigid Body Motion control validated with the current hardware and a single segment
  - To be modified: source wavelength (to 540 nm) and spherical mirror (to off-axis parabola)

- Next steps
  - Integrate a second segment and validate control algorithms
  - Integrate Shack-Hartmann in camera to validate alignment

- Breadboard is now functional and characterized. It will gradually be modified to a flight-like version of the telescope

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Plans for Next Year

John Baker

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Plan for next year

- Operate prototype deformable mirrors over a range of temperatures
- Complete the camera optical testing
- Operate and test the telescope optical breadboard
- Complete camera electronics design
- Prototype the camera electronics and mirror controller and integrate
- Run optical testbed with prototype electronics
- Boom testing and flange mount prototype testing

- Will be refined with the AE105 class instructors (Davis, Freeman, Scharf)