Ae105 Final Presentation

AAReST:
Autonomous Assembly of a Reconfigurable Space Telescope

1 June 2015

AAReST Mission Overview

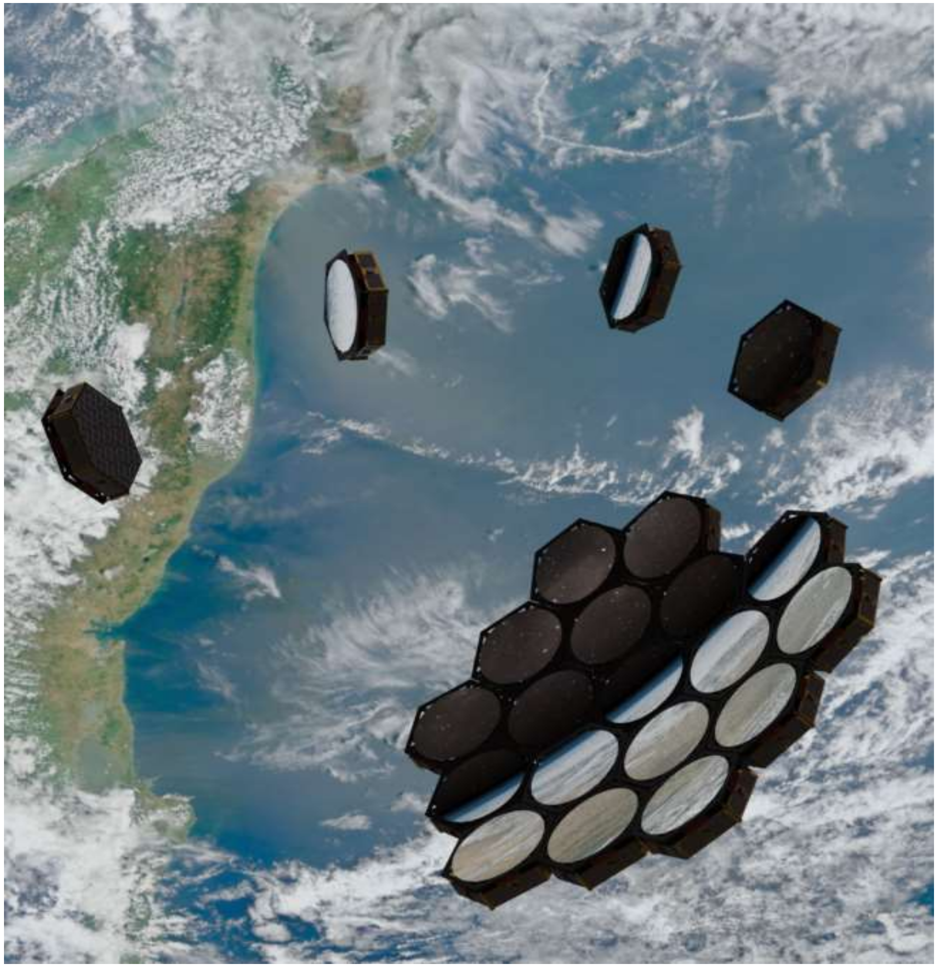
Manan Arya

Building Large Space Telescopes

- Mirror dia. of current and planned space telescopes limited by constraints of a single launch
  - Hubble (1990): Ø 2.4 m
  - JWST (2018): Ø 6.5 m
  - ATLAST (2020+): Ø 8-16 m

- New paradigms needed for Ø 30 m+ segmented primary:
  - Autonomous assembly in orbit
  - Active ultralight mirror segments

- Active mirrors relax tolerances for assembly and manufacturing, correct thermal distortions
- Modular, robust, low-cost architecture



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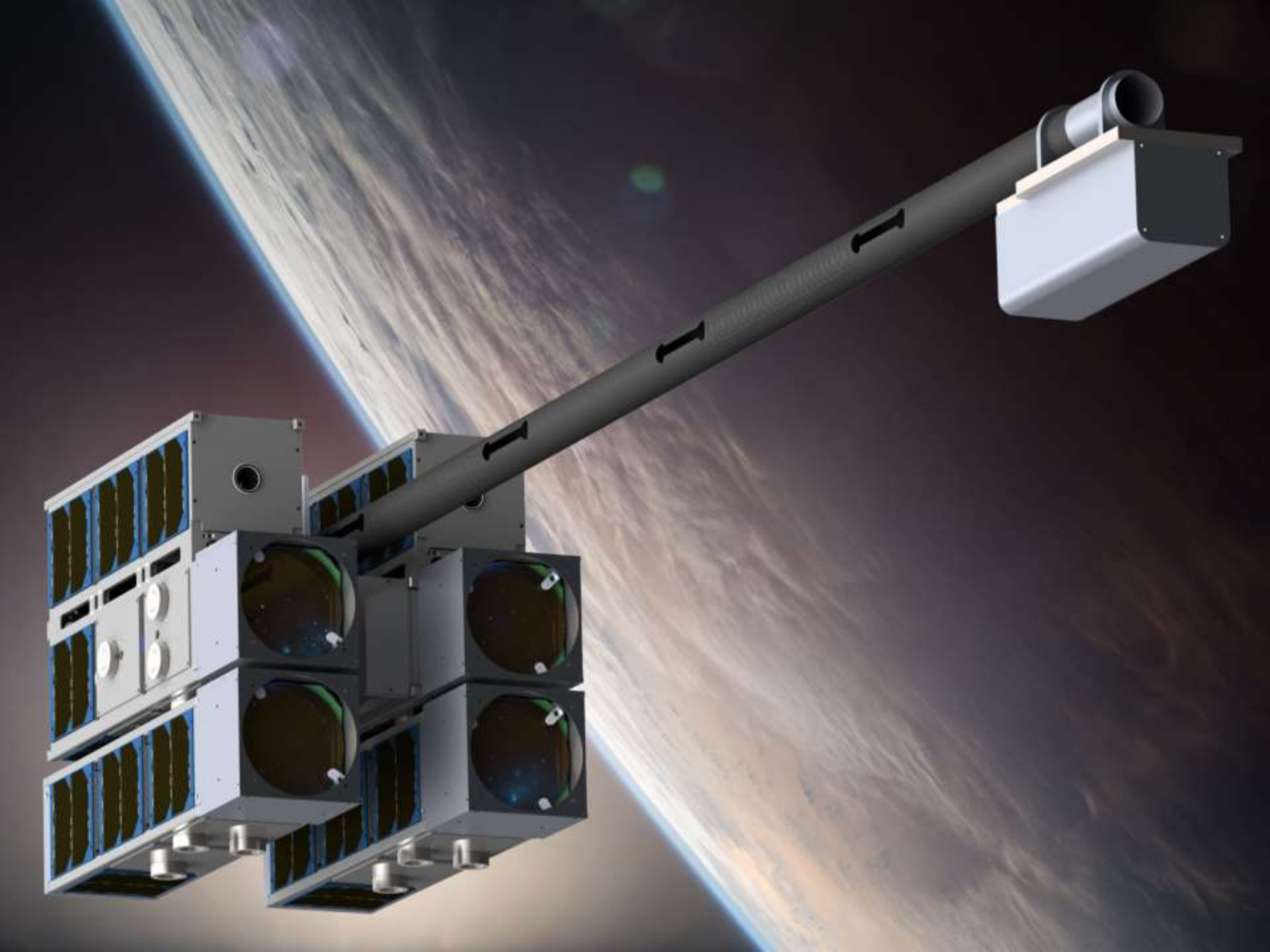
AAReST Objectives

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



AAReST Spacecraft

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AAReST Spacecraft

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AAReST Spacecraft

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

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

AAReST Spacecraft

MirrorSat (×2)
Reconfigurable free-flyers
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CoreSat
Power, Comm., Telescope ADCS
U. of Surrey

Deformable Mirrors (×2)
Active mirror segments
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AAReST Spacecraft

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

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

Reference Mirrors (×2)
Fixed figure mirror segments
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Deformable Mirrors (×2)
Active mirror segments
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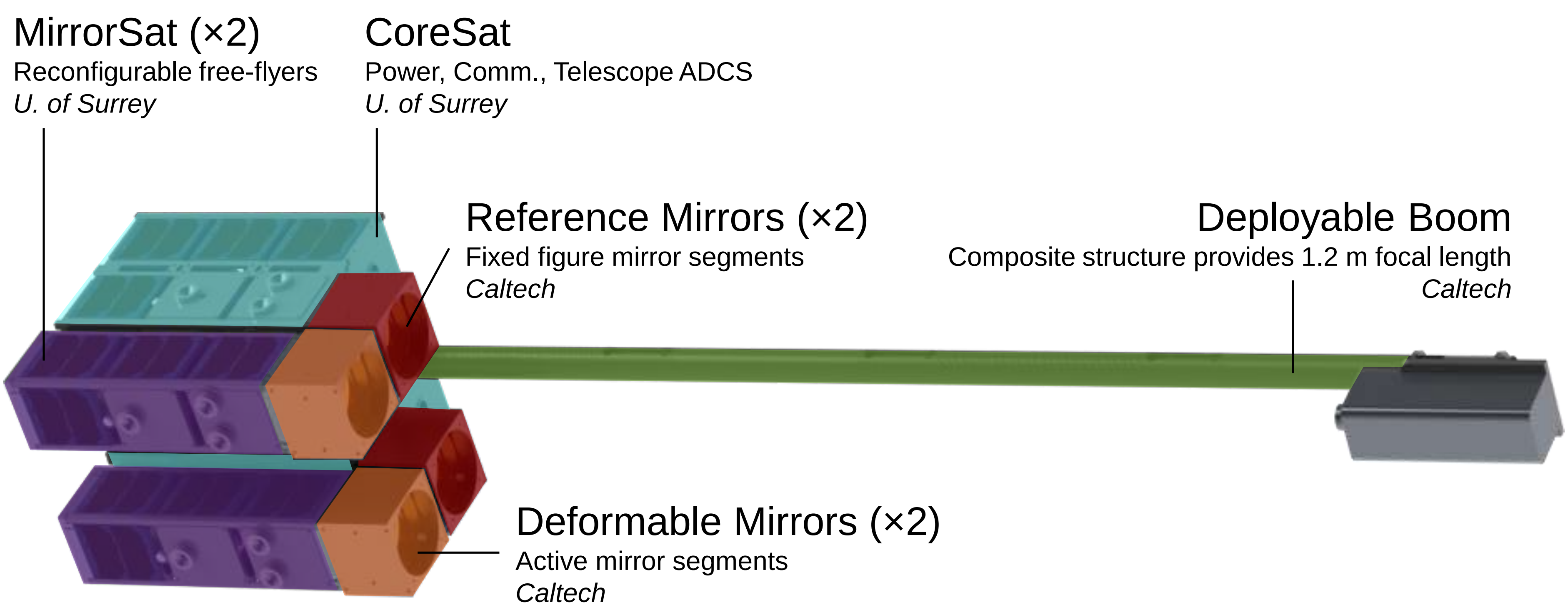
AAReST Spacecraft



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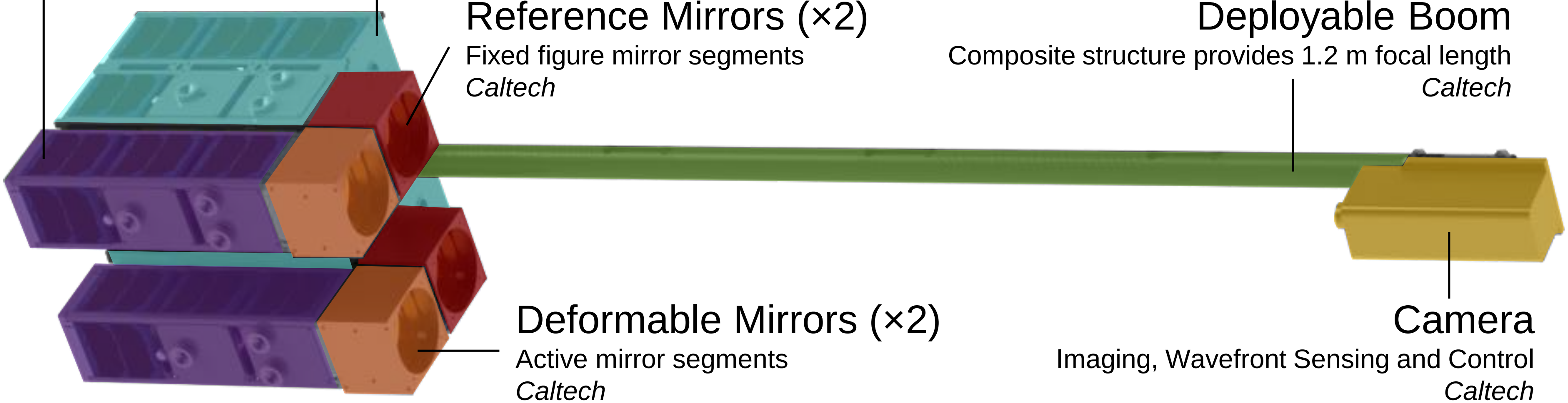
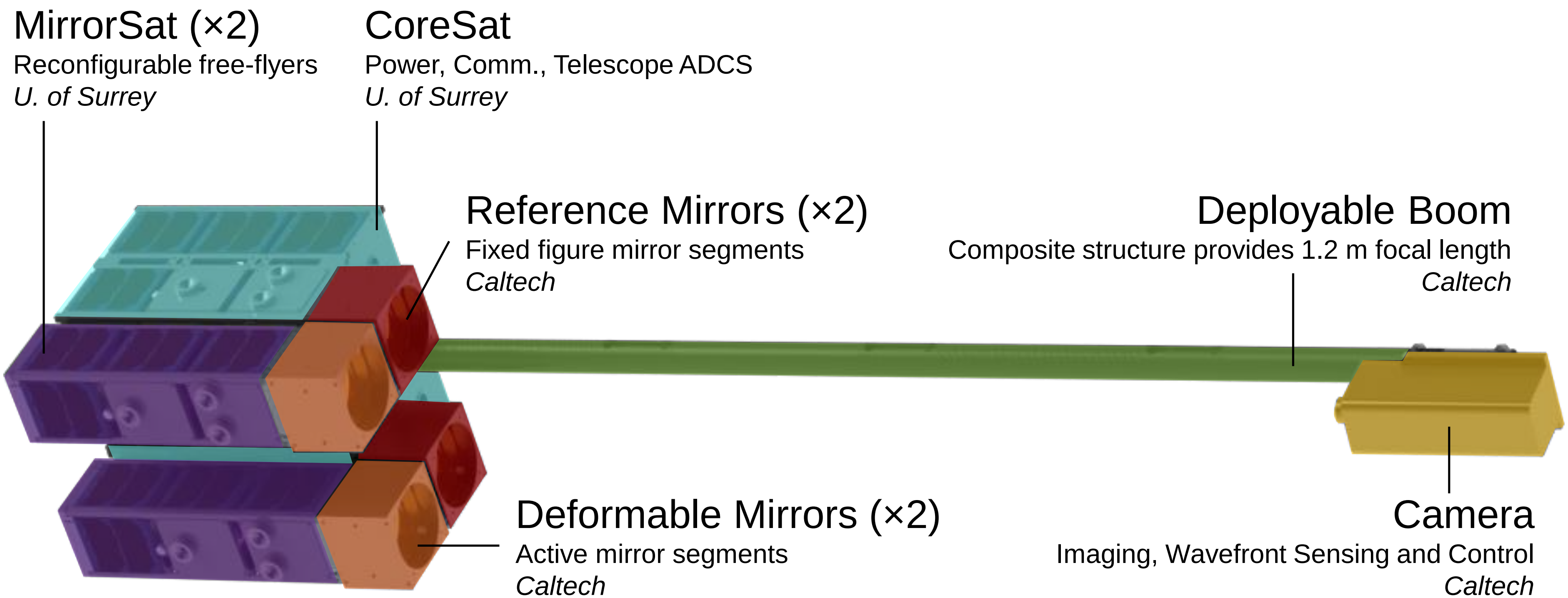
AAReST Spacecraft



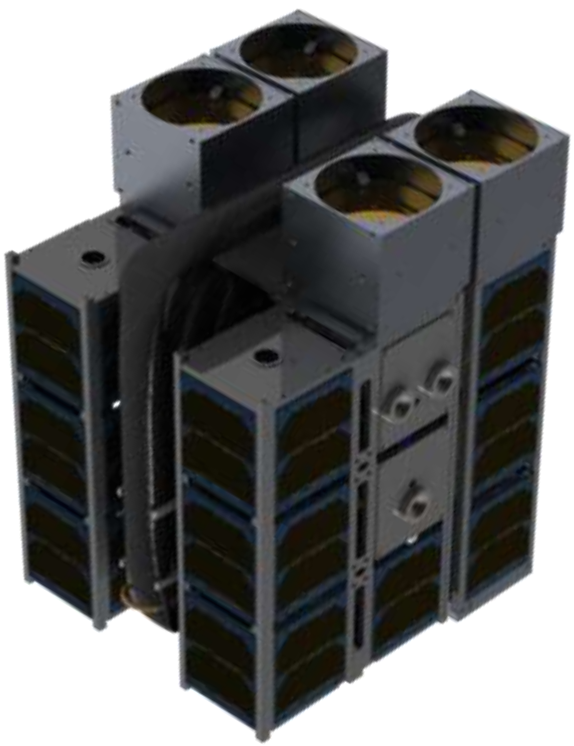
AAReST Spacecraft



Mass: <40 kg	Prime focus telescope	UHF down (9600 bps)	Ref. orbits:
CoreSat: 20 × 30 × 35 cm	465 nm – 615 nm bandpass	VHF up (1200 bps)	~650 km SSO
MirrorSat: 10 × 10 × 30 cm	0.3 deg. field of view	S-Band ISL	ISS (400 km,
Boom: Ø 38 mm,1.5 m long	1.2 m focal length		52 deg. incl.)

Concept of Operations

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



Launch in a compact, stowed volume

- 30 cm × 35 cm × 45 cm

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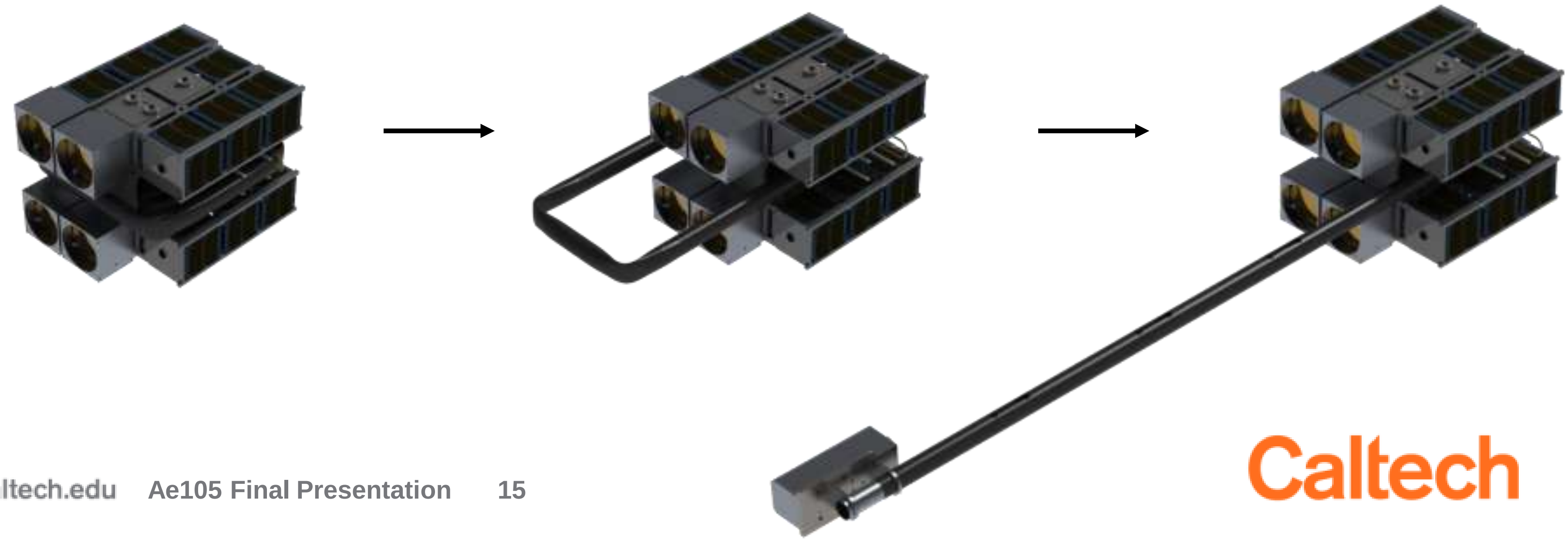
Concept of Operations

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

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

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



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Concept of Operations

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

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

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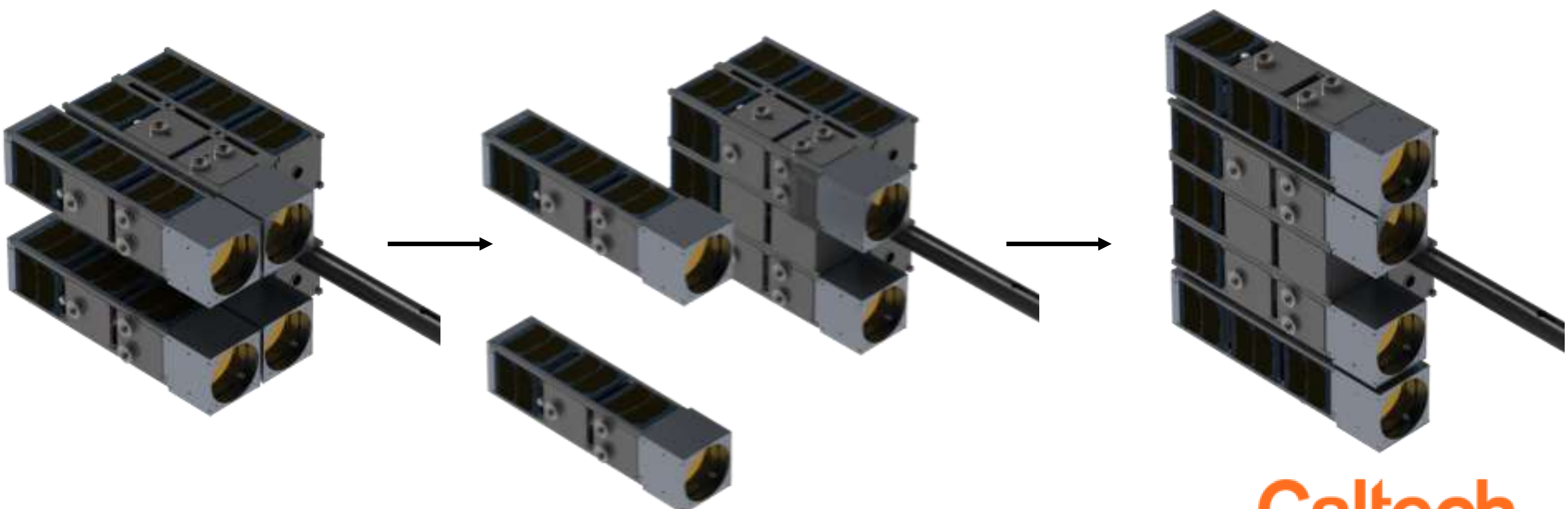
Concept of Operations

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

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



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Concept of Operations

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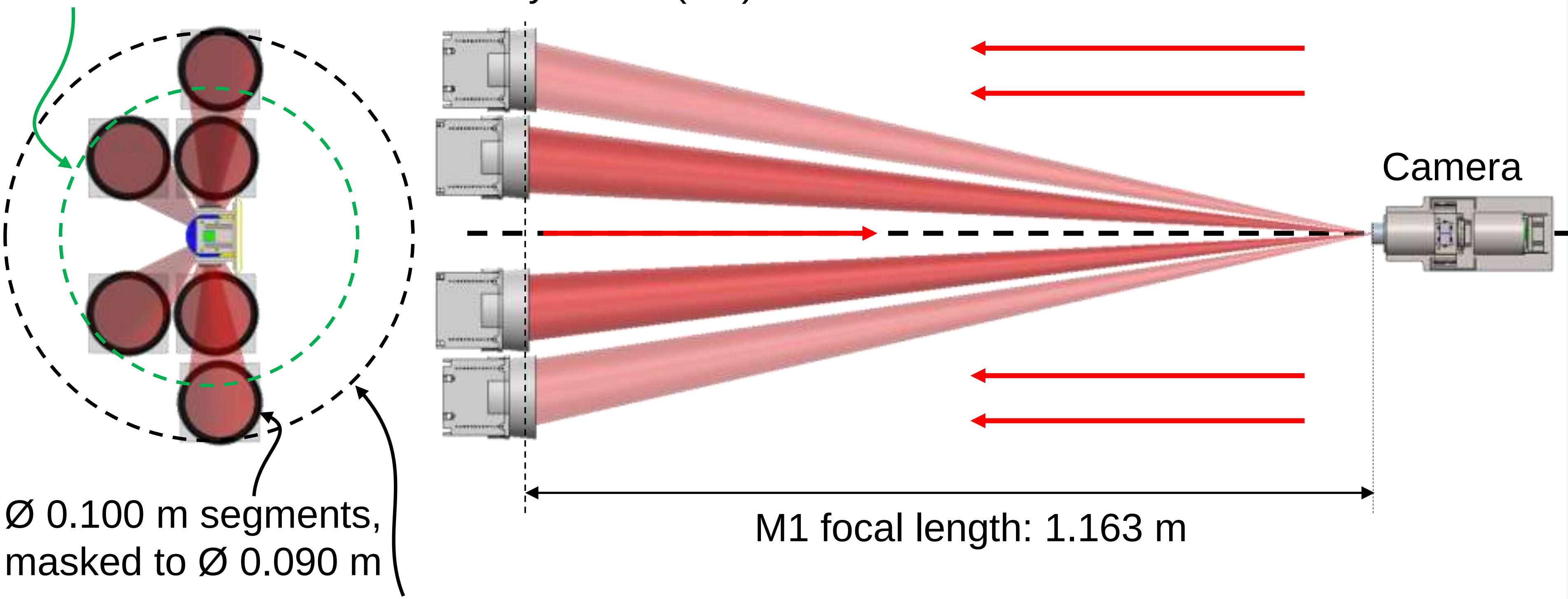
Concept of Operations

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

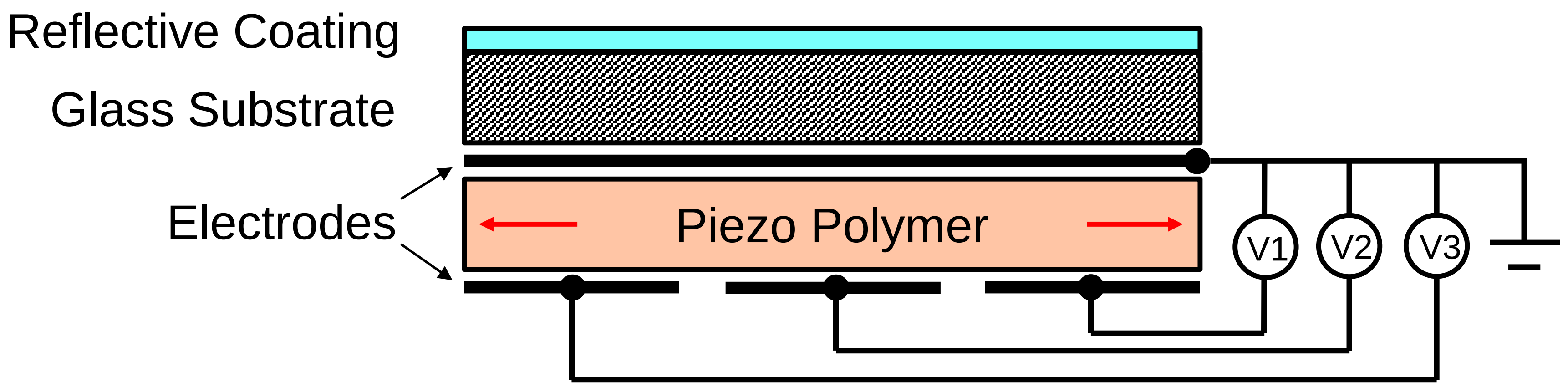
- Co-align star images from different segments to improve SNR
  - Pre-cursor to co-phasing
- Produce images of extended sources (e.g. Moon, Earth) for outreach

AAReST Optical Overview

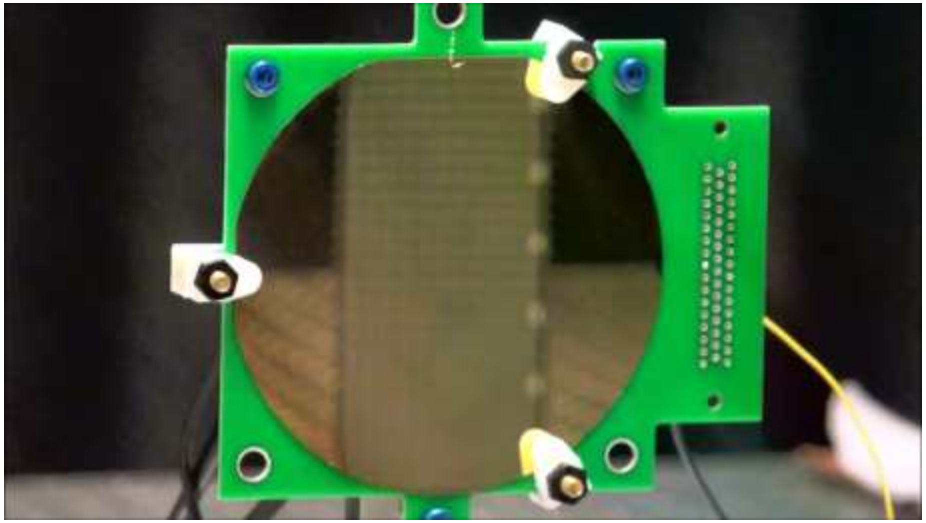


- Full Field of View : 0.3°
- Optical bandwidth: 465-615 nm (540 nm center)

Deformable Mirror Overview



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



AAReST History

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

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

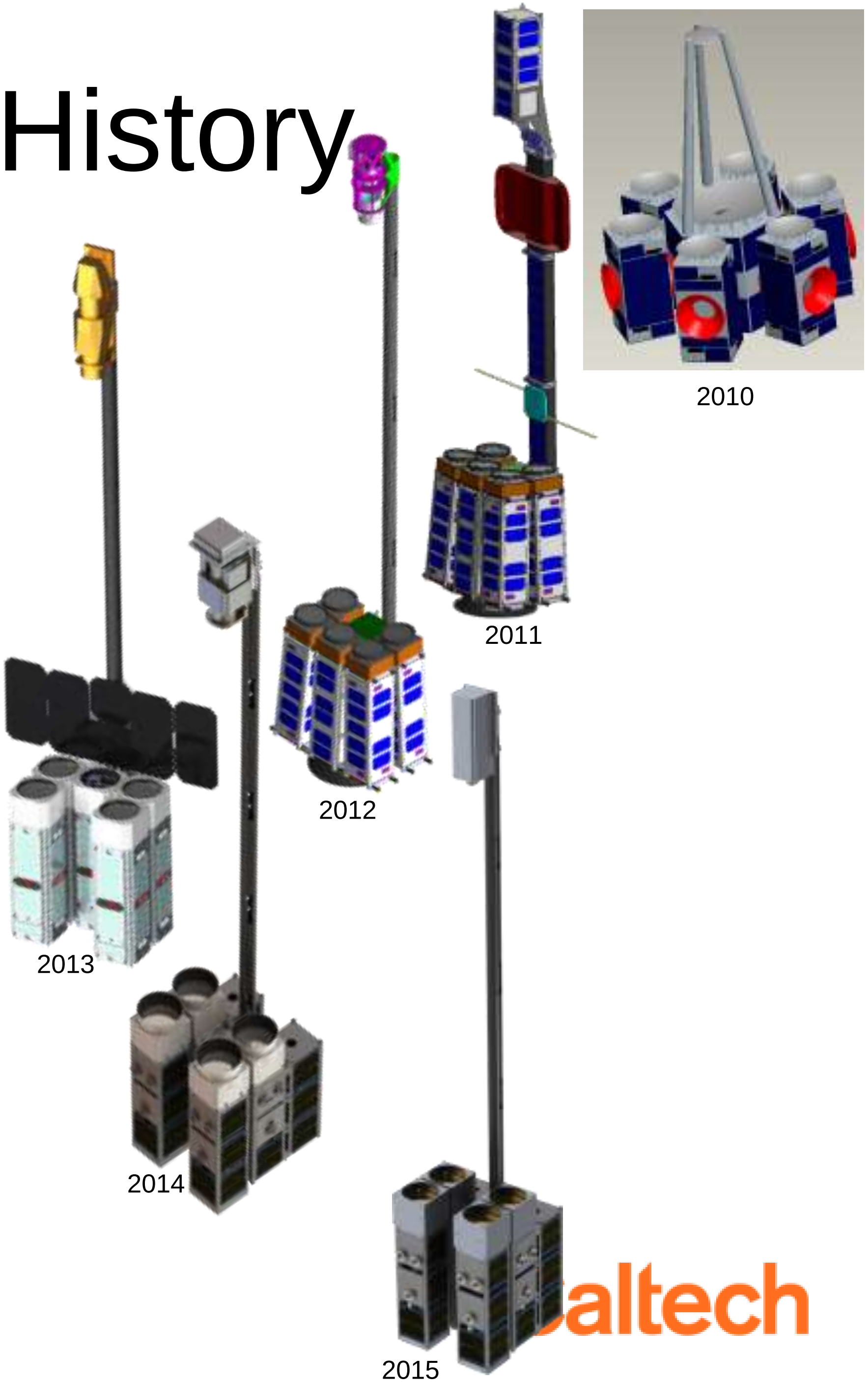
2012 June: Ae105
- Composite boom design and experiments
- Reconfiguration and docking experiments

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

2013 June: Ae105
- Detailed camera design
- Thermal modeling

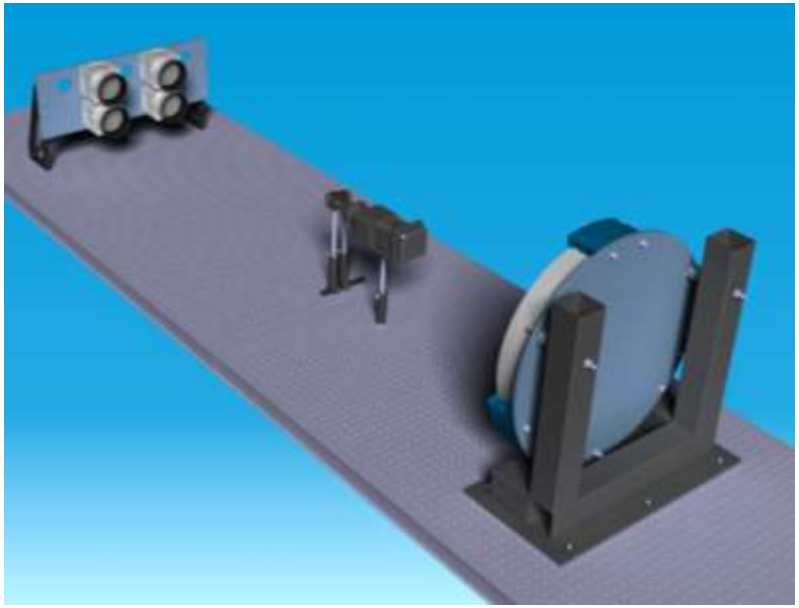
2013 September: Preliminary Design Review
2014 June: Ae105
- Camera opto-mechanical prototype
- Boom gravity offload deployment testing
- Mirror vibro-acoustic experiments
- TVAC chamber commissioning
- Telescope testbed commissioning

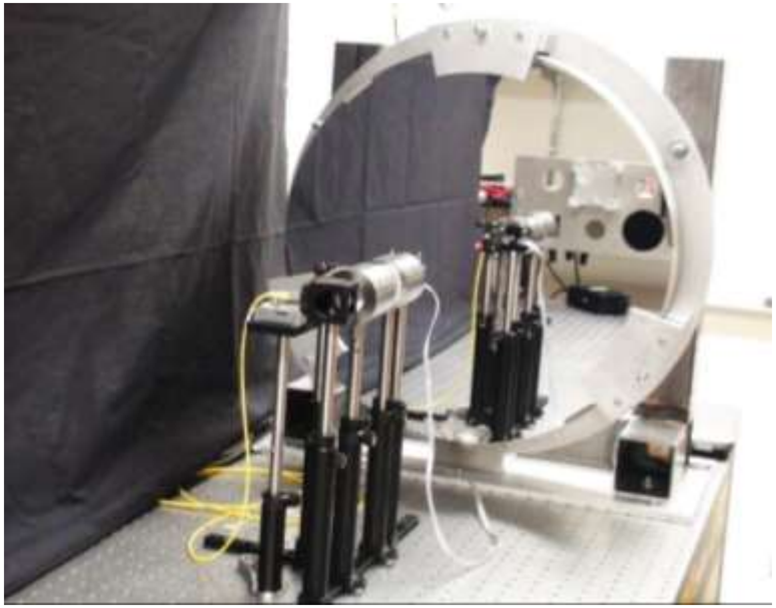
2014 September: Detailed Design Review
2015 June: Ae105
- Engineering models/prototypes of boom, camera
- Mirror thermal characterization
- Software and algorithms prototyping and testing



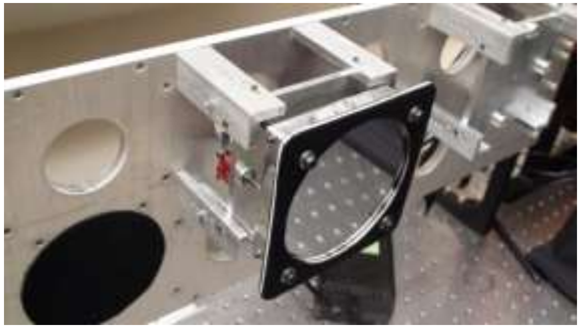
2014 Ae105 Accomplishments

Telescope Testbed Commissioning





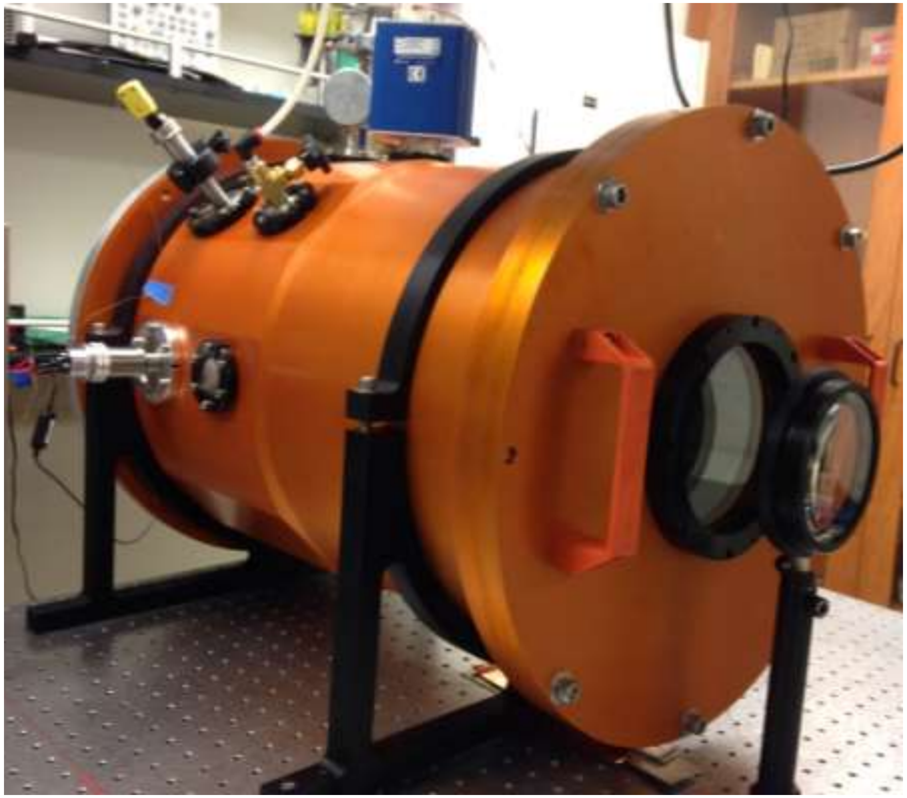
- Full-scale telescope testbed
- Autocollimation to simulate incoming starlight
- To test mirror + camera hardware, and calibration software



2014 Ae105 Accomplishments

TVAC Chamber Commissioning

- Need deformable mirrors to be thermally balanced
- Built a TVAC chamber to study mirror thermal deformations
- Optical window allows mirror figure to be measured at all times



2014 Ae105 Accomplishments

Boom Stage 2 Gravity Offload Testing

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Presentation Outline

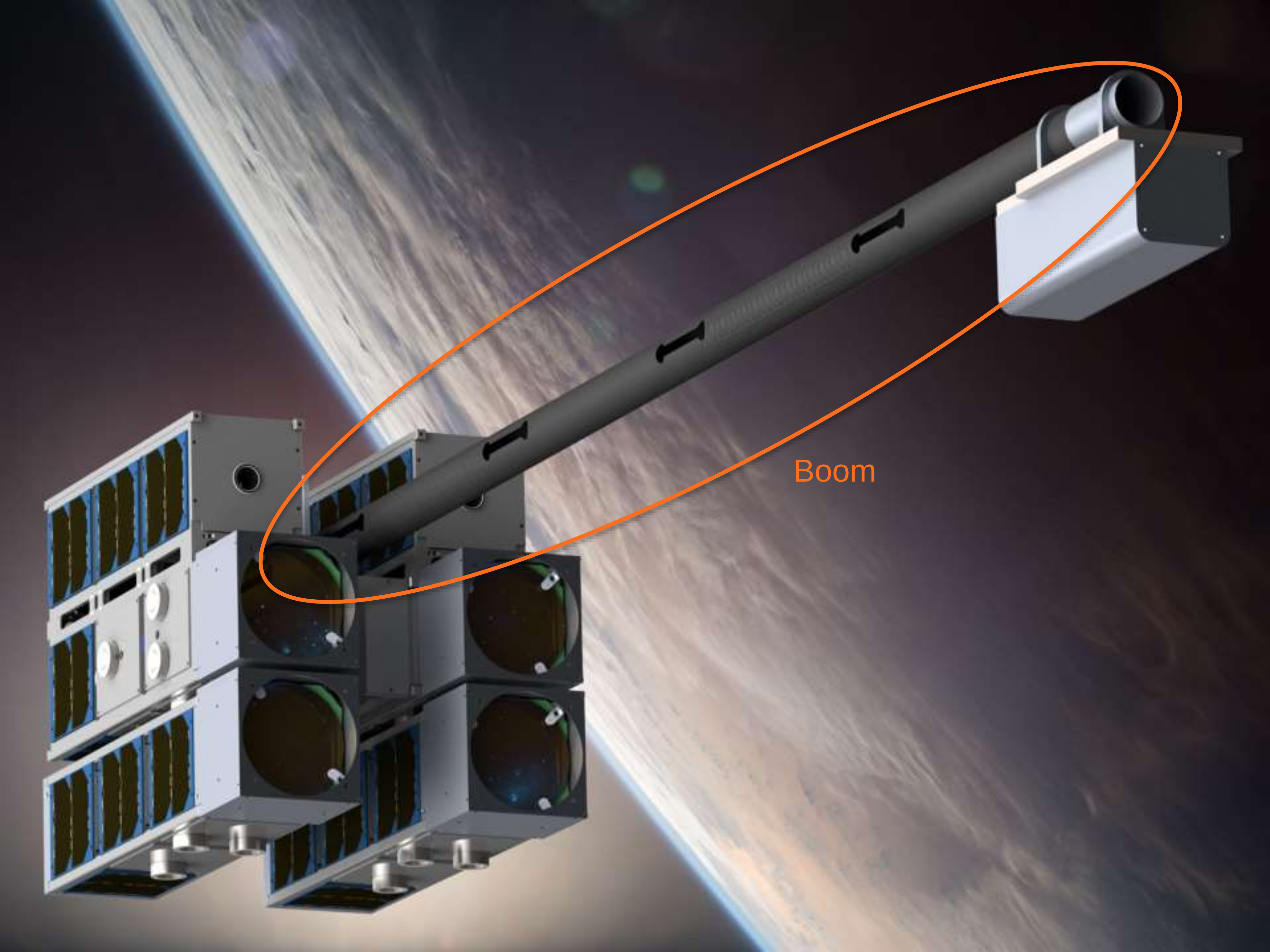
1. Boom Subsystem Validation
   – Stage 1 deployment testing & long-term storage effects
2. Mirror Thermal Deformation Testing
   – Designing a thermally balanced mirror segments
3. Mirror Box Mechanical Design
   – Designing mirror mounting and launch restraint systems
4. Camera Prototyping
   – Opto-mechanical prototype manufacturing and testing
5. Mirror Calibration Algorithms
   – Mirror segment search, pointing, and surface figure control
6. On-Board Software
   – Telescope software architecture design and implmentation

– 15 min. presentations + 5 min. discussion

Boom Subsystem Validation

Serena Ferraro
Christophe Leclerc
Kirsti Pajunen

Mentor: Arturo Mateos


Boom

Boom Subsystem Overview

Purpose:

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

Team Responsibilities:

- Evaluate deployment sequence
- Design and test boom and boom-CoreSat interfaces
- Currently in verification and validation phase

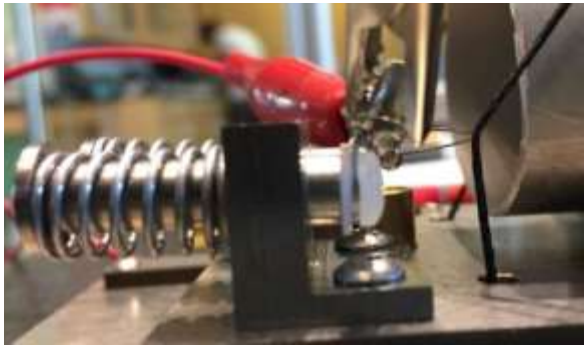
Stage 1 Deployment →

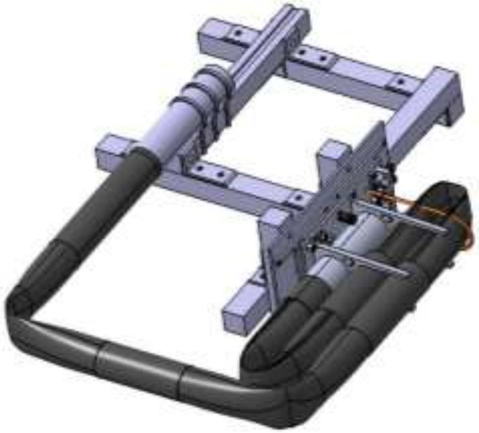
Stage 2 Deployment →

Tasks

1. Long-term storage behavior characterization

2. Manufacturing and testing of Boom-CoreSat Interfaces (kinematic mount and separation device)





3. Stage 1 deployment experiments

Long-term Storage Behavior

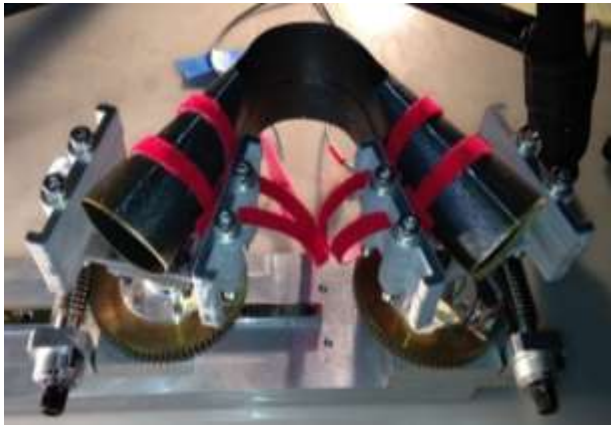
Objective: Ensure boom retains sufficient potential energy for deployment after long-term storage

- Composite: AstroQuartz, carbon fiber, and cyanate ester resin
- Cyanate ester resin was selected due to low moisture absorption and outgassing

Approach:

Manufacture hinges
$[\pm 45_{AQ} / 0_{3CF} / 90_{CF} / \pm 45_{AQ}]$

Characterize viscoelastic properties and perform accelerated aging tests



Examine mechanical response

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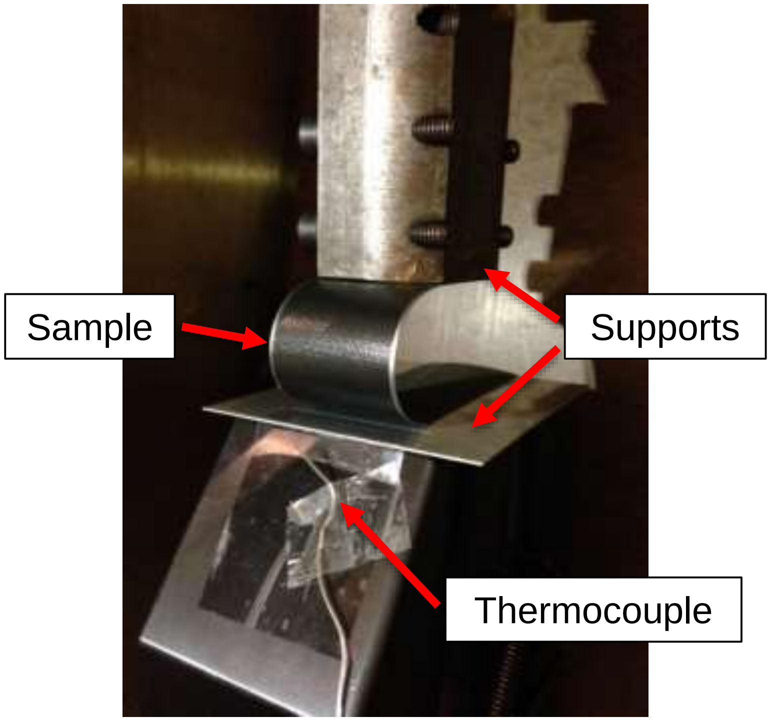
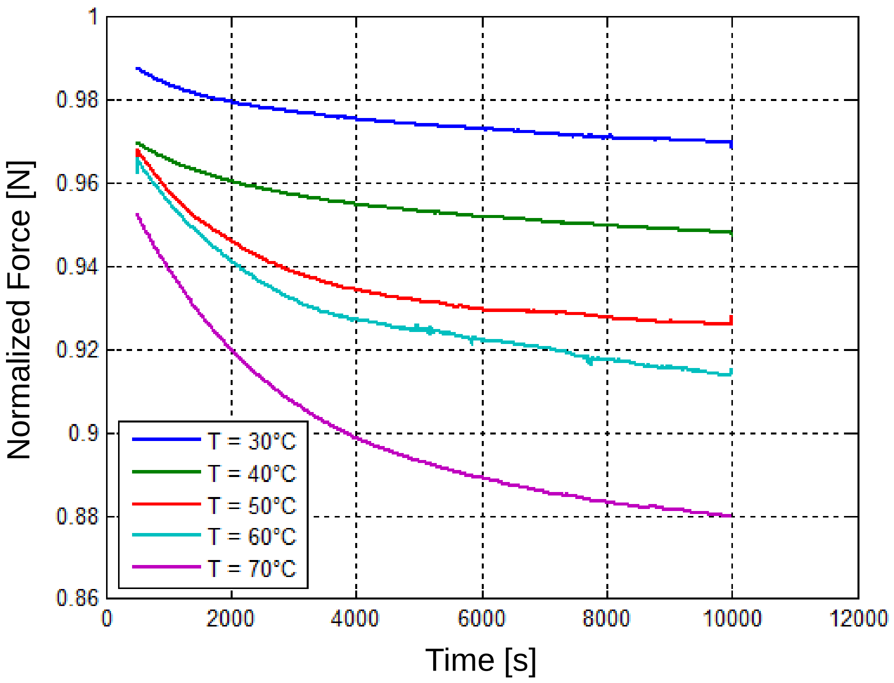
Long-term Storage Behavior

Viscoelastic Properties

Test Method:
- Sample buckled and positioned inside a preheated thermal chamber
- Supports kept at fixed distance to simulate stored radius of curvature
- Reaction force exerted by the sample measured with load cell

Results: Obtained force-time relations over chosen range of temperatures, examine the time-temperature superposition for this specific composite and generate a master curve





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Long-term Storage Behavior

Viscoelastic Properties

How did we obtain a master curve?

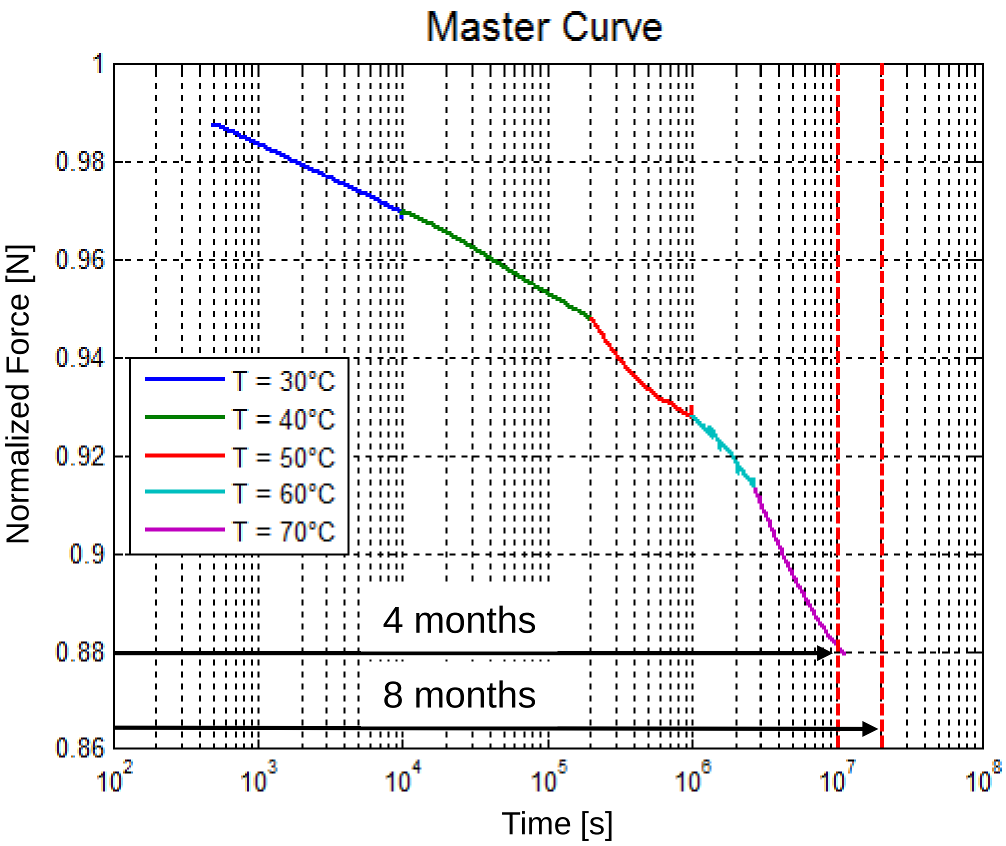
- Experimental curves shifted on a logarithmic time scale with respect to reference curve at 30°C

Why is the master curve useful?

- Samples need to be aged 157 minutes at 70 °C in order to reach 4 months of storage time
- Expect **~10%** decrease in reaction force

What can be observed?

- Only 10 more minutes of aging at 70 °C would correspond to 8 months of storage time
- From curve trend, 8 months storage would lead to ~12% total decrease in reaction force



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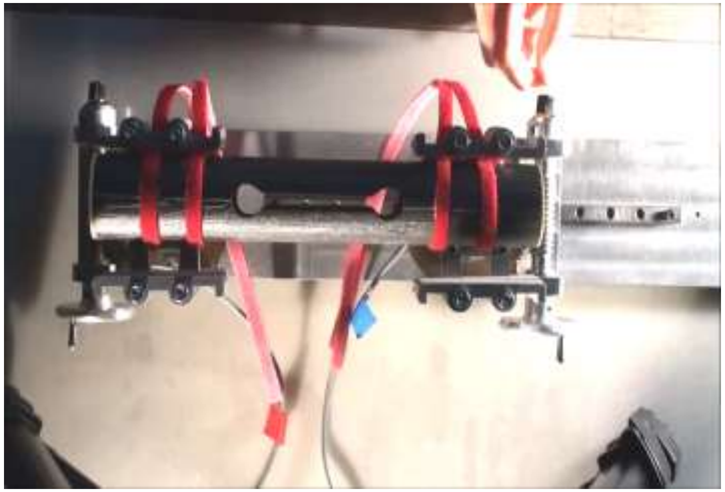
Long-term Storage Behavior

Mechanical Response

Objective: Measure the moment exerted by the hinge with respect to the hinge configuration, which is determined by its angle

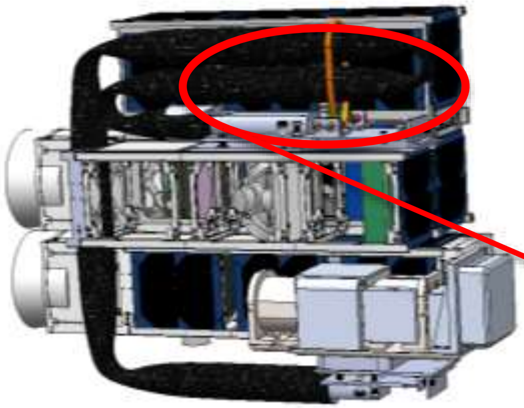
Results: **~10%** decrease in moment if behavior at the peak is neglected

Conclusions: - Quasi-static deployment test confirms master curve prediction
- Reduced moment did not prevent successful hinge deployment
- Information obtained from this test and master curve indicates that longer storage time will not compromise hinge deployment



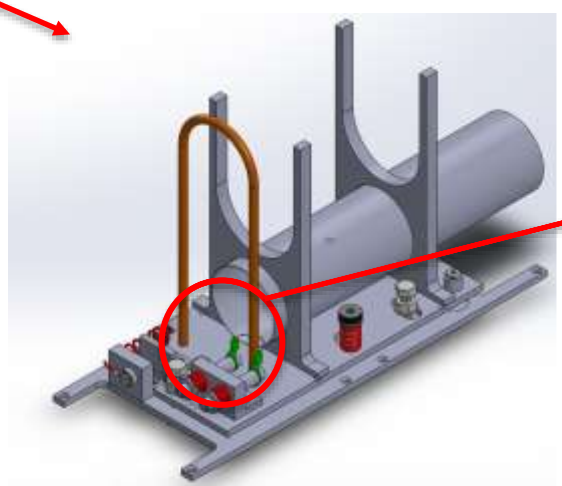
Boom-CoreSat Interfaces

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

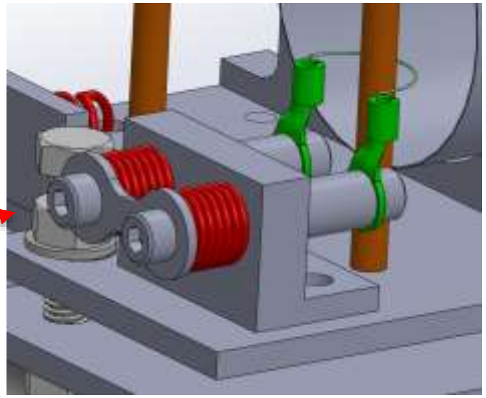


Kinematic Mount allows adjustment of camera relative to CoreSat before final storage

- Corrects for misalignments



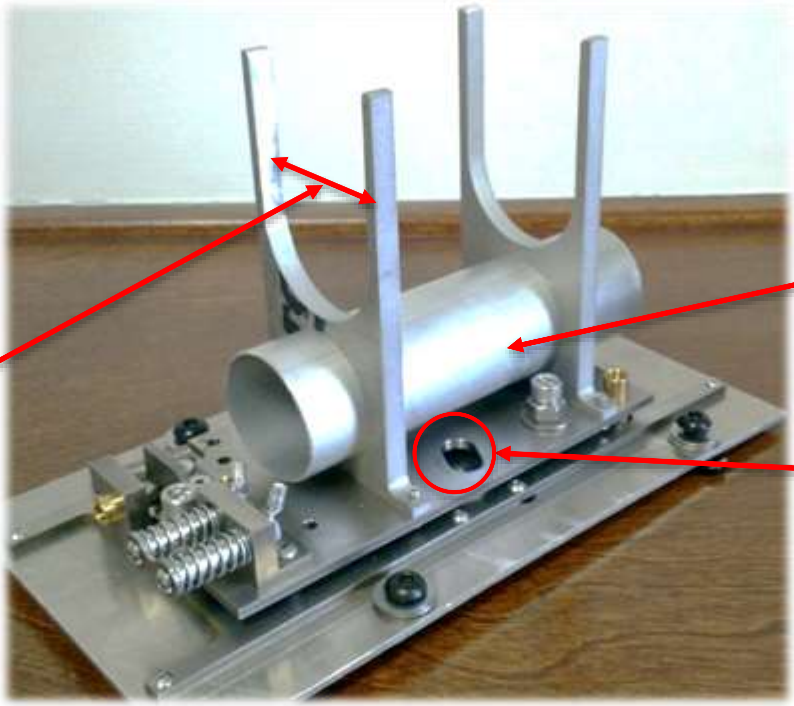
Separation Device constrains boom during storage and releases stage 1 during deployment



Boom-CoreSat Interfaces: Manufacturing

- Manufactured first prototypes from existing designs
- Some modifications were necessary in order to be tested:

Wider brackets to allow boom storage and deployment



Addition of **set screws** to fix the mandrel

Larger slots to obtain adjustment range

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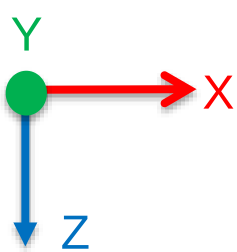
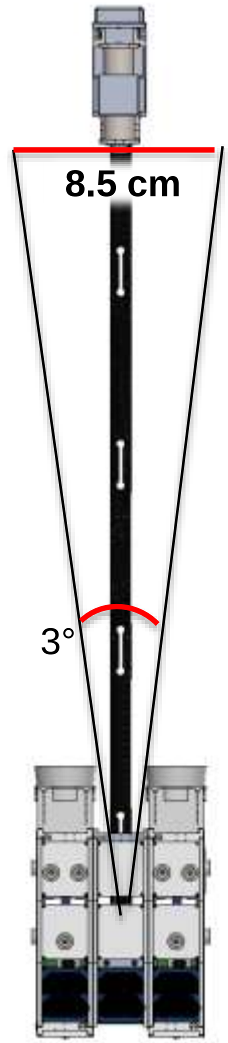
Boom-CoreSat Interfaces: Testing

Kinematic Mount

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

- More than enough adjustability in all 3 axes of rotation



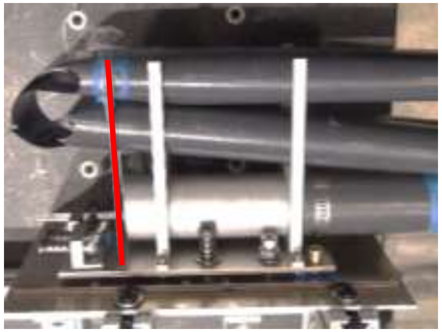


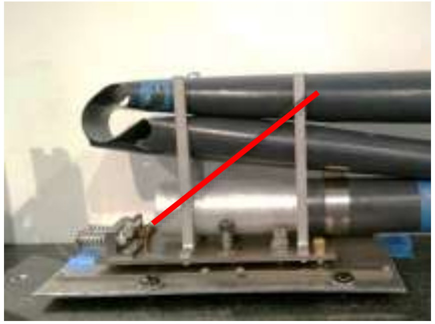
Separation device

- Ran multiple trials at various currents
- Several Vectran configurations and tensions (need angled cable)

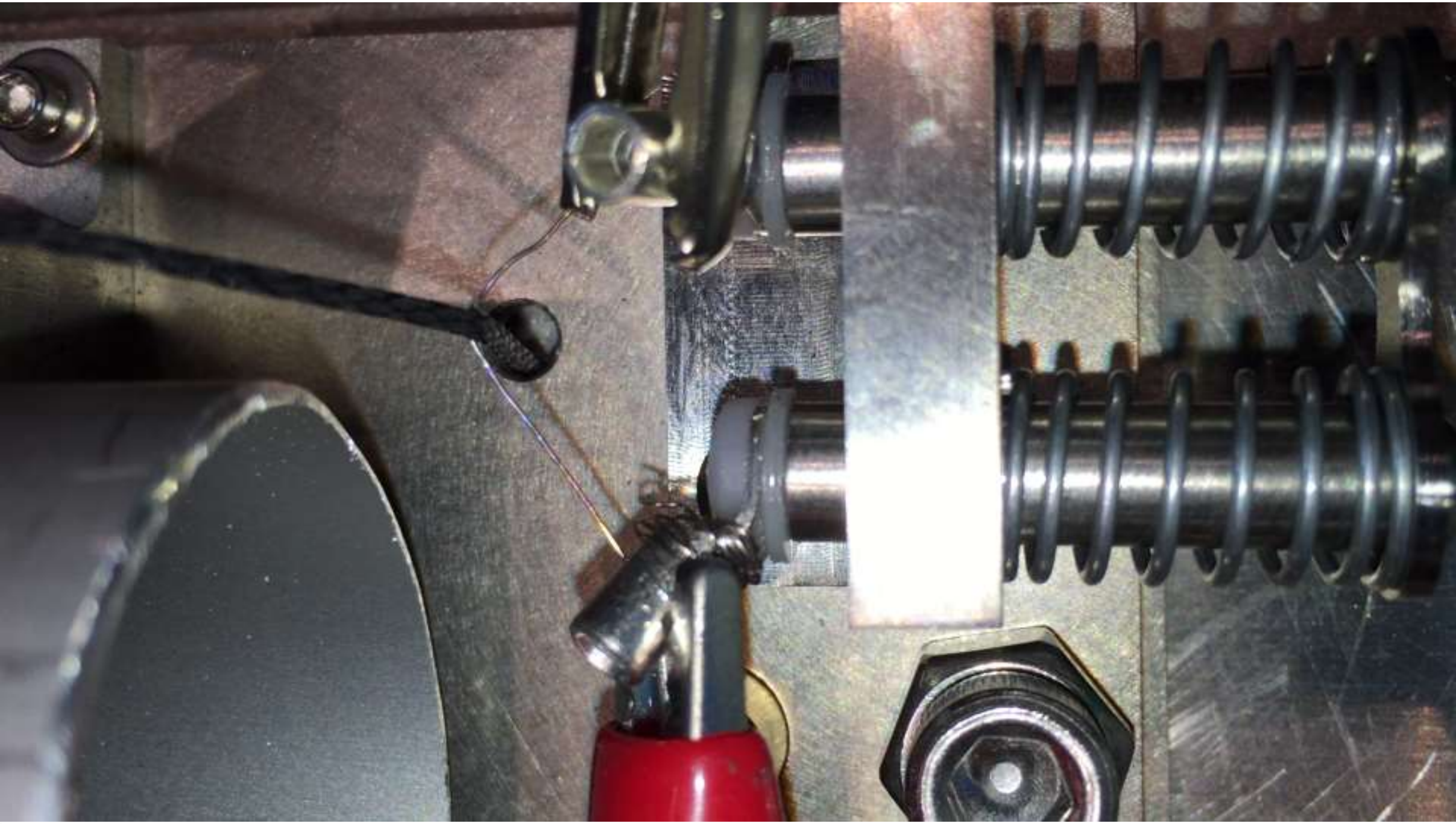
- **9 sec** cut time for **1.6 A**

- Tension does not affect cutting time
- **Reliable**: no failure in 26 tests





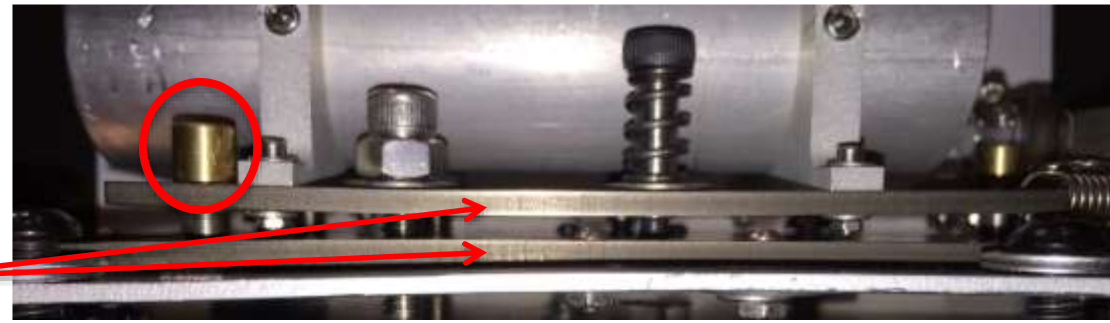
Separation Device Testing



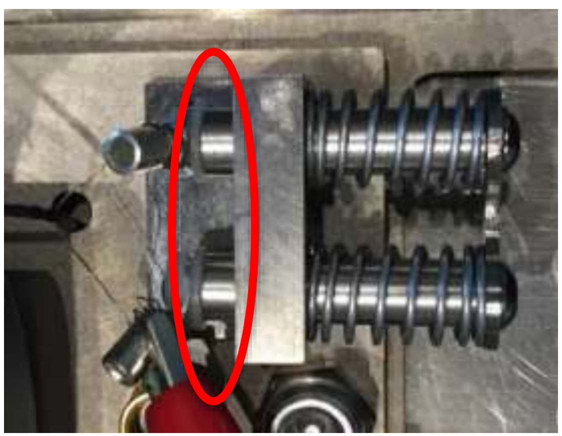
Boom-CoreSat Interfaces: Future Improvements

Kinematic mount

- Placement of the Vectran cable
- Resolution of plate bending issue



- Attachment of boom on mandrel



Separation device

- Larger displacement is required to maintain tension
- Addition of redundancy

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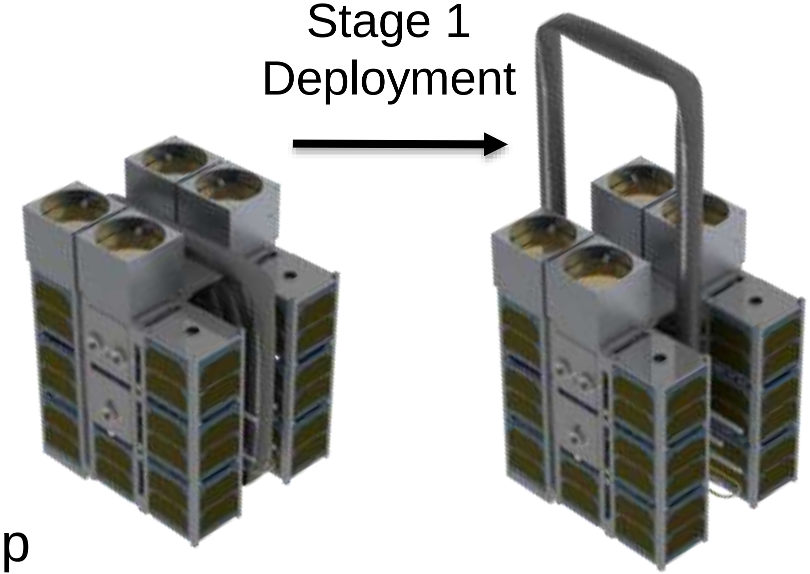
Stage 1 Deployment Test

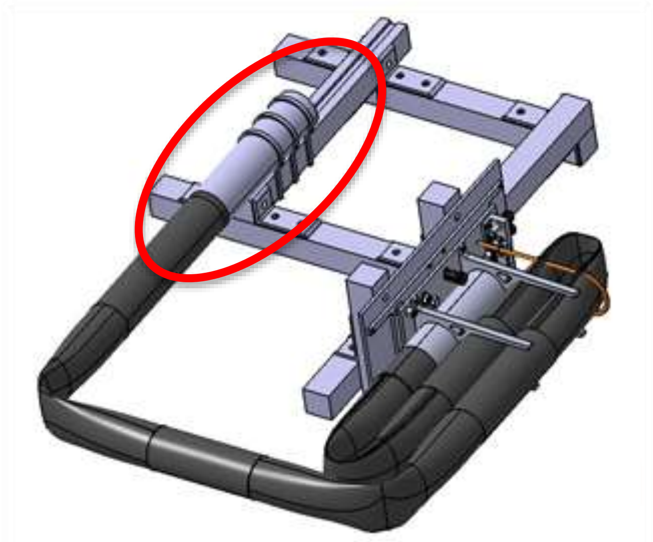
Motivation:

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

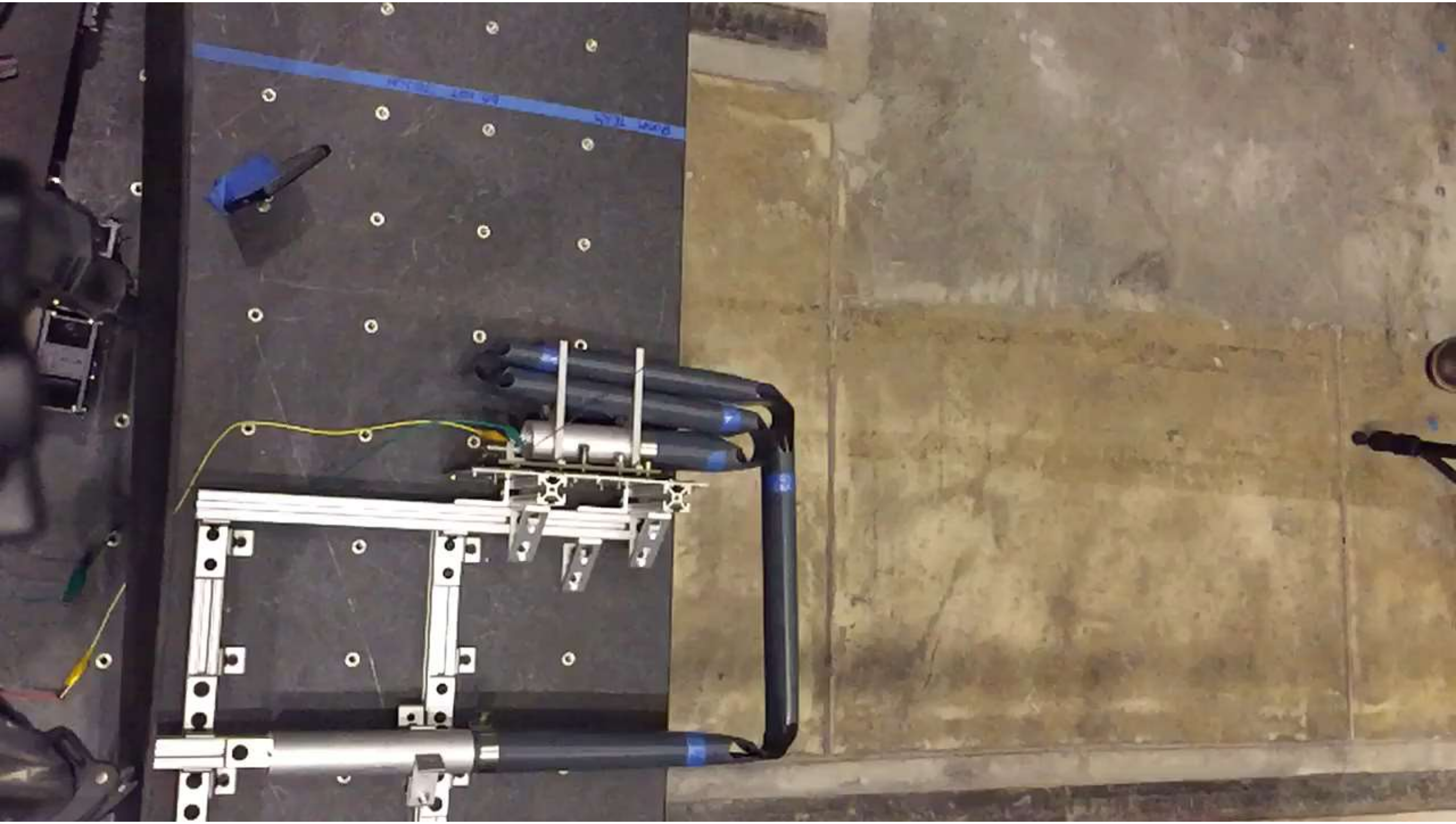


Objectives:

- Design and build a highly modular setup
  - Possibility to add boom-camera interface
- Validate stage 1 deployment kinematics
- Validate kinematic mount
- Test separation device
- Find final position of stage 1 deployment



Stage 1 Deployment Test: Video 1



Stage 1 Deployment Test: Video 2

Stage 1 Deployment Test: Results

- **Repeatable** initial condition obtained for stage 2 deployment experiments
- Small lateral deflection occurred due to previous geometric optimization
  - Bending moment of **15 Nm** exerted on camera-CoreSat interface
  - Experimental setup more rigid than final boom-camera interface
- Boom-CoreSat interfaces worked as expected

Summary of Completed Work

Long-Term Storage

- Generated a master curve for cyanate ester resin
- Moment exerted by hinges decreased ~10% after 4 months storage
- Aging did not prevent single hinge deployment

Boom-CoreSat Interfaces

- Manufactured and tested interfaces
- *Kinematic Mount*: Ample range of motion achieved to align optical systems
- *Separation Device*: Reliably cuts Vectran wire for stage 1 deployment

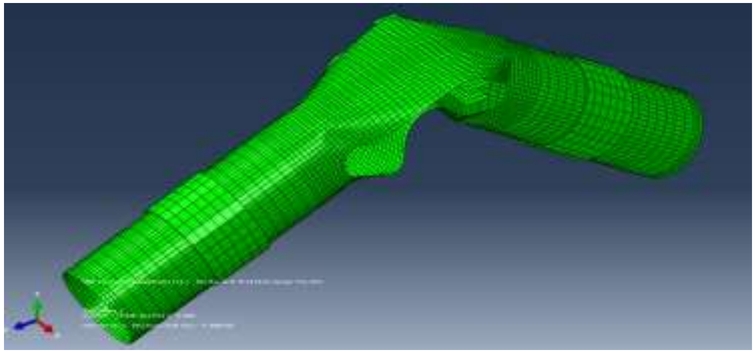
Stage Experiments

- Multiple successful stage 1 deployments using interface prototypes
- Characterization of the initial conditions for stage 2 deployment

Future Work

Long-Term Storage

- Compare results with FEM simulations from previous years
- Analyze full boom deflection after deployment



Boom-CoreSat Interfaces

- Perform separation device tests in vacuum chamber
- Analyze kinematic mount design from thermal and structural standpoint and make necessary modifications

Stage Experiments

- Complete stage 1 and 2 experiments
- Further analyze the effect of the bending moment exerted on camera-CoreSat interface

Outgassing

- Identify outgassing level of boom composite and contaminants

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Questions?

Study of mirror deformations under thermal loading

Nicolas Meirhaeghe
Pranav Nath
J.P. Voropaieff

Mentor: Christian Kettenbeil

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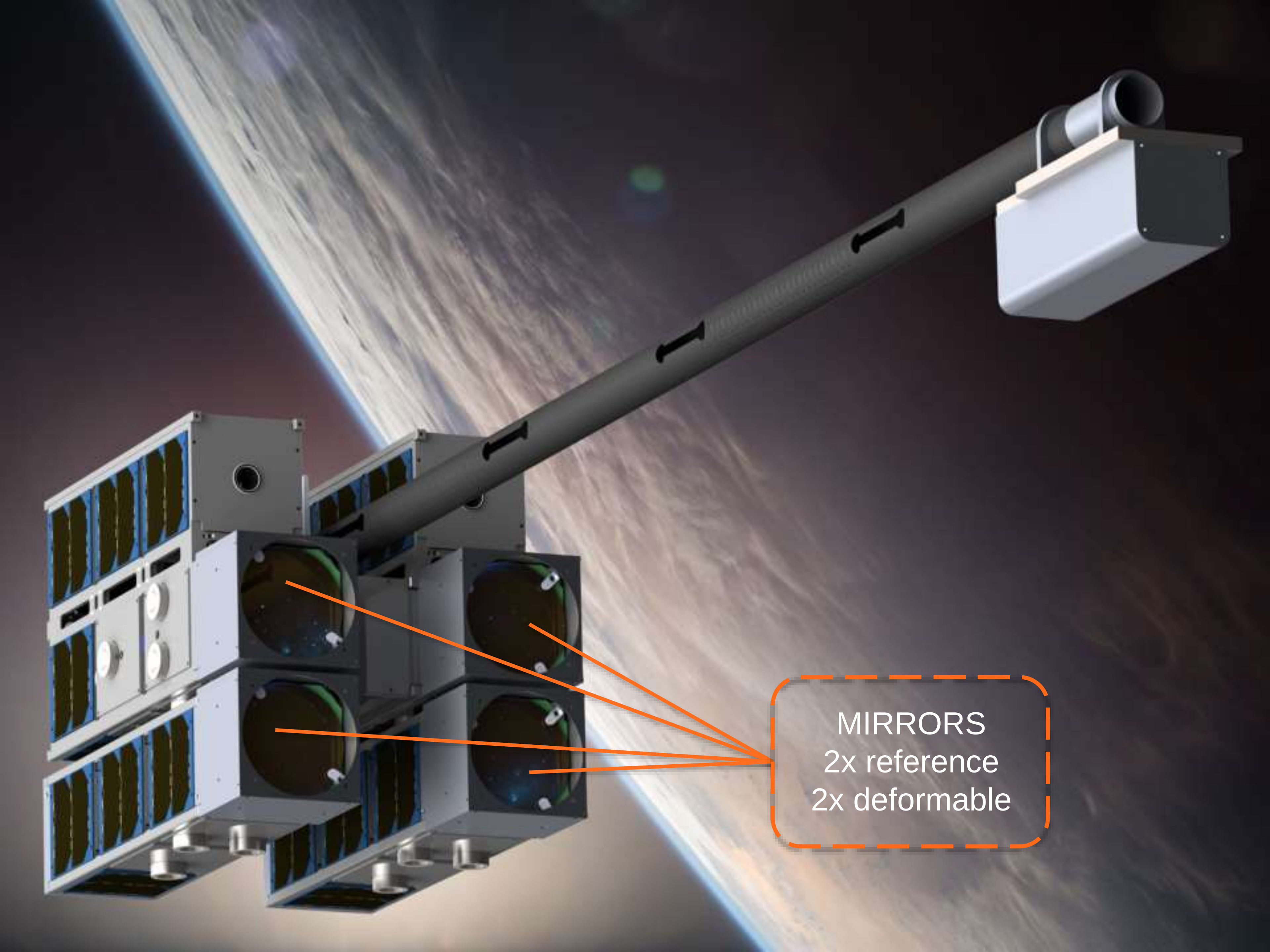
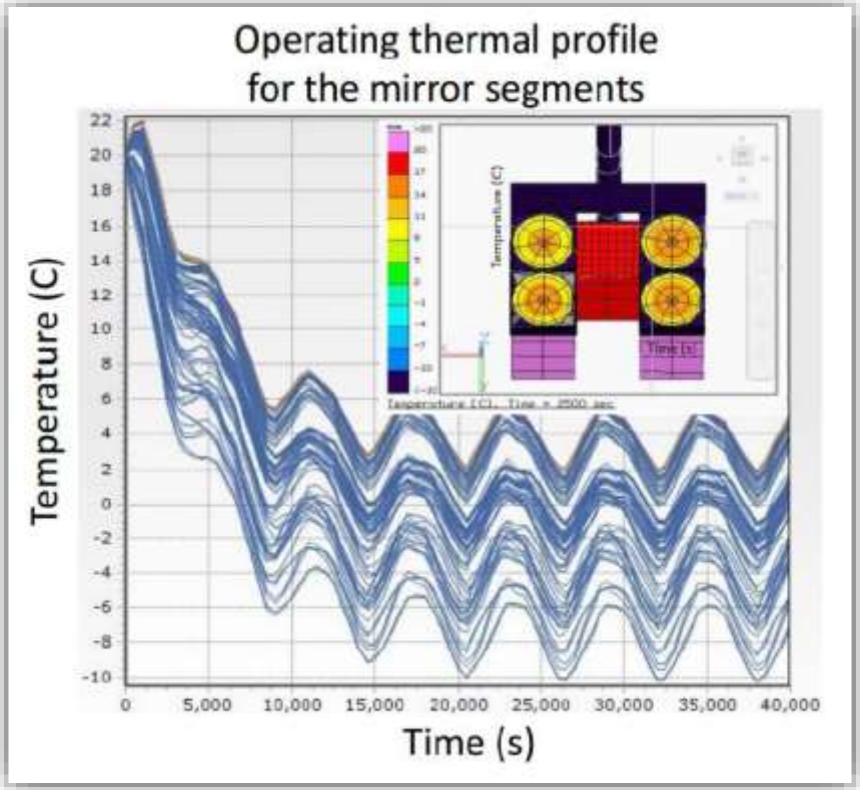

MIRRORS
2x reference
2x deformable

Thermal environment



Simulation of on-orbit thermal loads (SSO)

Temperature range:
[-6°C; 10°C]

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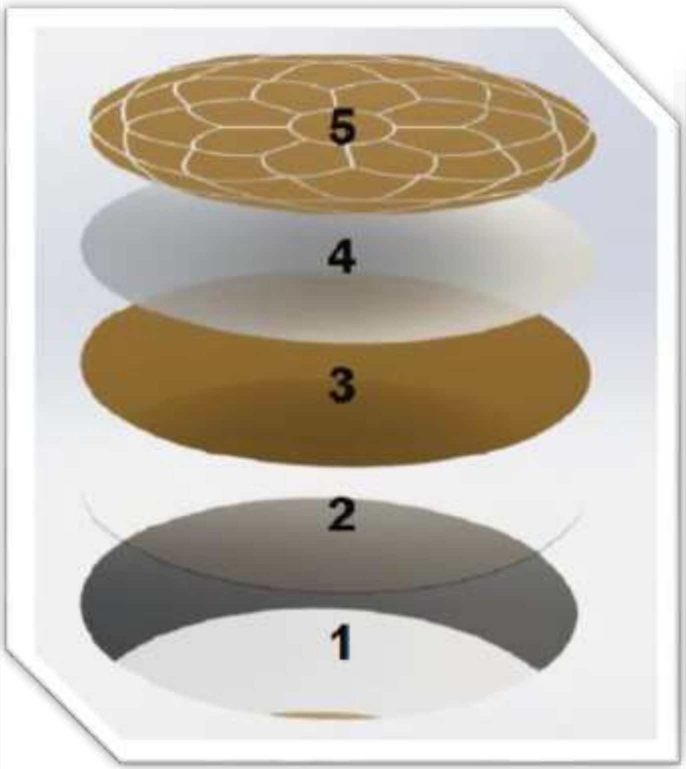
Mirror Structure

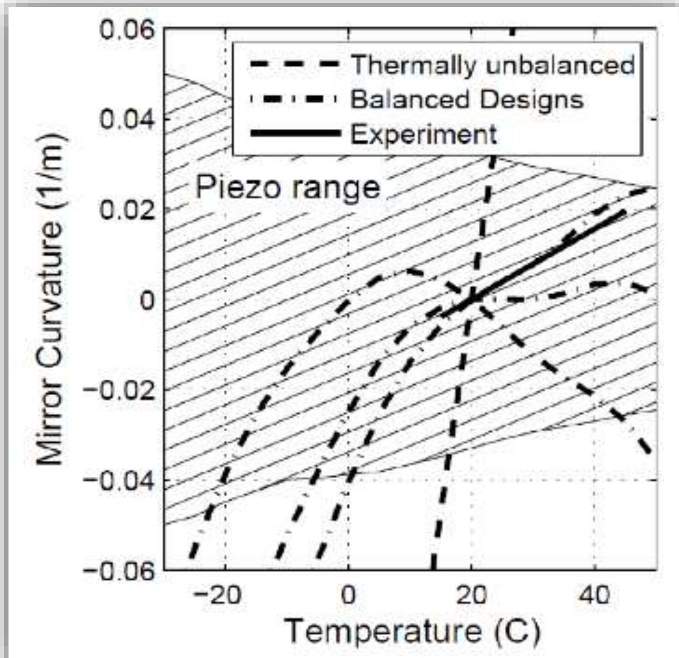


Layer Architecture of the Deformable Mirror (DM)

Position	Mirror layer	Material	Thickness (μm)	Order	Method(s)
1	reflective surface	Al, Ag, or Au	0.1	2	sputtering evaporation
2	substrate	Si or Glass	200	1	(slumping)
	adhesion	Ti	0.01	3	sputtering evaporation
3	ground	Au	0.1	4	sputtering evaporation
	adhesion	Ti	0.01	5	sputtering evaporation
4	active	P(VDF-TrFE)	20	6	spin coating
	adhesion	Ti	0.01	7	sputtering evaporation
5	electrodes	Au	0.1	8	sputtering +ion mill

Composition of each layer

Limitations of the active layer



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3	ground	Au	0.1	4	sputtering evaporation
	adhesion	Ti	0.01	5	sputtering evaporation
4	active	P(VDF-TrFE)	20	6	spin coating
	adhesion	Ti	0.01	7	sputtering evaporation
5	electrodes	Au	0.1	8	sputtering +ion mill

Piezo Capabilities

Piezo compensates for:

1) Thermal deformations
2) Wavefront errors
3) Electronic drift
4) Manufacturing errors, etc…

Caltech

Goal of the project

" Ensuring operability of the deformable mirrors under on-orbit thermal loading conditions "

- Keep thermal deformations within piezo range (+ margin)

- Operating temperature range [-20℃; 20℃]
  - Based on simulation (+ margin)

- Survivability range [-60℃; 50℃]
  - Account for:
    - ✓ Drop in temperature when electronics is off
    - ✓ Potential overheating under extreme conditions

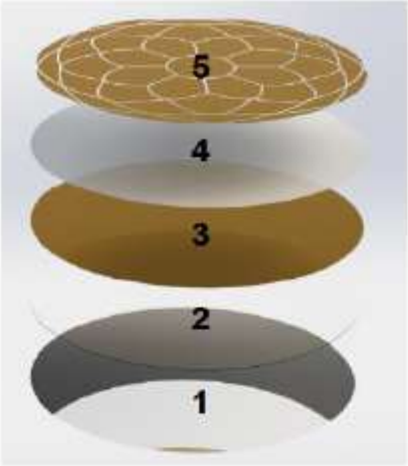
Caltech

Objectives of the project

1) Characterization of pre-designed mirror samples

- Testing of 4 different « recipes »
- Only reflective layer composition varies

Sample	Chromium [nm]	Aluminum [nm]	# of Layers	Total Thickness [µm]
1	50	500	3	1.65
2	50	250	6	1.8
3	50	500	4	2.2
4	50	250	8	2.4



Caltech

Objectives of the project

2) Validation of a theoretical model for thermal deformation

- Simplified model (*Stoney's Formula*)
- Relates radius of curvature of mirror to material properties of each layer and temperature loading

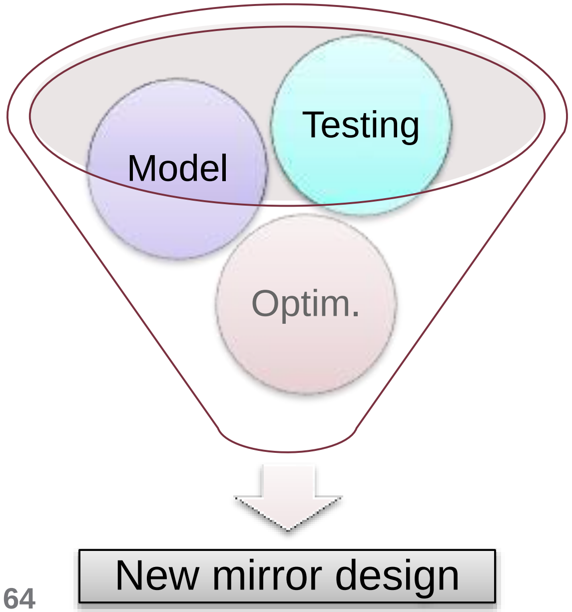
$$\kappa = \frac{6\Delta T}{t_s^2 M_s} \sum_i s_i \left(\alpha_i - \alpha_s\right) M_i t_i \, ,$$

Caltech

Objectives of the project

3) Optimization of mirror composition

- Cost function: curvature change over operating range
- Free parameter: thickness of reflective layer
- Design recommendations for new mirror



Caltech

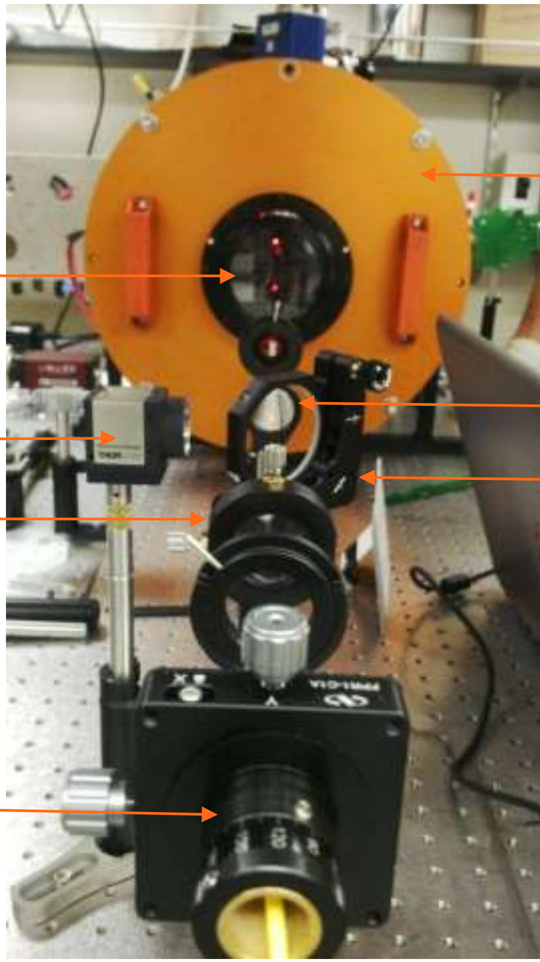
Objectives of the project

4) Testing of the new design

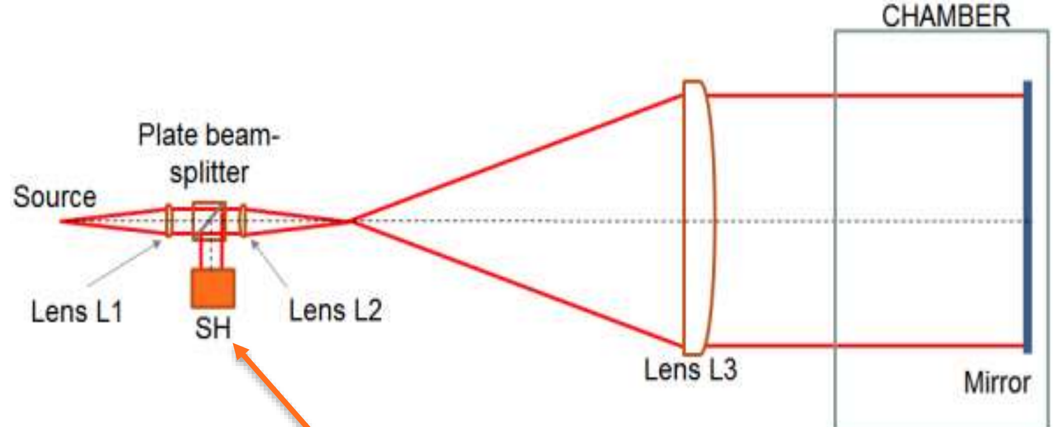
- Check if optimization yielded better performances
- Verify that requirement is met

Caltech

Experimental setup



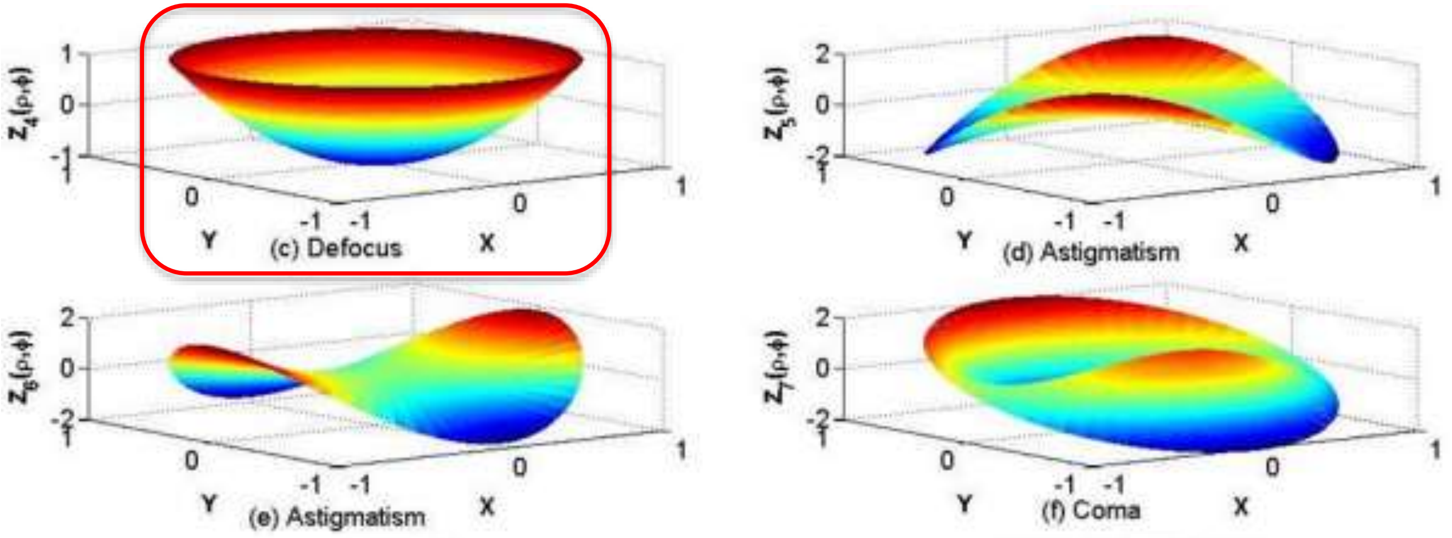
Vacuum chamber
with cooling system

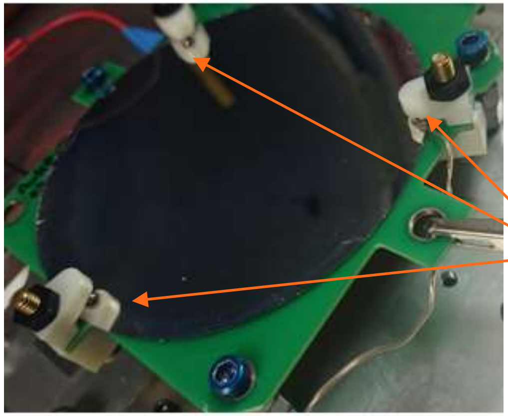


Shack Hartmann WF sensor

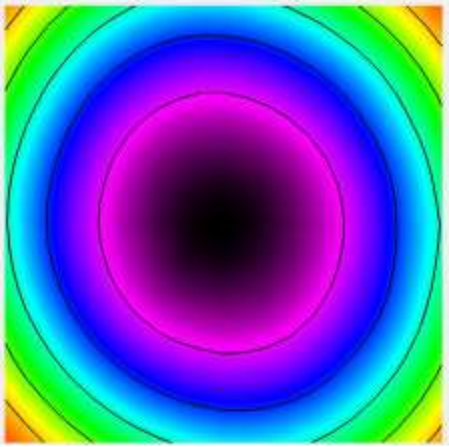
Caltech

Mirror deformation: defocus





Kinematic mounts

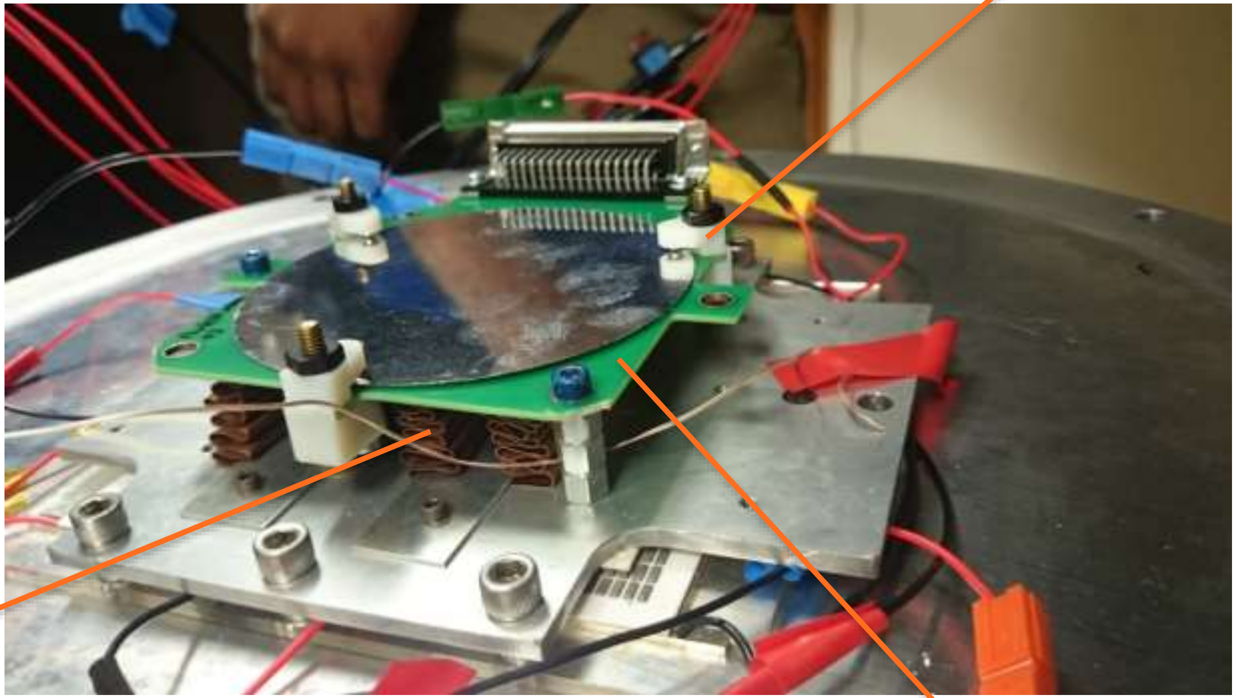


SHWS measurement of Sample1

Caltech

Problems with the old setup

Plastic ⟶ poor conduction



Copper springs (press against plate)

Plastic PCB plate (deforms mirror)

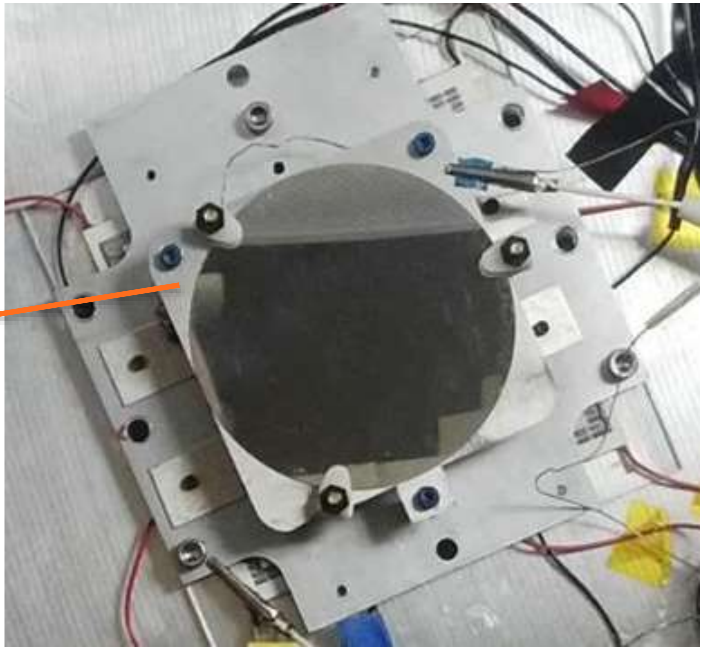
Caltech

Improvements

- New setup
  - Better conduction
  - Included radiation shield
  - Aluminum plate stiffer

After improvements:
-4°C on mirror

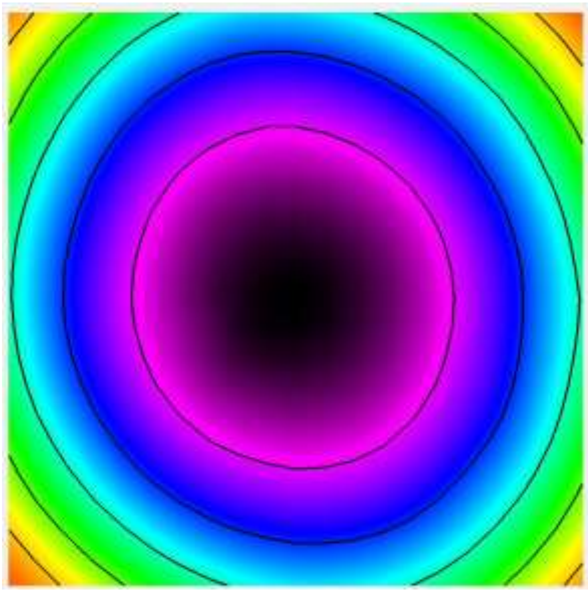
Aluminum plate



Caltech

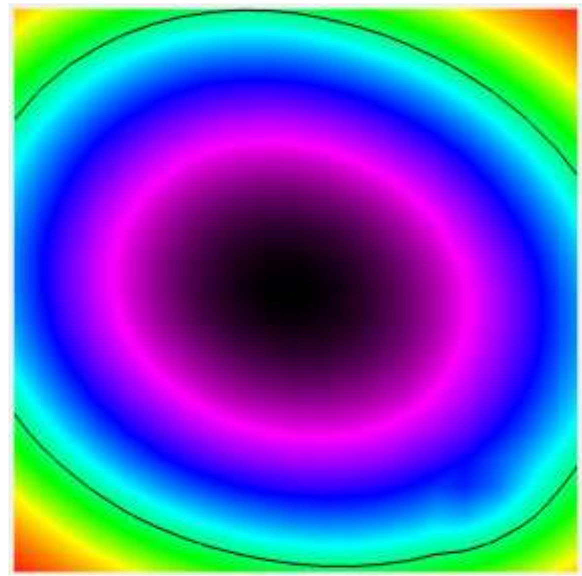
Sample Testing

- Sample 3 shows too much initial astigmatism (Z4 & Z6)



Z 4(2/-2) -0.159
Z 5(2/ 0) 2.281
Z 6(2/ 2) 0.243

Sample 1



Z 4(2/-2) -0.536
Z 5(2/ 0) 3.055
Z 6(2/ 2) -0.761

Sample 3

Samples 2 and 4 were much more astigmatic

- Only sample 1 used for analysis

Caltech

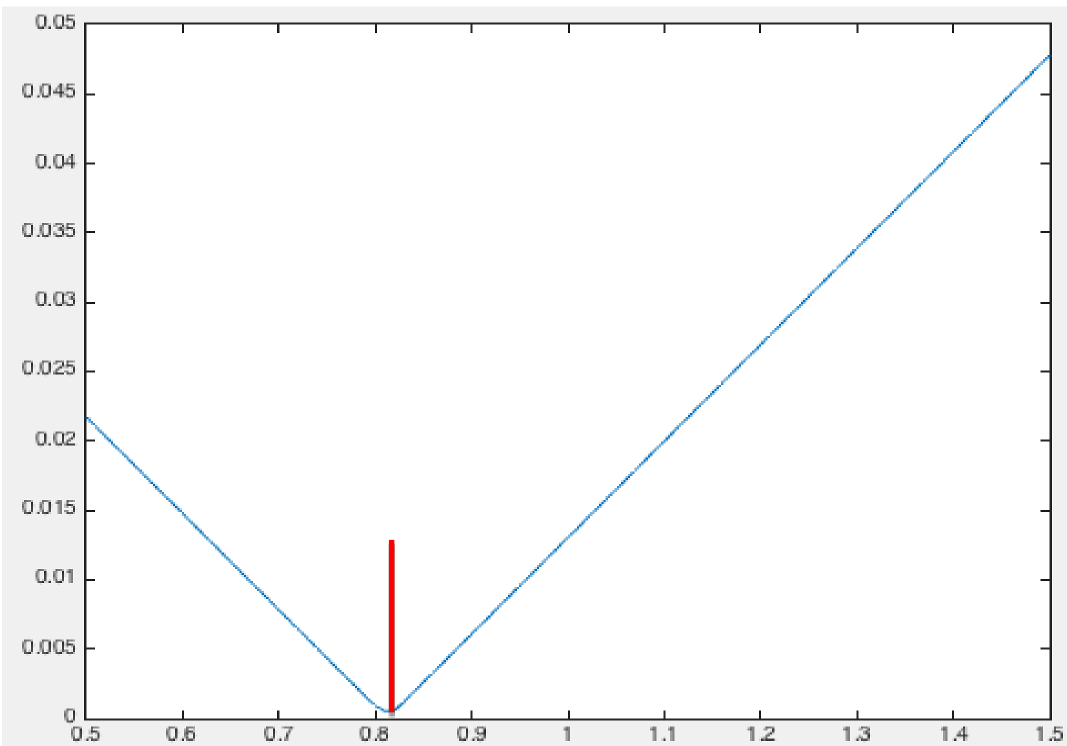
Results and Analysis

Determination of Material Properties

Stoney's Formula $$\kappa = \frac{6\Delta T}{{t_s}^2 {M_s}^2} \sum_i s_i(\alpha_i - \alpha_s) M_i\, t_i$$

Cost function : $\varepsilon_{abs}(\Delta T, E_{Al,}, \alpha_{Al}, E_{Cr}, \alpha_{Cr}) = \left|\kappa_{theoretical}(\Delta T, E_{Al,}, \alpha_{Al}, E_{Cr}, \alpha_{Cr}) - \kappa_{experimental}(\Delta T)\right|$

Error between data and model



Free Parameter a

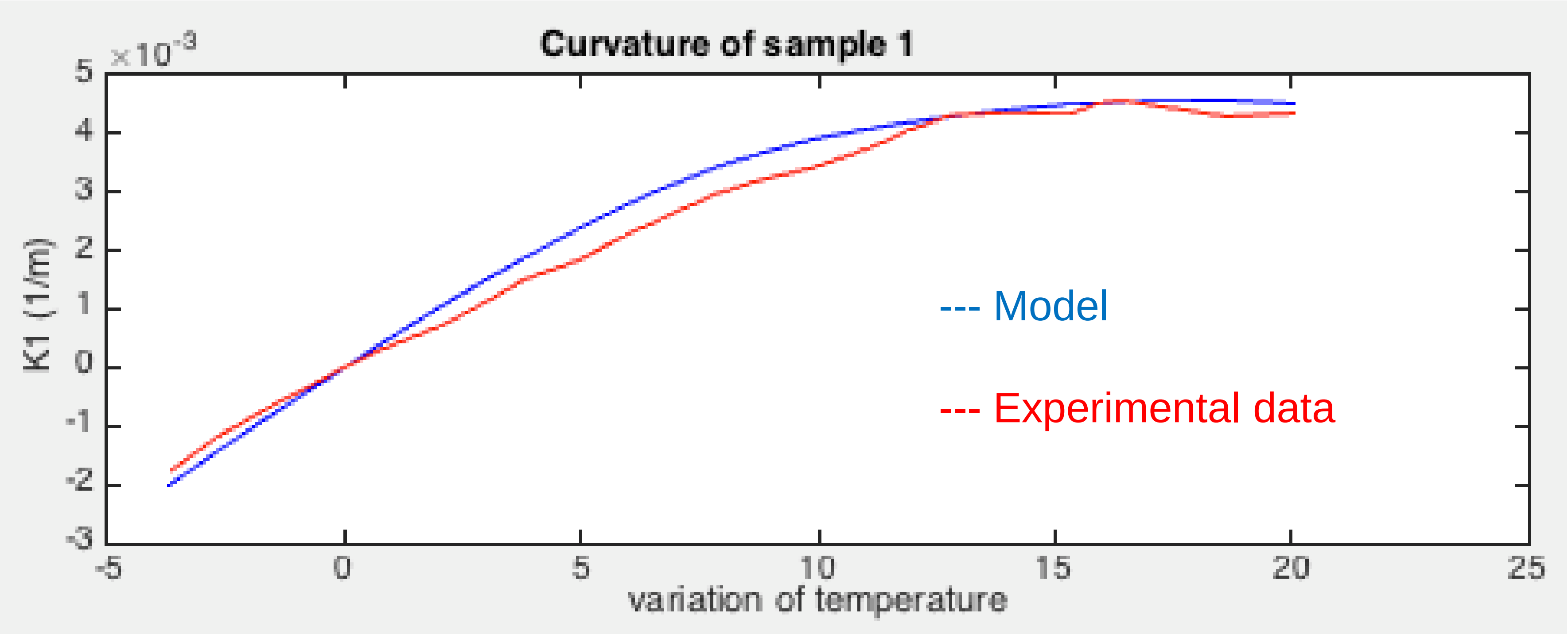
Range expected :

- E_{Al} = [50;70Gpa]
- E_{Cr}= [140;250Gpa]
- α_{Al}= $[18; 23 10^{-6}\ \mathrm{K}^{-1}]$
- α_{Cr} = $[4.5; 5.5 10^{-6}\mathrm{K}^{-1}]$

Results of curve-fit:

- $E_{Al} = a * E_{Al,bulk} =$ 56.7 Gpa
- E_{Cr}= 202.5 Gpa
- α_{Al}= 20.1 $10^{-6}\ \mathrm{K}^{-1}$
- $\alpha_{Cr} = 4.9\ 10^{-6}\mathrm{K}^{-1}$

Model Validation



- Maximum relative error = 24%
- Mean relative error = 11%

Error due to:

- Initial curvature of sample
- 3D effects

Model validated

Caltech

Optimization strategy

Design choices

- Reflective layer composition: Aluminum + Chromium (stiffer)
  - 3 sublayers of Al
  - 3 sublayers of Cr
- Ratio Al/Cr = 10 ⟶ $t_{Cr} = t_{Al} / 10$

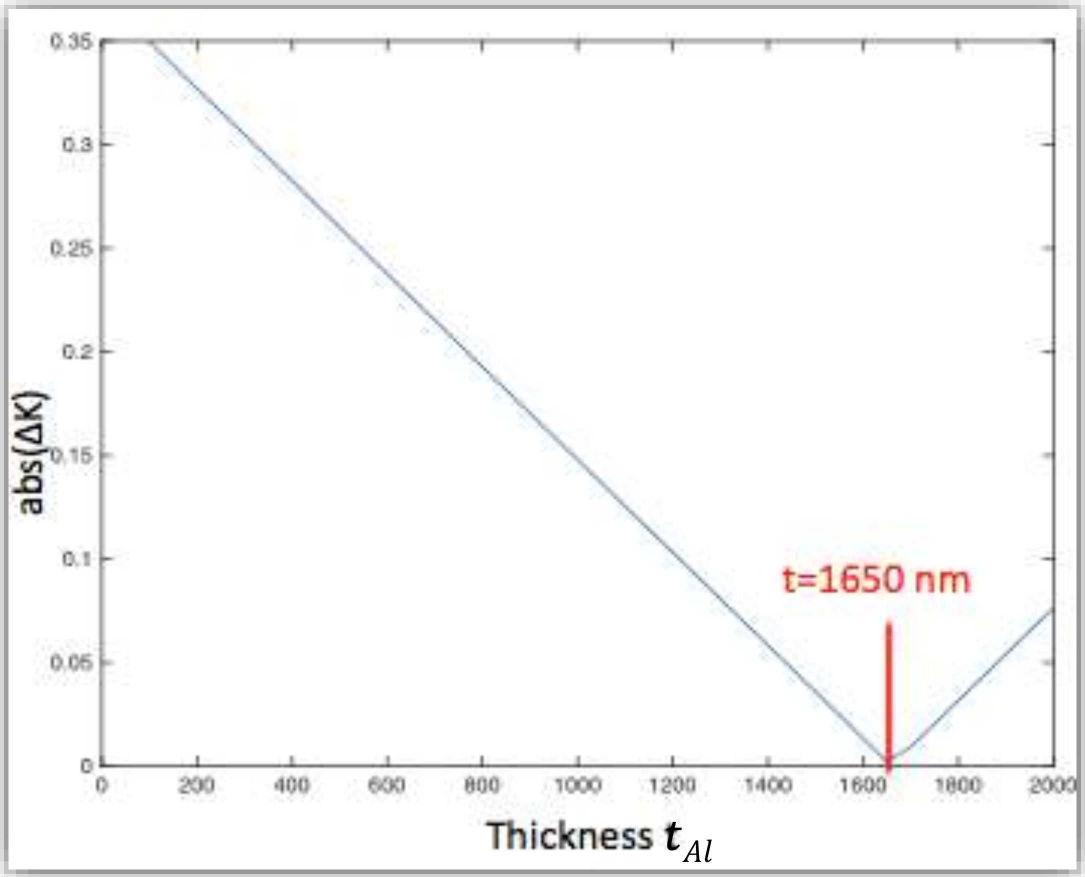
$$|\kappa(t,\Delta T)| = \left| \frac{6\Delta T}{{t_s}^2 {M_s}^2} \left(3t(\alpha_{Al} - \alpha_s) M_{Al} + 3\frac{t}{10}(\alpha_{Cr} - \alpha_s) M_{Cr} \right) - \frac{6\Delta T}{{t_s}^2 {M_s}^2} \sum_j \left(\alpha_j - \alpha_s \right) M_j \, t_j \right|$$

Cost function: $\varepsilon(t) = max_{\Delta T}(|\kappa(t,\Delta T)|)$

Caltech

Optimization of reflective layer

$$\varepsilon(t_{Al}) = max_{\Delta T}(|\kappa(t_{Al}, \Delta T)|)$$



Final Design Recommendation for composition of reflective layer:

- 3 sublayers of Aluminum of thickness t_{Al} = 1.65 µm
- 3 sublayers of Chromium of thickness t_{Cr} = 0.165 µm

➢ Overall thickness :
$t_{Reflective}$ = 5.445 µm

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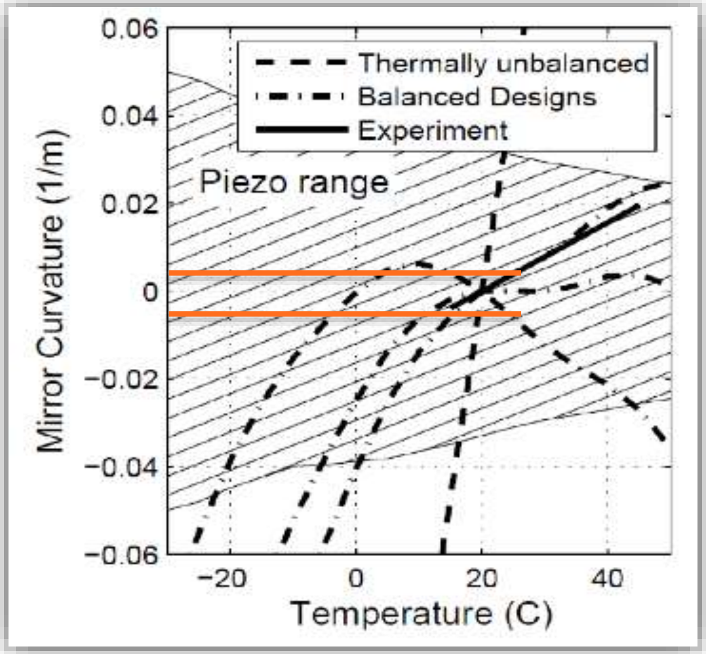
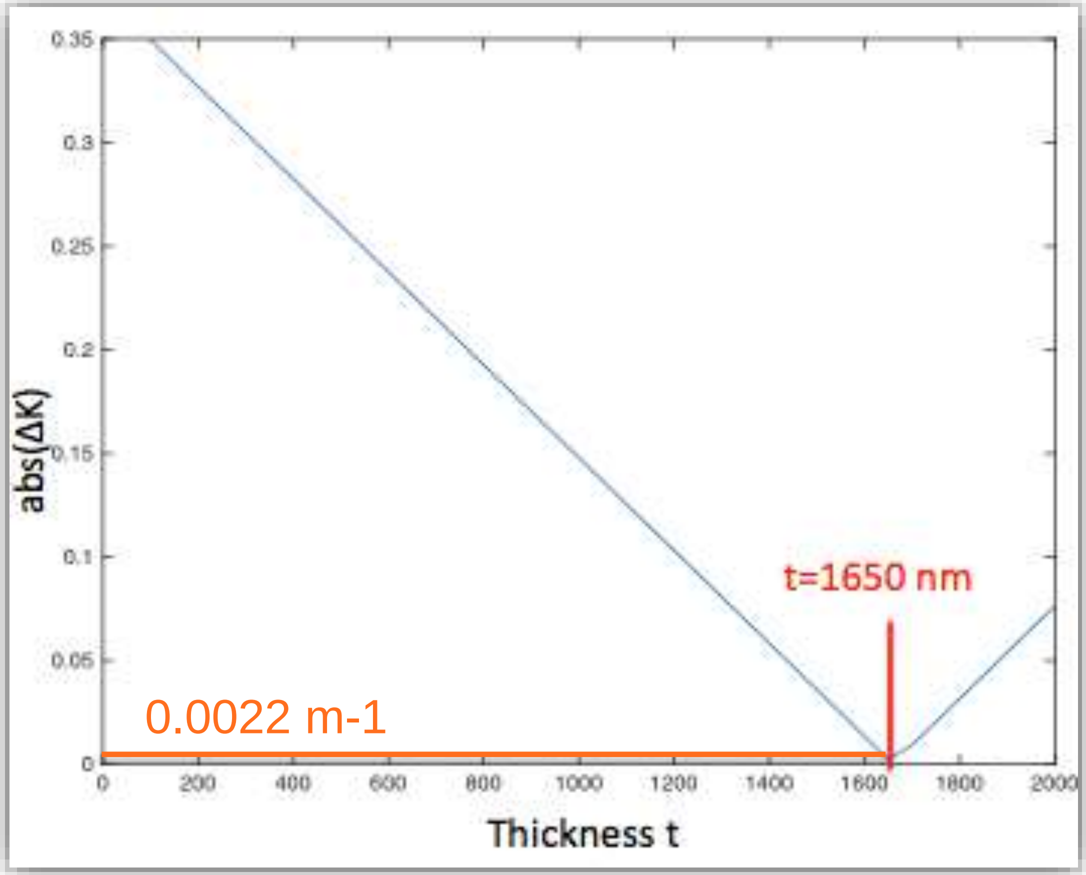
Requirements are met





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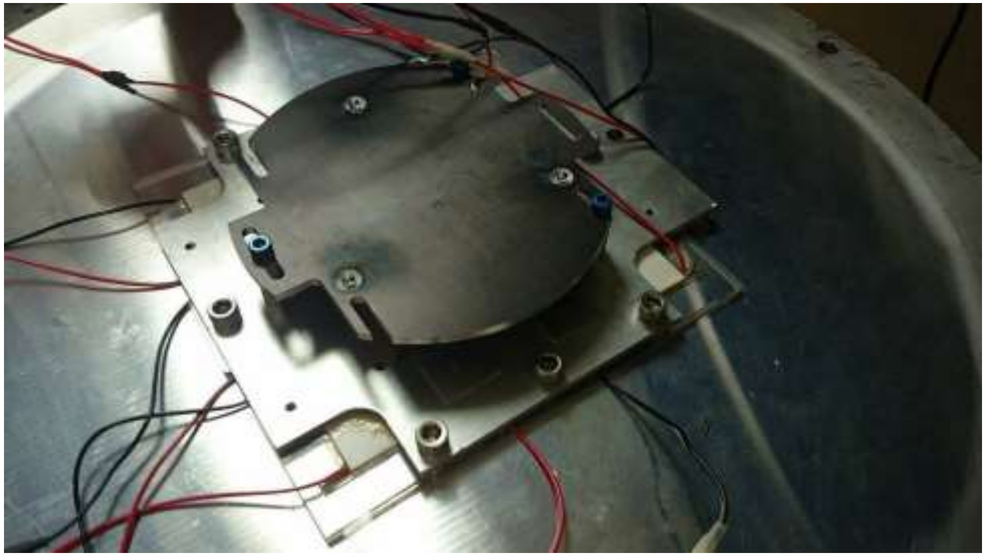
Testing of new design

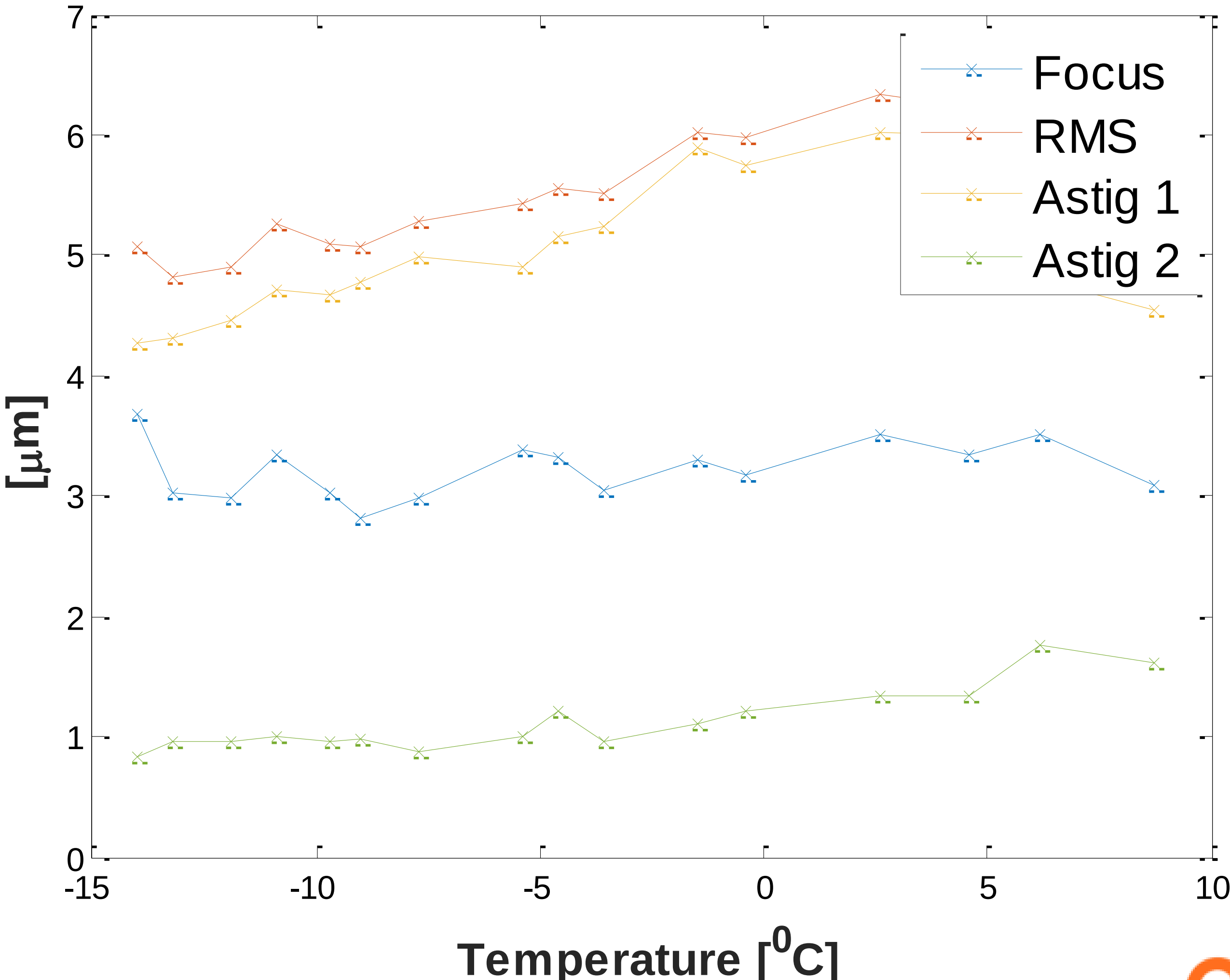
- Latest setup (reached -16℃ on mirror)



- Reversed Hartmann

Caltech

Results for new design



Caltech

Conclusion

Work completed:

- ✓ Testing and characterization of mirror samples
- ✓ Developed Simulation tool
- ✓ Optimization of mirror layering
- ✓ Design recommendation
- ✓ Testing of new design

Future work:

- Improvement of cooling capacities
- More testing of latest design
- Error budget

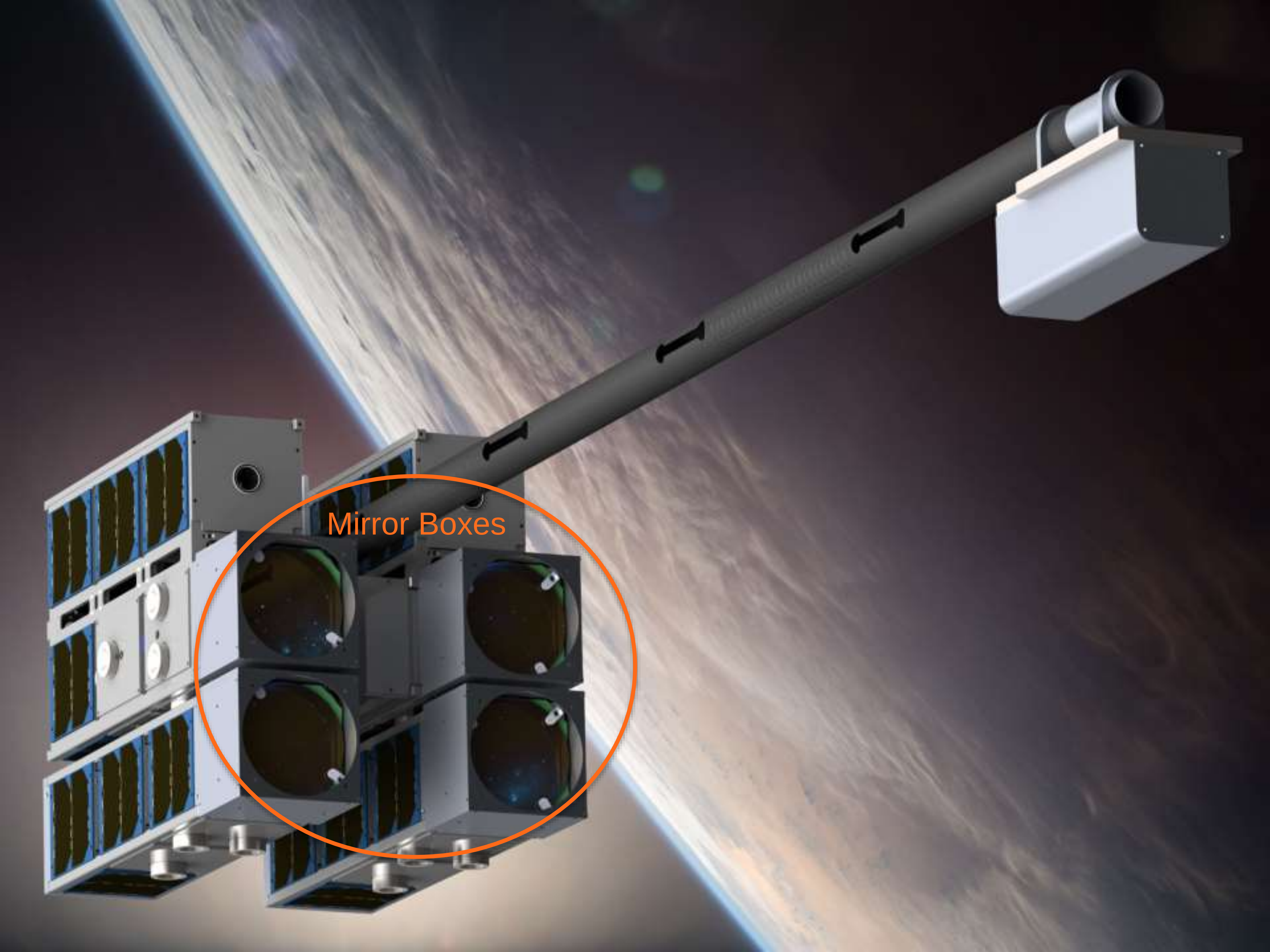
Caltech

Mirror Box

Tatiana Roy
Albert Yang

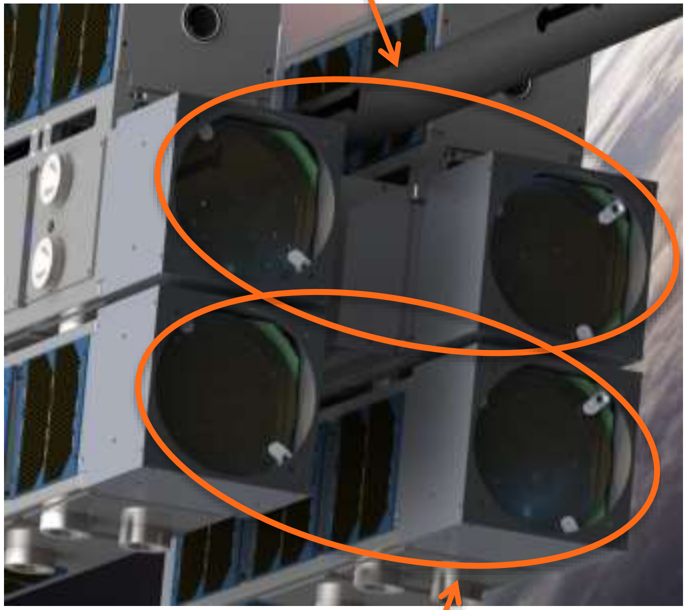
Mentor: Lee Wilson

Caltech


Mirror Boxes

Two Types of Mirror Boxes

- Mirror box contains all required infrastructure for telescope mirrors
  - Two reference (rigid) mirrors and two deformable mirrors in total
  - Will focus primarily on the deformable mirrors



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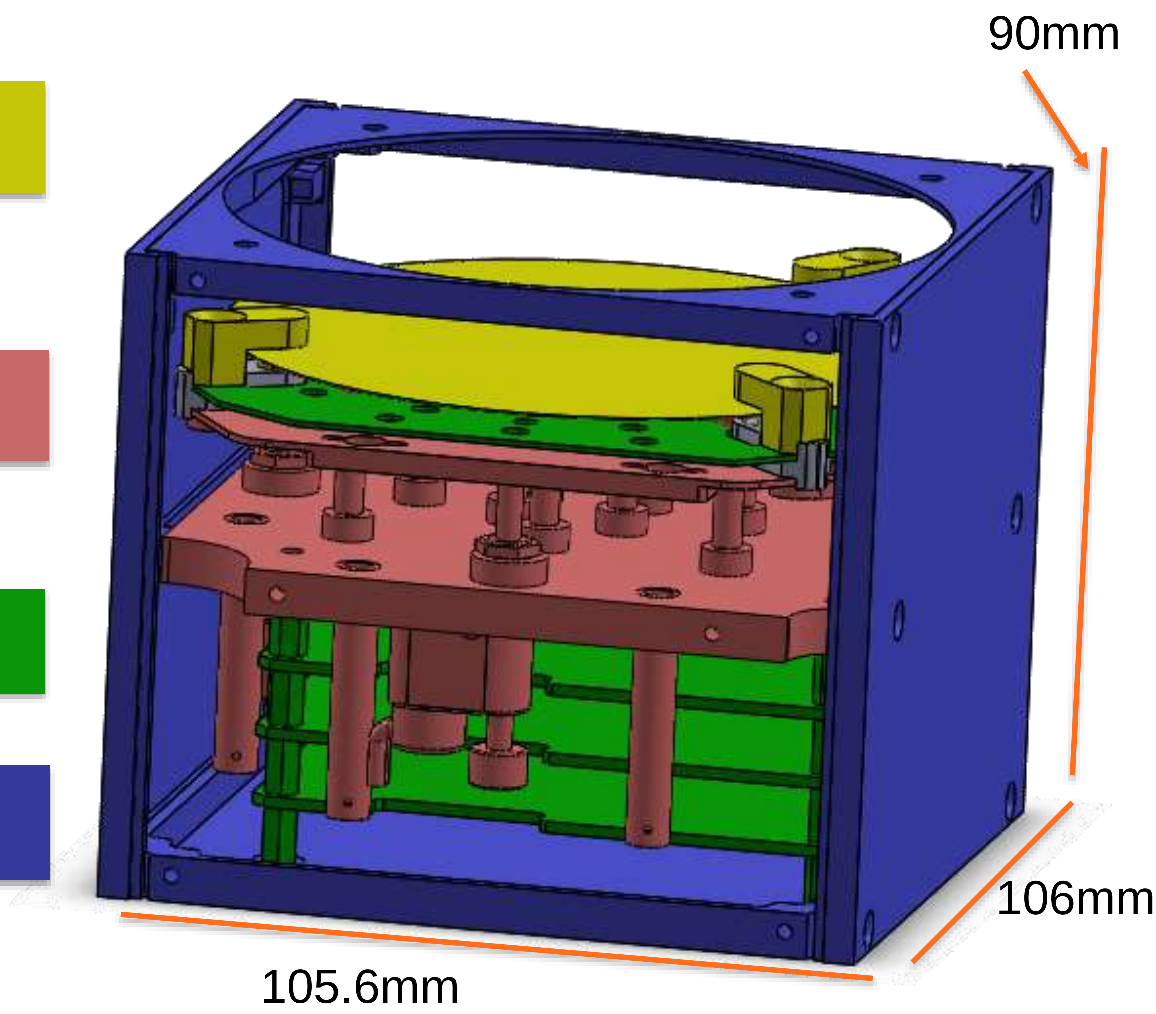
Box Subsystems

- Mirrors
  - Mirrors subsystem holds the mirror in place
- Picomotors
  - Piston/tip/tilt the mirror
- Electronics
  - House electronics
- Frame
  - Hold all mirror box elements and interface with CoreSat



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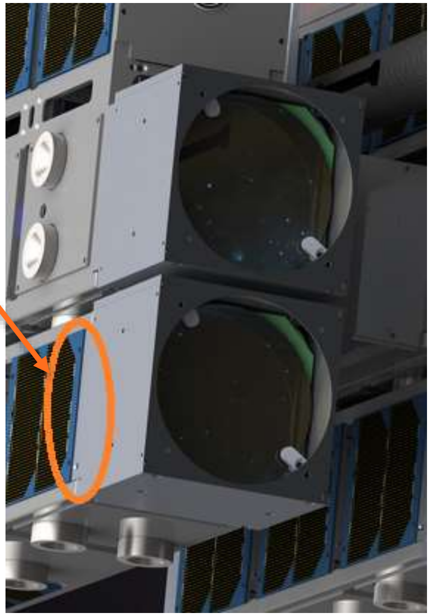
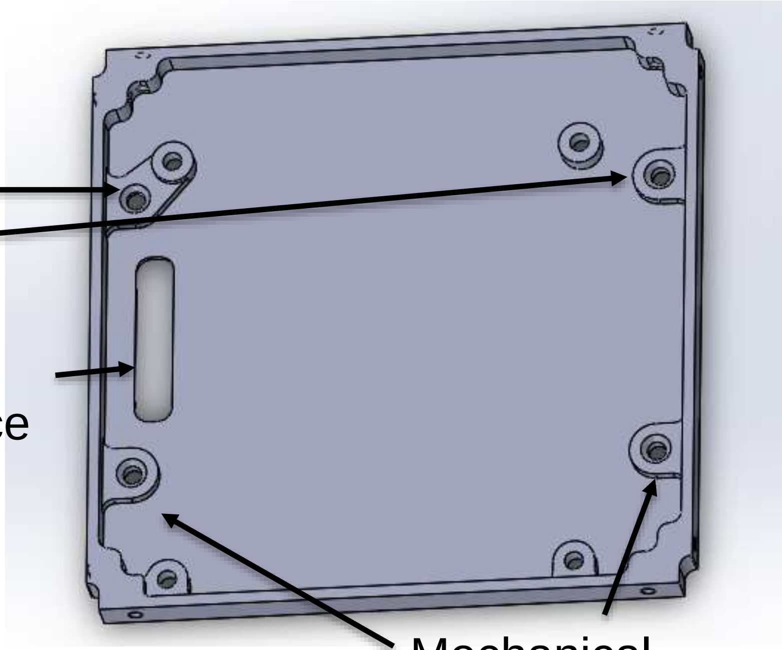
CoreSat Interface

- Must match with pre-established Surrey mechanical and electrical interfaces





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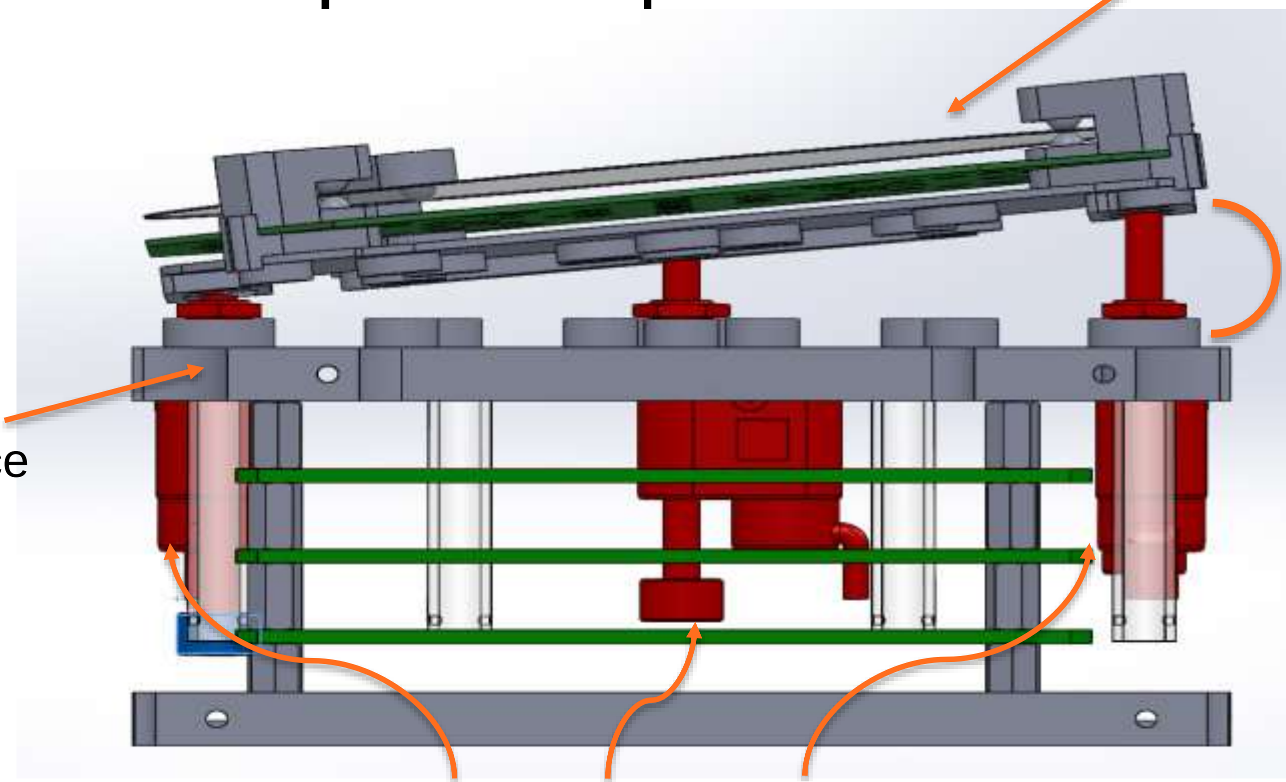
Functional Requirements

- Survive launch loads
- Provide mechanical support for a set of deformable mirrors, rigid mirrors, and mirror electronics
- Allow mirror to operate within the required range of tip, tilt, and piston positions)

Performance Requirements

- Provide tip/tilt of up to 6.85°



Mass Budget

- Mass Requirement: <680g per box

Current Best Estimate:

Subsystem	Current Mass (g)	% total	Contingency (g) (30%)	Total (g)
Mirror*	28	5.5	9	37
Picomotors	263	51.7	79	342
Electronics	38	7.5	12	50
Frame	180	35.4	54	234
Total Mass	**509**		**154**	**663**

Caltech

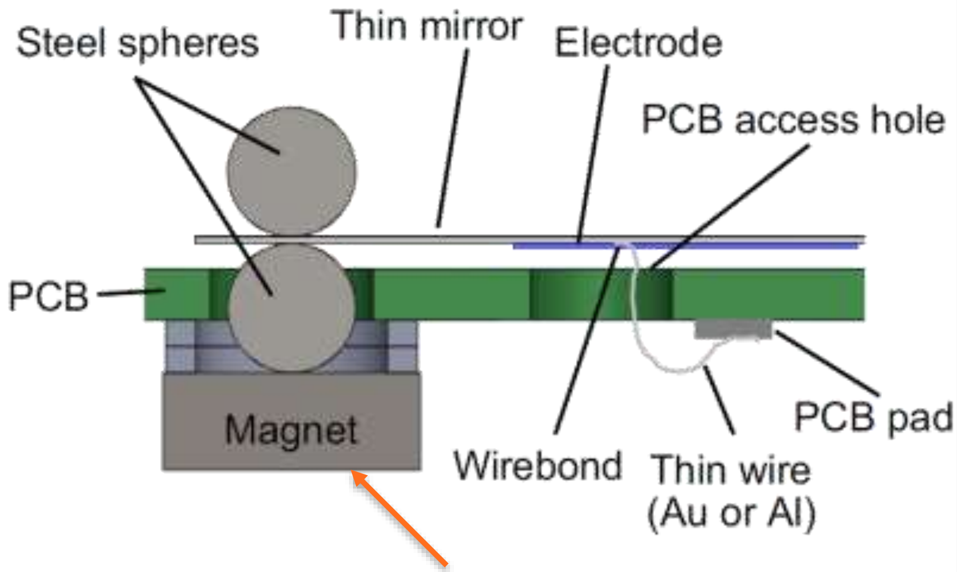
Addressing Requirements

- Mirror Mounts
  - Updated mount design to solve pinching issue
  - Tested new mount design
- Damping Columns
  - Designed damping columns to interface with mirror box and mitigate launch loads
  - Chose damping material
- Updated mirror box design

Caltech

Mirror Mount: Old Design

- Curved mirror is extremely thin. Mirror is prone to deformation near mounting sites
  - Old mounts designed for flat mirrors
  - Curved mirrors need different mounts
  - Changes in shape will lead to reduced overall performance

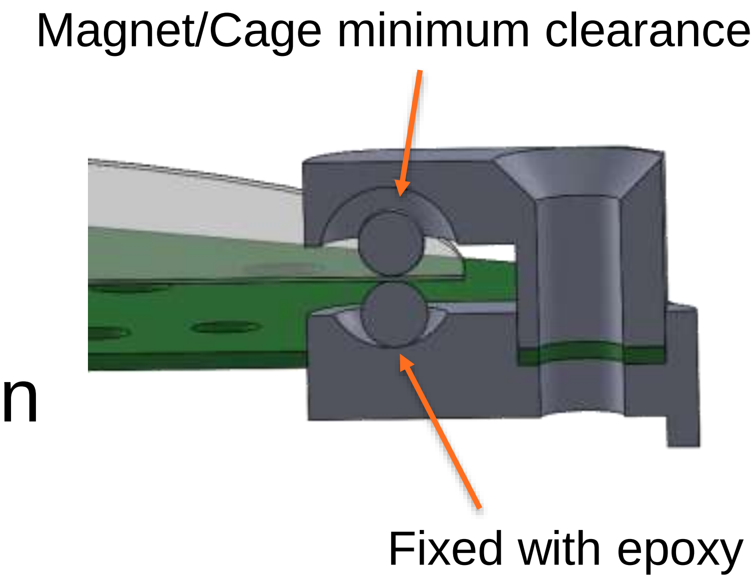


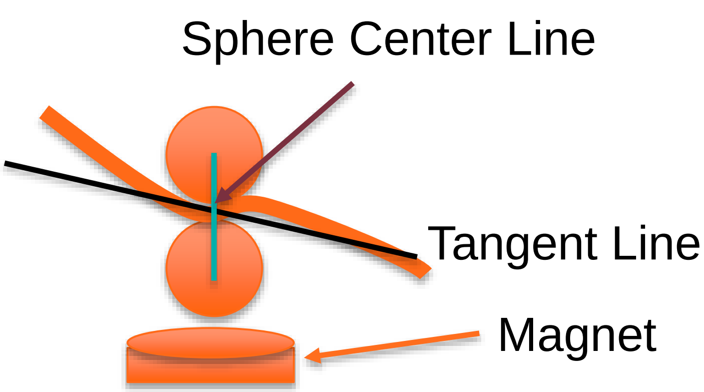
Old Design Relied on Cylindrical Magnets

Caltech

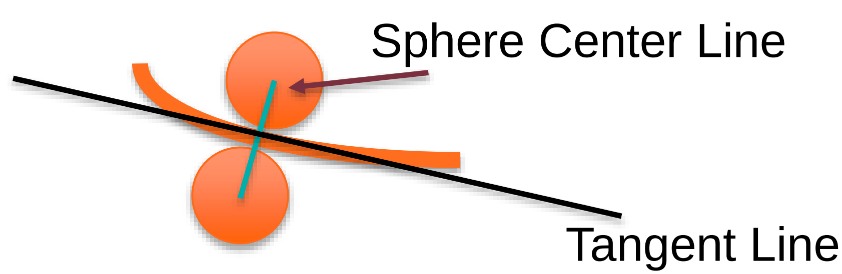
Mirror Mount: New Design

- Designed new mount
  - Single point of contact on each side of the mirror
  - Top cage required to retain magnet





Old Mounts

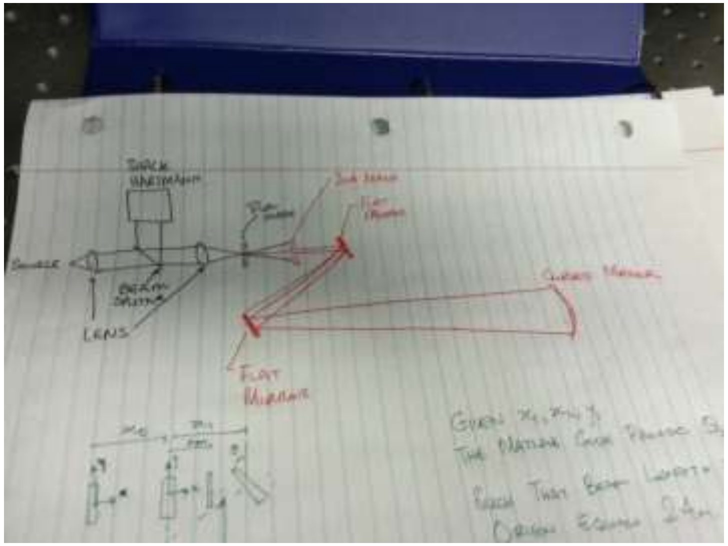


New Mounts

Caltech

Testing Mirror Deformations

- Zernike coefficients were calculated using SHWS to measure deformations
  - Need 2.4m (radius of curvature) path to SHWS
  - Independent test also conducted
  - Looking for trefoil shape deformation in mirror

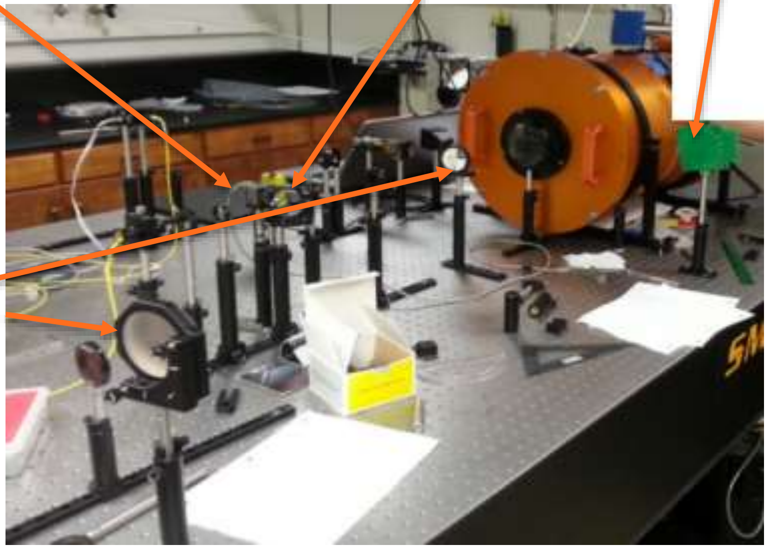


Mirror Fixture

Beam Splitter

SHWS

Flat Mirror



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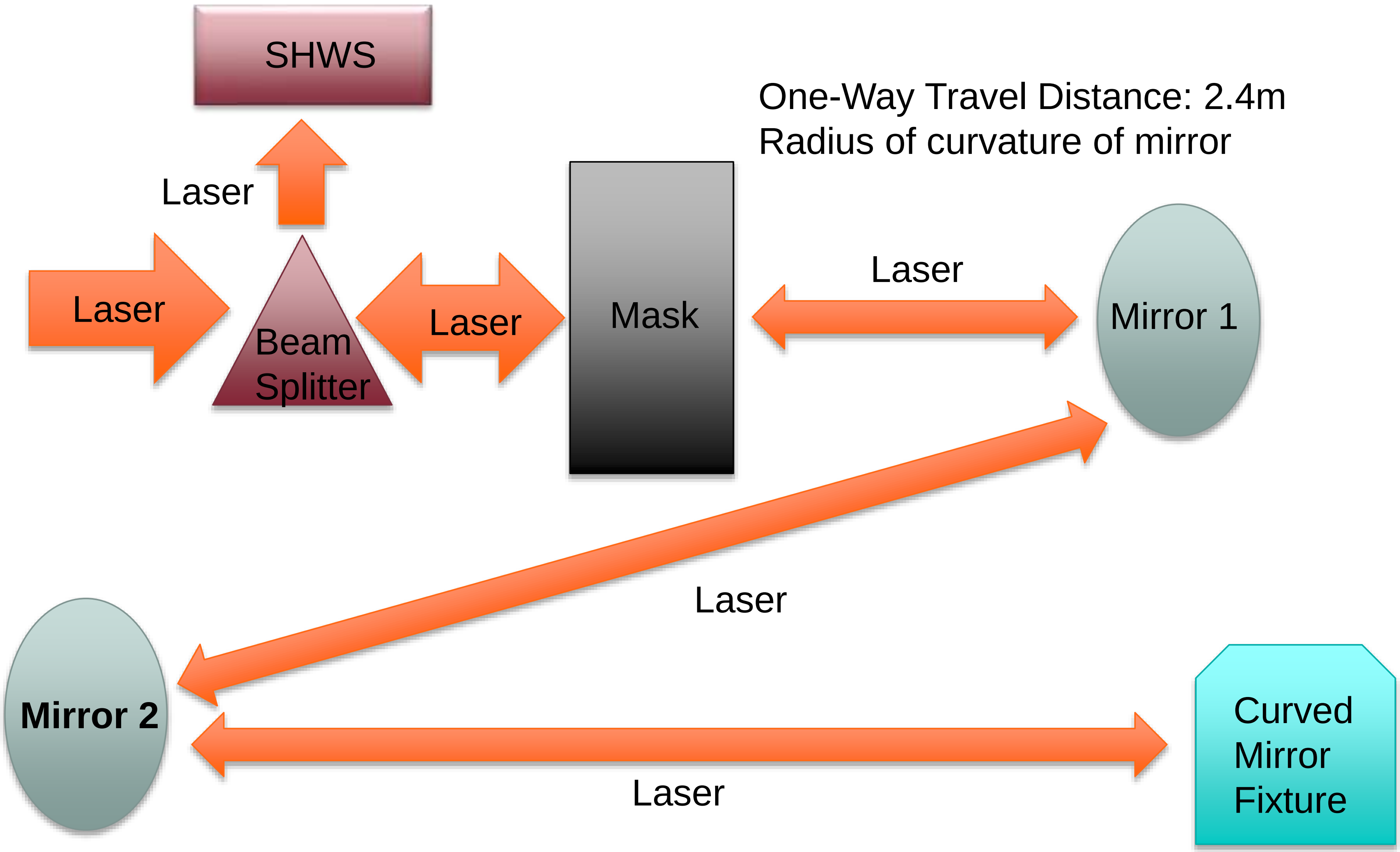
Mirror Deformation Testing Setup

One-Way Travel Distance: 2.4m
Radius of curvature of mirror



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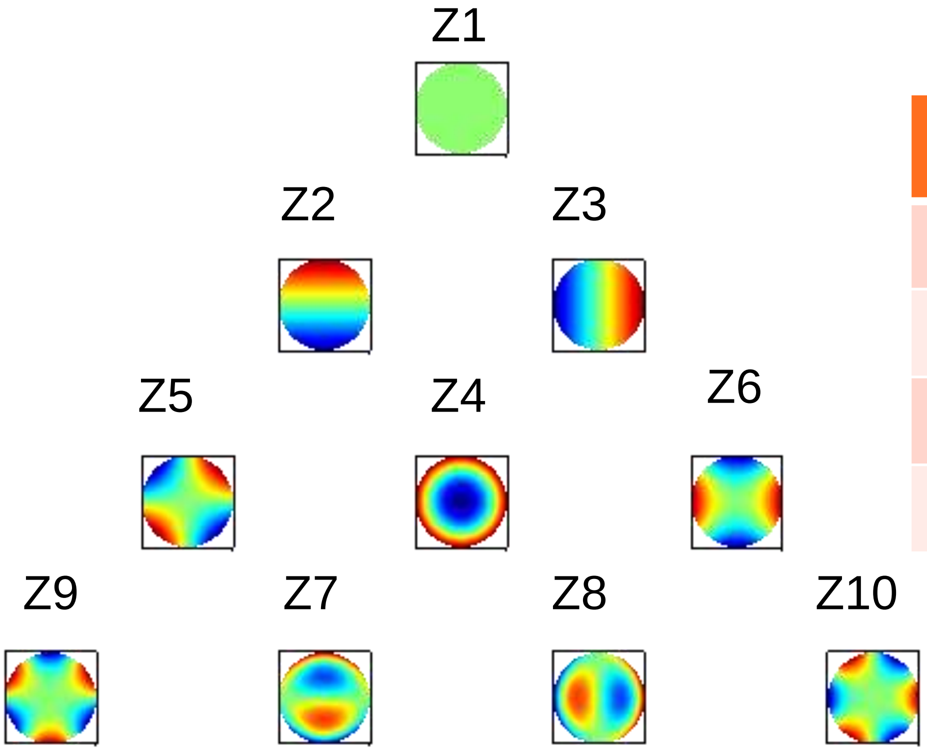
Mirror Mount Deformation Results

- Mirror had high Z4 and Z5 values
- Z9 and Z10 are not present in our test

Consequently, mirror mounts do not deform mirror



Zernike	Tested	Name
4	.7	Defocus
5	2.5	Oblique Astigmatism
9	<.1	Vertical Trefoil
10	<.1	Oblique Trefoil

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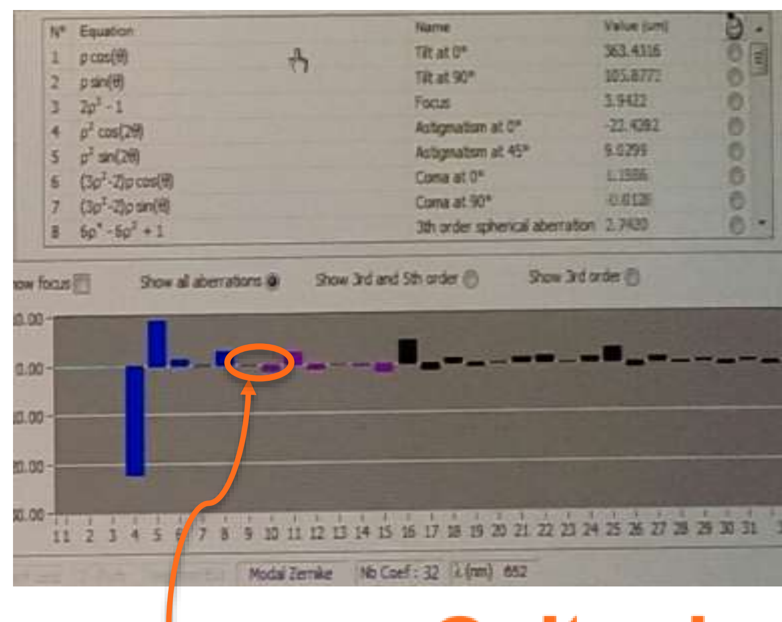
Mirror Mount Characterization

- A test was also performed on a Haso SHWS by Caltech Post-Doc Steve Bongiorno
  - Performed on different mirror, manufactured to have less errors
  - Concluded mirror aberration was dominated by astigmatism, and not by any trefoil shape



Low Relative Values

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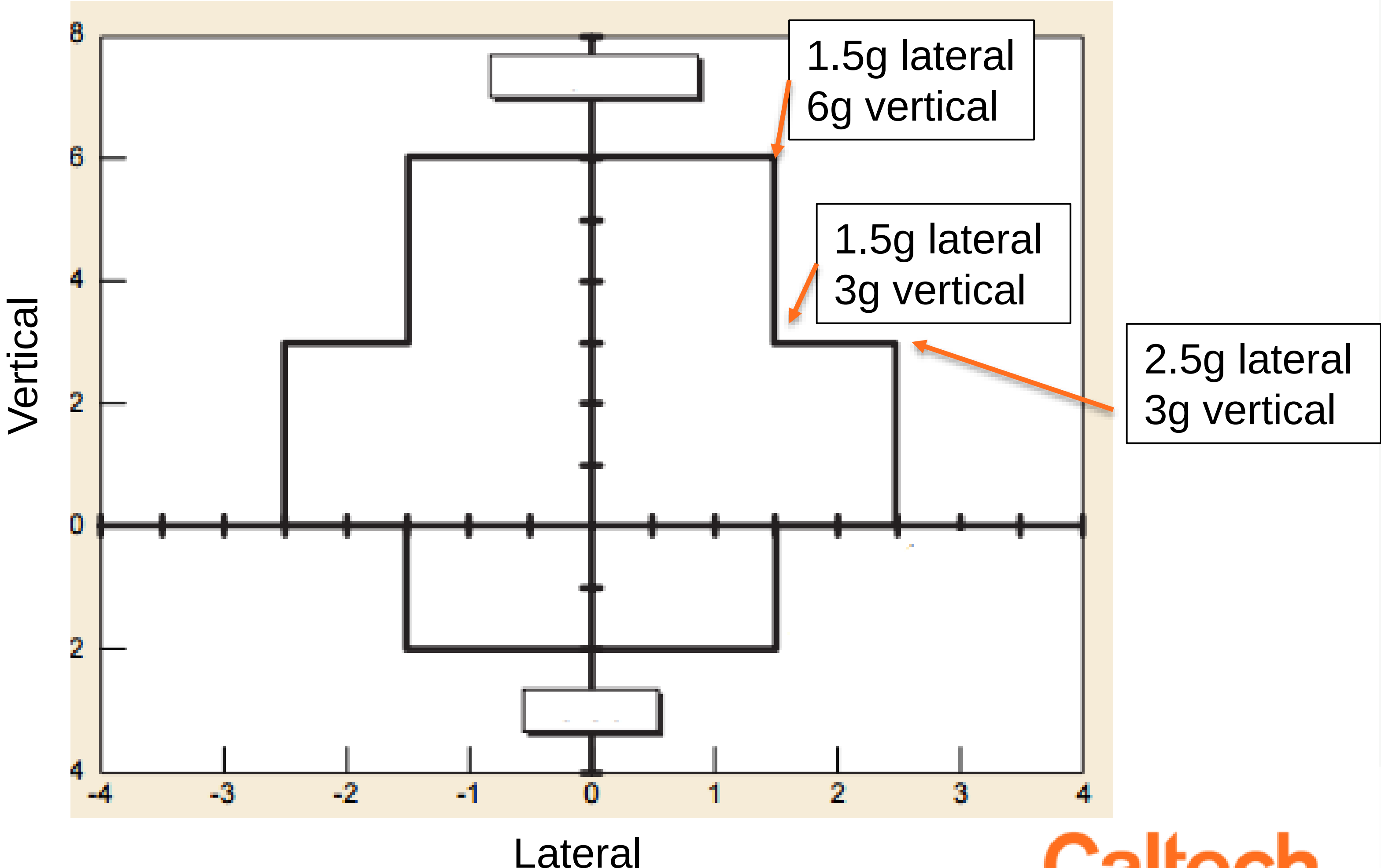
Launch Survival

- Large vibration loads during launch: Mirror will vibrate and possibly shatter

From Delta IV Handbook



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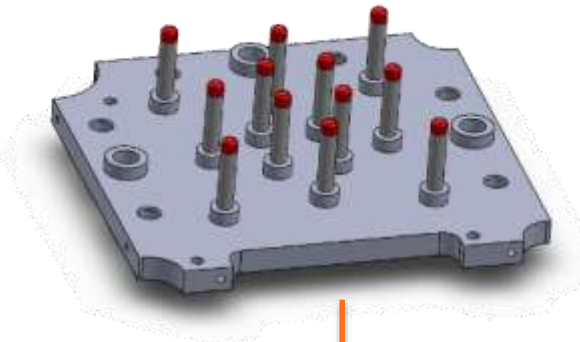
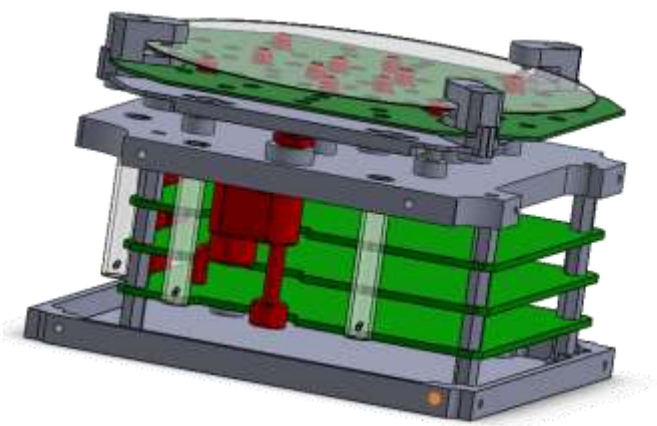
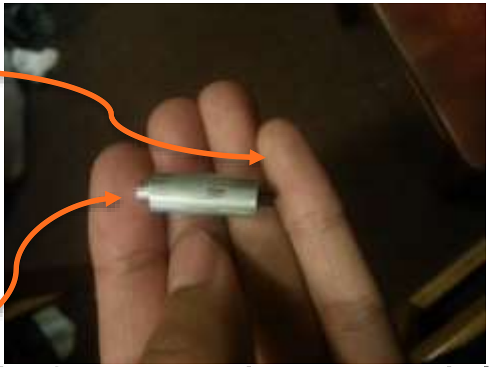
Damping Columns

- Damping columns attenuate vibrational energy by physical contact during launch
  - Damping columns are separated from the mirror after launch





Set screw in a tapped hole



Extruded Tip for Damping Material

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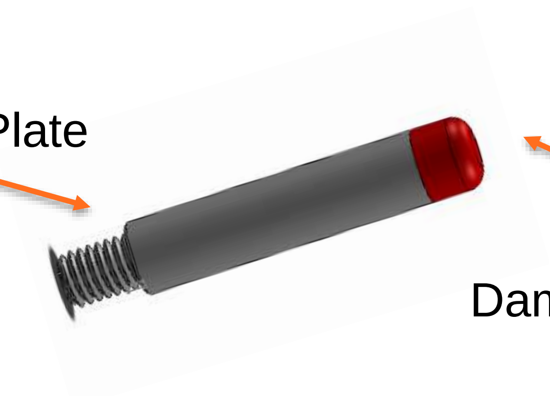
Damping Material

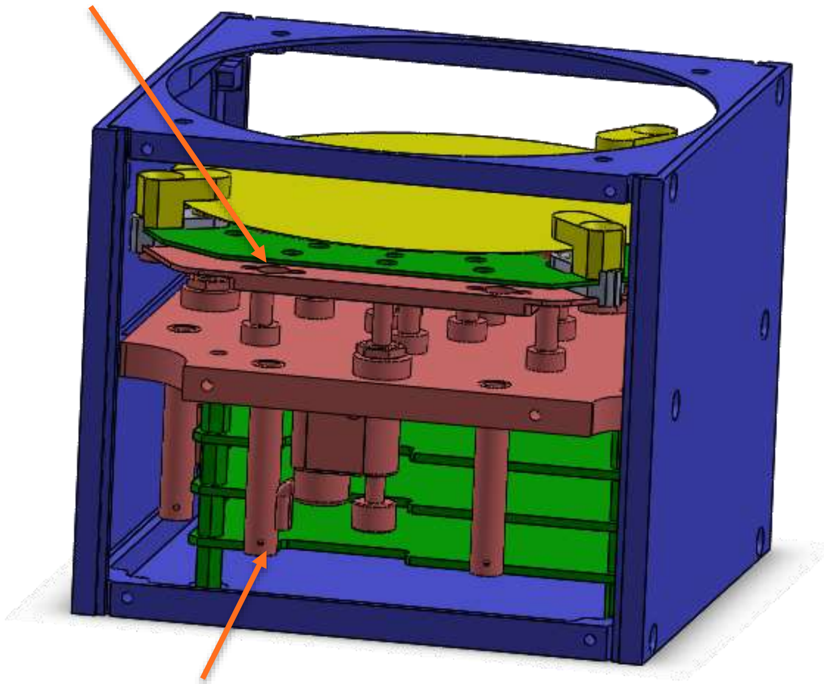
- Chose Red Silicone foam as damping material
  - Reported CVCM (collected volatile condensable materials) of <0.005 (lowest possible)
  - Rated for -100F to 400F (required -50F to 50F)



Updated CAD: Spring Tubes

- Keep mirror plate connected to reference plate while still allowing for normal picomotor operation
- Springs housed by tubes connect reference plate and mirror plate

One end attaches at mirror plate



One end attaches at bottom of tube

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Summary of Mirror Box Progress

- Designed new mirror mounts to solve mirror pinching issue
  - Prototyped new mounts and characterized with SHWS test
  - Showed no appreciable deformation
- Designed damping columns and chose damping material
  - Fabricated sample damping column
- Updated CAD to reflect design changes

Further Work Required

- Finish launch vibration survivability test
  - Finish profiling vibration table to make sure it can reach the frequencies required
- More SHWS tests with different configurations for the mirror
  - Test mirror with current mount vs. no mount
- Design and assemble reference mirror box

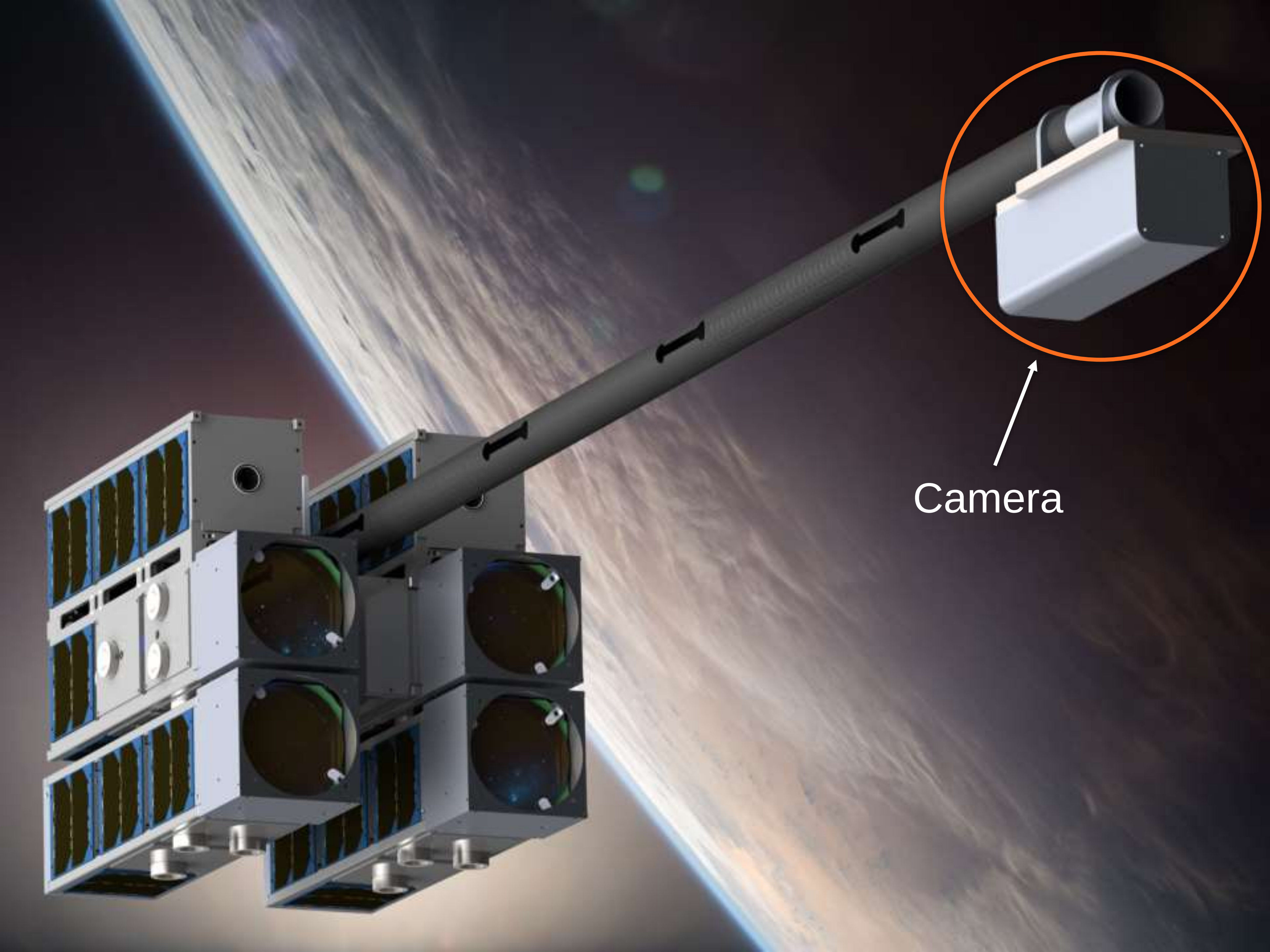
Questions?

Camera Prototyping

Kevin Bonnet
Christopher Chatellier
Monica Li

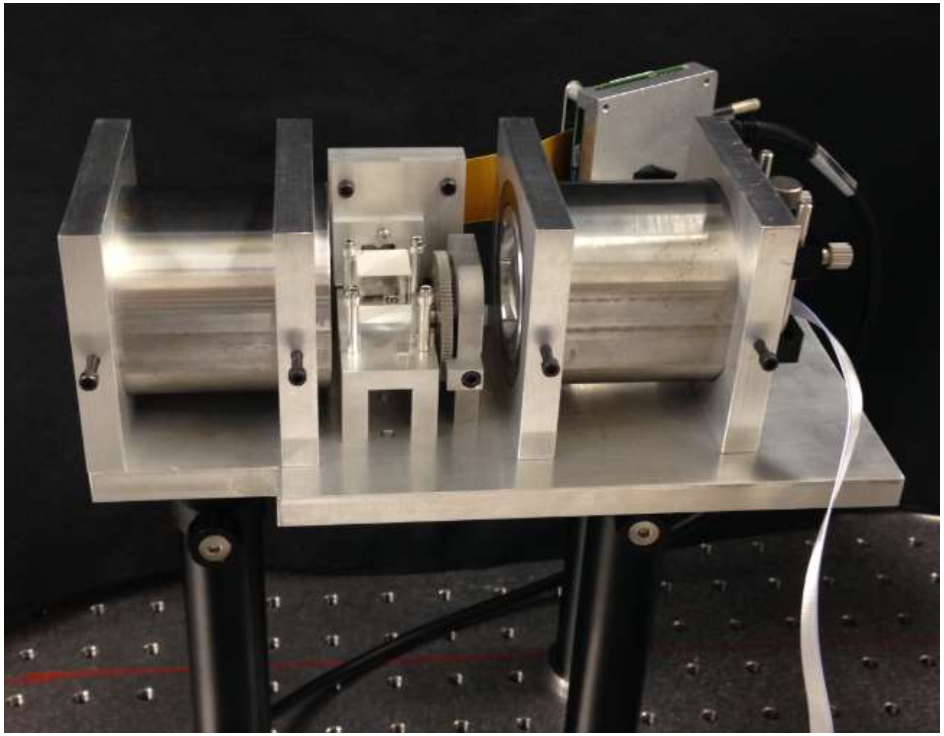
Mentor: Maria Sakovsky

Caltech


Camera

Overview

1. System Definition
2. Requirements
3. Camera Design
4. Prototype Testing
5. Future Work



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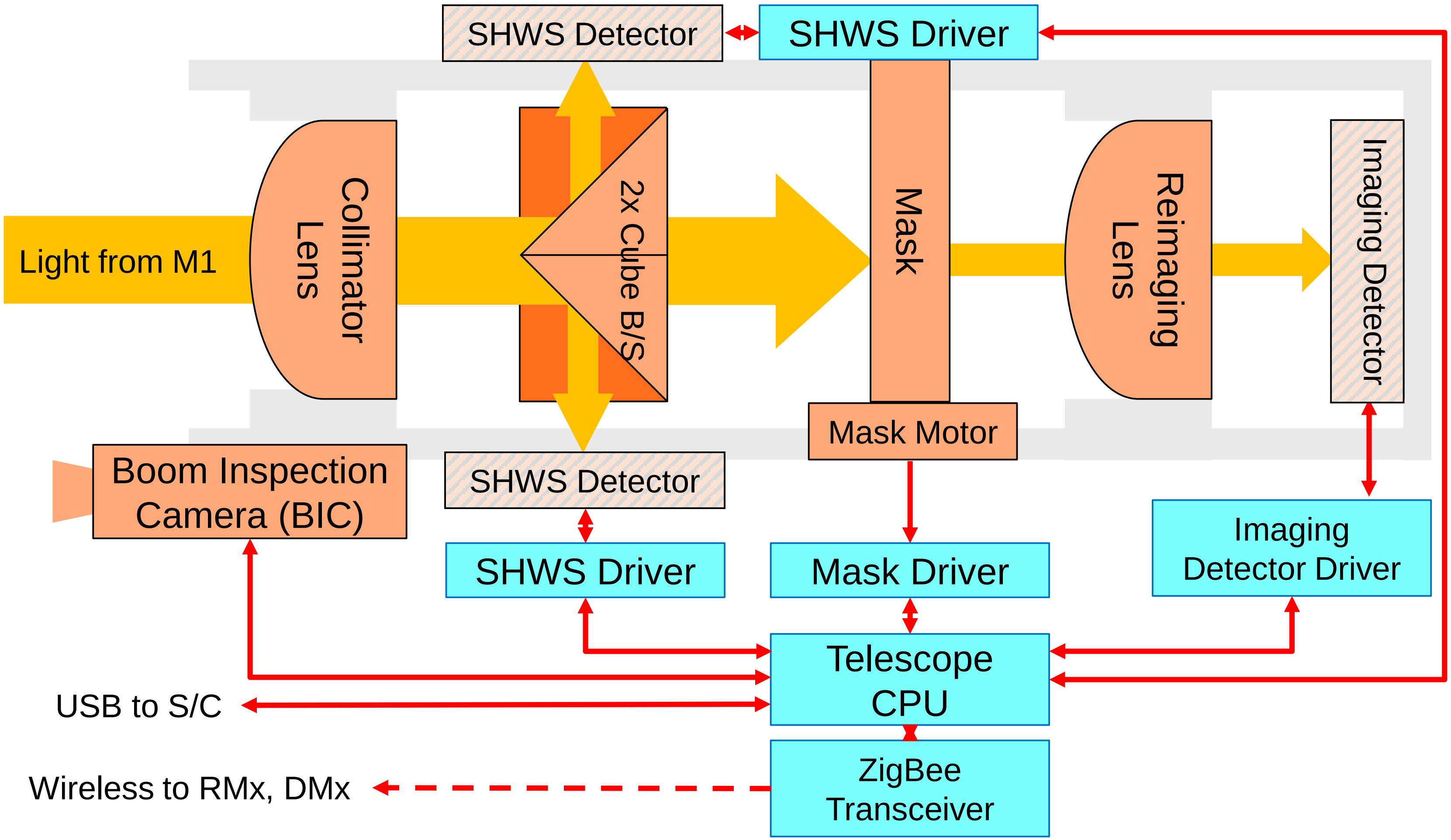
System Definition



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System Requirements

Functional:

- Work with reconfigurable primary mirror (**Mask Mech**)
- Provide feedback during primary mirror calibration (**SHWS)**
- Science imaging (**Entire Subsystem**)

Performance:

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

Constraints:

- Mass < 4kg (Currently **3.82 kg**)
- Volume < 10 × 10 × 35 cm (Currently **8.0 x 9.6 x 23.2 cm**)
- *Power < 5W (Currently ~ **7.1W peak power**)*

Task Overview

<u>Camera Mechanical</u>

- Mask Mechanism
- Beam Splitter
- Component Interfaces

<u>SHWS & Optics</u>

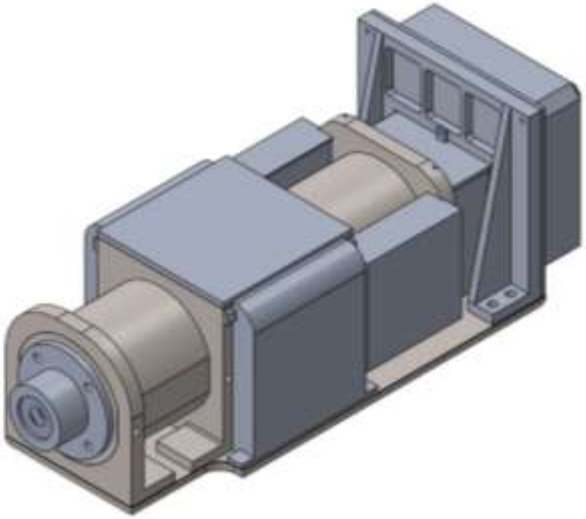
- Mount Design
- Alignment & Calibration

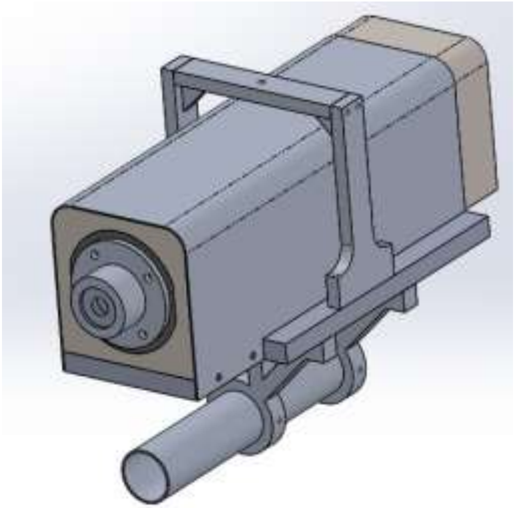
<u>Camera Prototype</u>

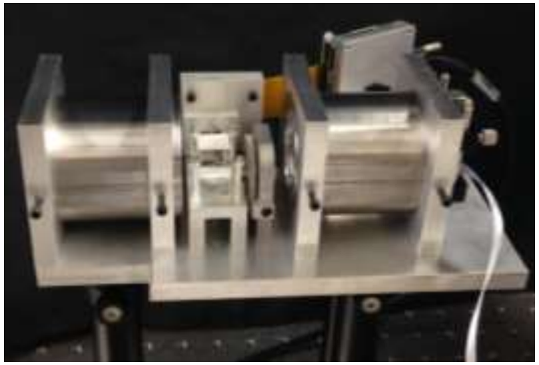
- Manufacture & Integrate
- Verification & Validation

→ **Mechanically Integrated Camera Prototype**

Camera Design







Initial Design

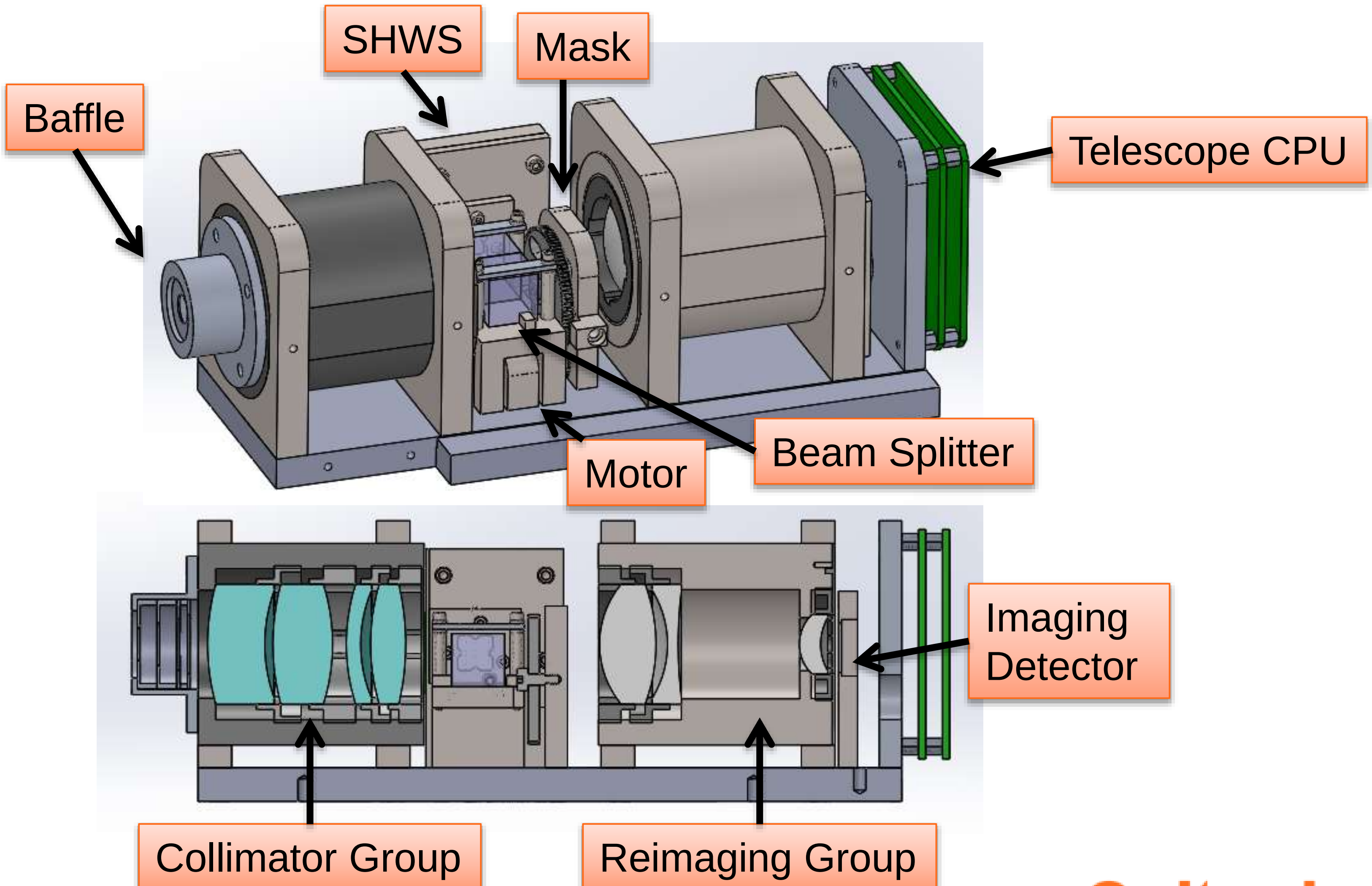
- Mechanical re-design after optical modeling
- Manufacture collimator & reimaging groups
- Mass ~ 2.9 kg

Current Design

- Modifications due to interface design
- Finalized & manufactured prototype
- Initial Design for external interfaces
- Mass ~ 3.8 kg (with 10% margin)

Caltech

Camera Mechanical

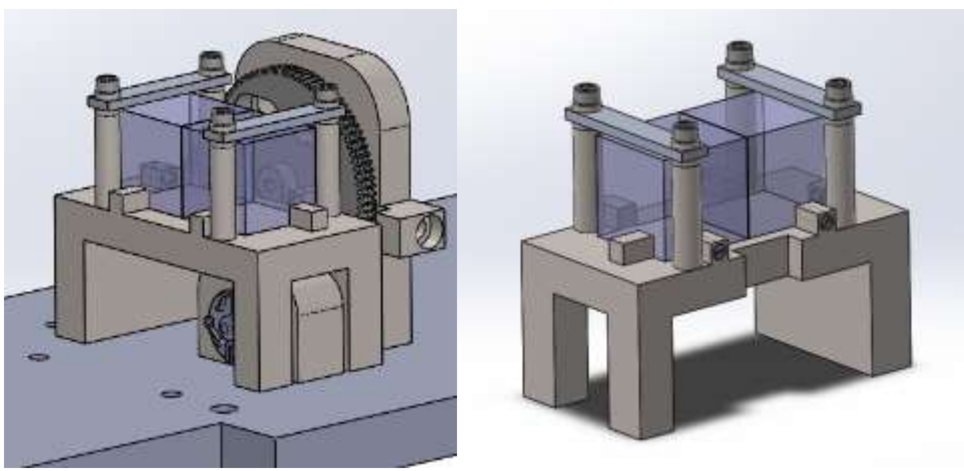


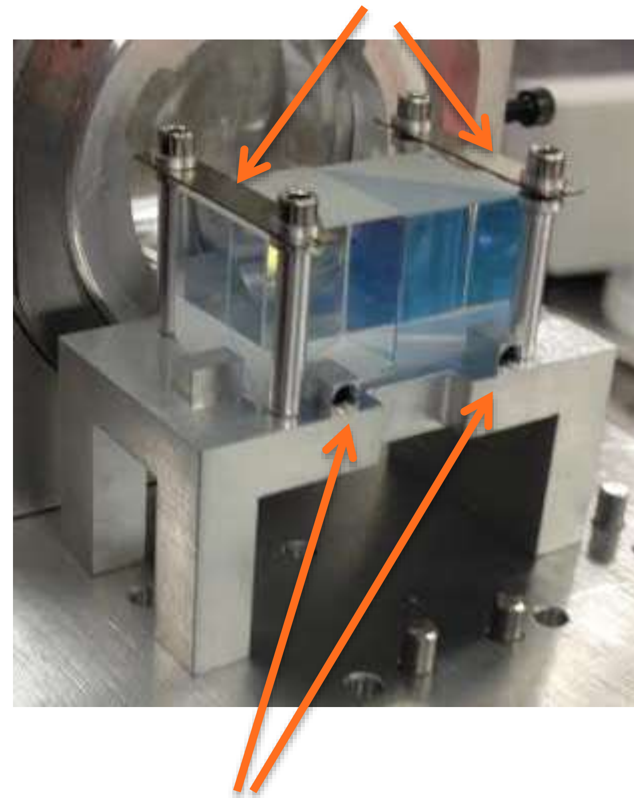
Caltech

Beam Splitter Assembly

- Designed for integration of neighboring components

- Utilized detents and spring steel to allow for thermal expansion

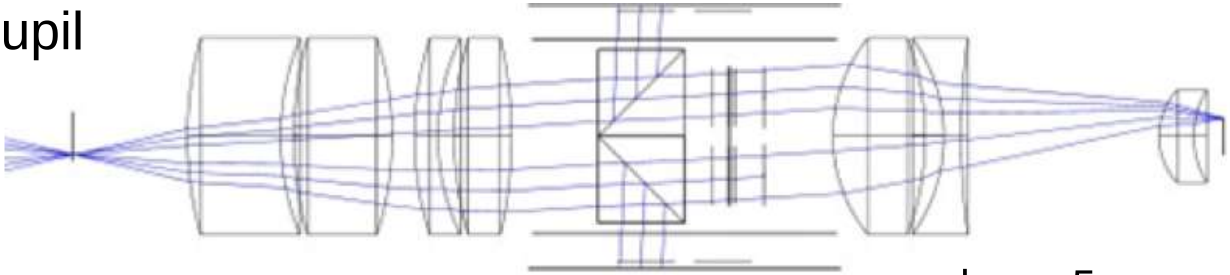


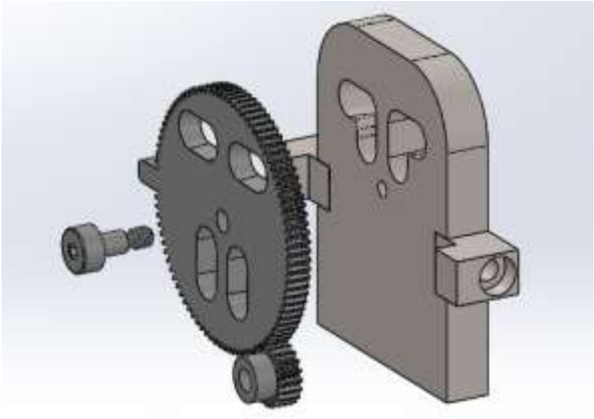


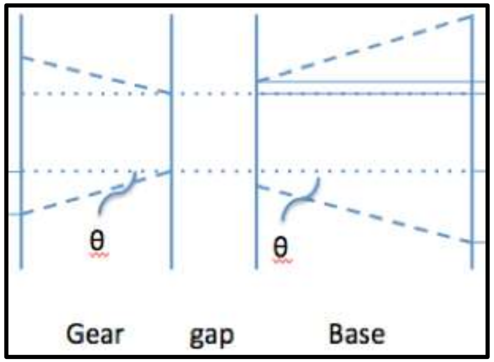
Caltech

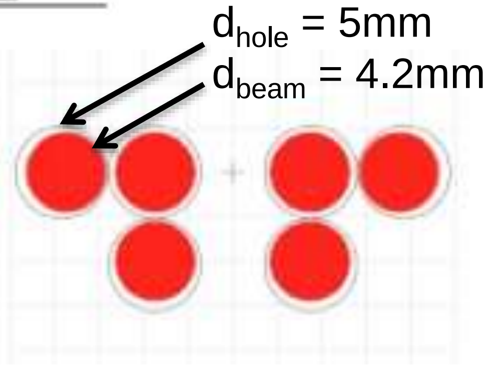
Mask Mechanism

- Designed for change between two configurations
- Used ray tracing software to determine optical path at max field angle (4° from pupil conjugate)





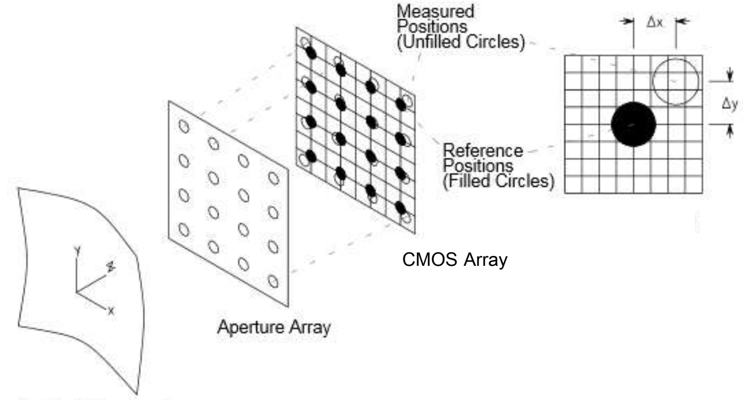




Caltech

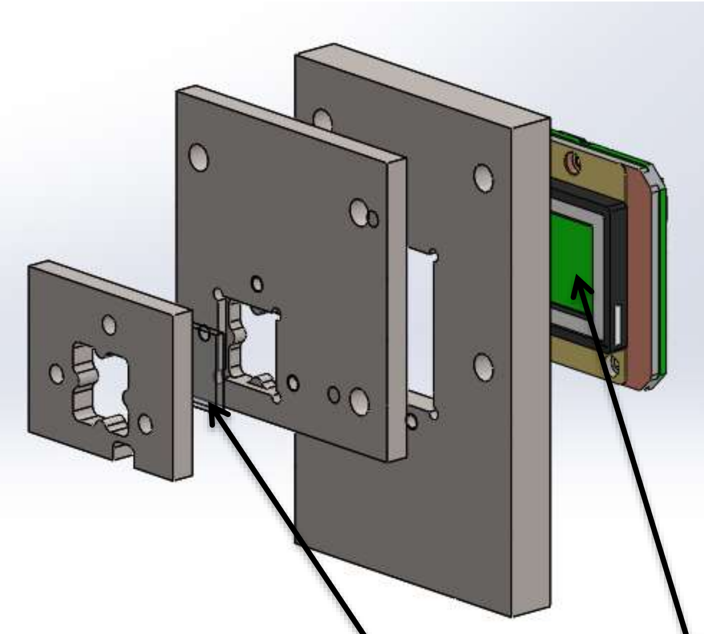
Shack-Hartmann Wavefront Sensor

- Designed a mount to account for:
  - Small space available
  - Mass
  - Alignment constraints



Spiricon Inc. (2004). Hartmann Wavefront Analyzer Tutorial [Online]. Available: http://www.ophiropt.com/user_files/laser/beam_profilers/tutorial-hartman.pdf

- Sank lenslet array into plate with RTV for padding

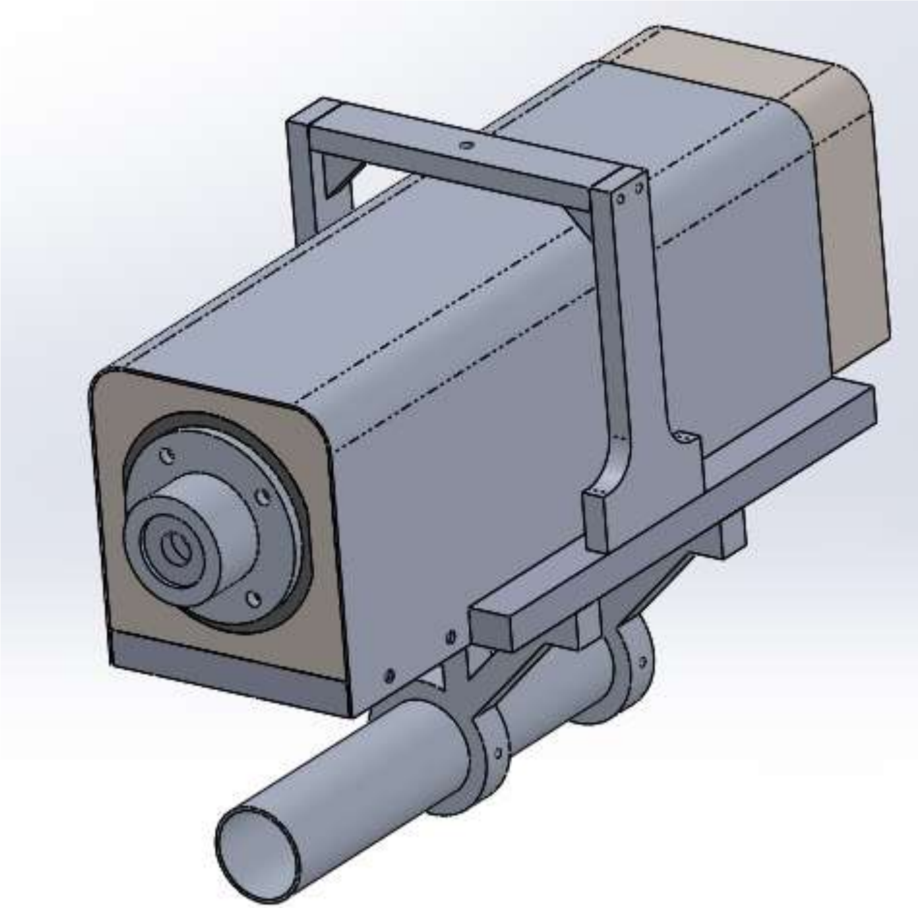


Caltech

External Interfaces

- Frangibolt (FD04) for CoreSat interface
- Mount with mandrel for boom interface
- Interfaces aligned with camera CoM

* Image from TiNi Aerospace



Caltech

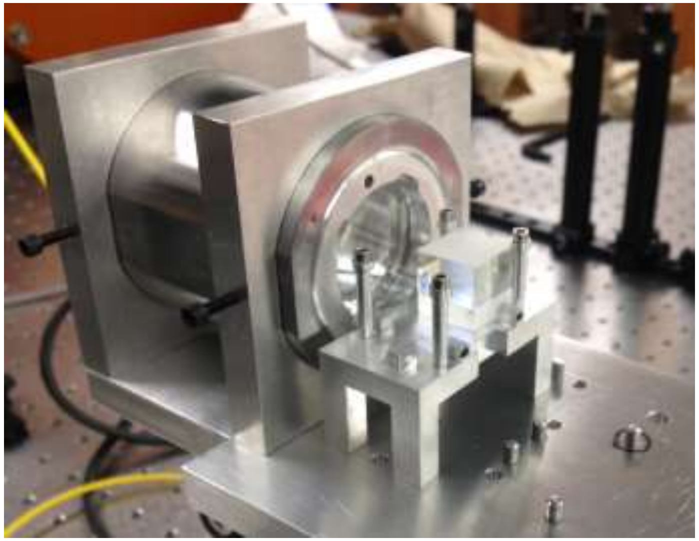
Test Plan

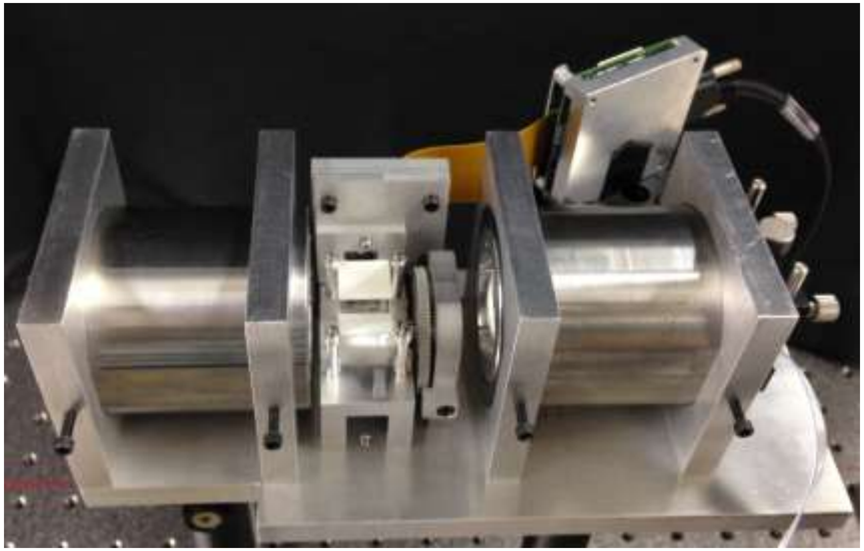
Component Level Testing

- ❑ Collimator Group
- ❑ Beam Splitter
- ❑ SHWS
- ❑ Mask Mechanism
- ❑ Reimaging Group
- ❑ Detector Mount

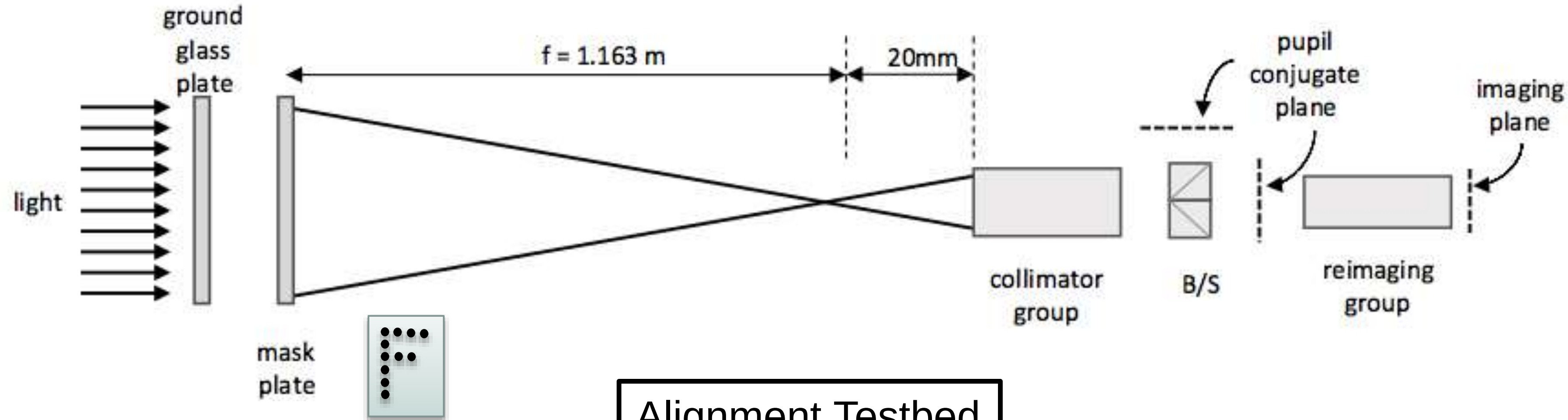
End to End Testing

- ❑ Verify Spot size
- ❑ Verify Spot shape
- ❑ Thermal Testing
- ❑ Shake Testing

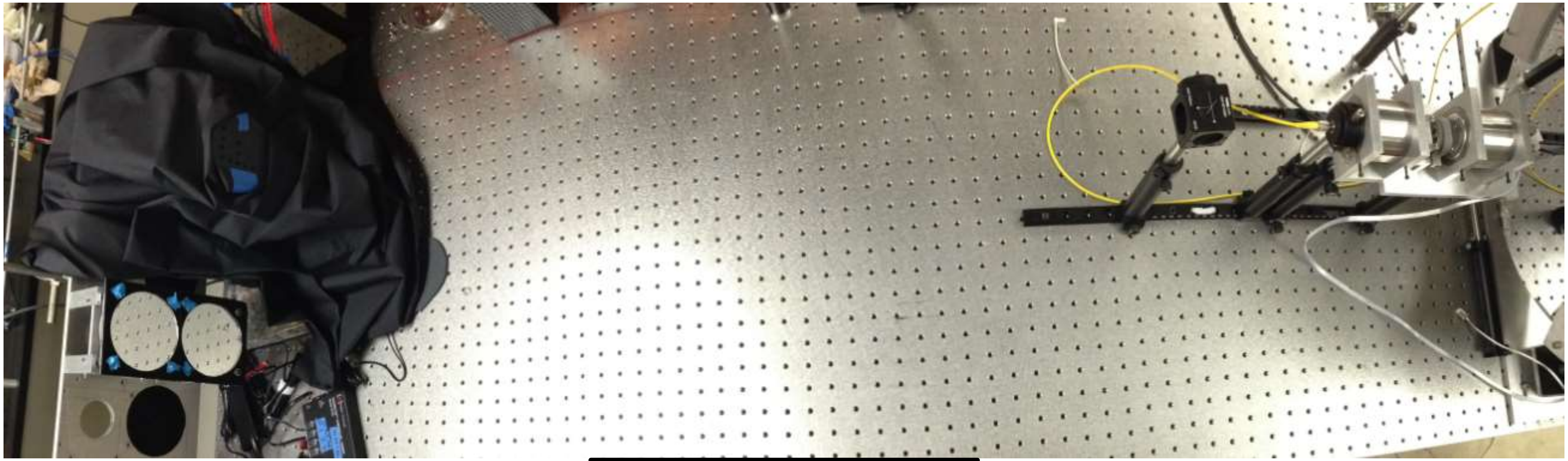




Testbed Setup



Alignment Testbed



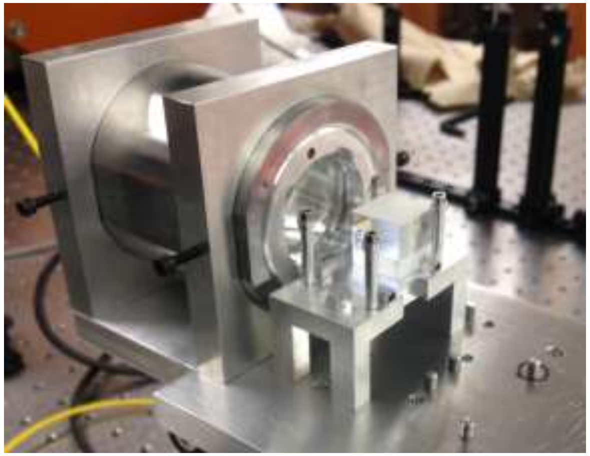
Telescope Testbed

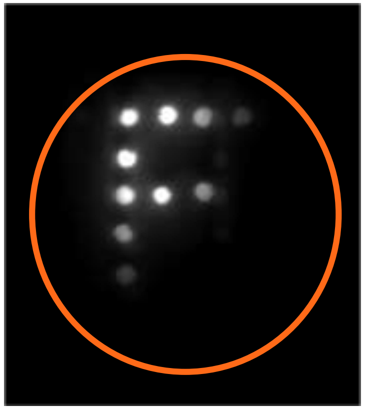
Pass/Fail Criteria

Component	Criteria
ALL	• Light unobstructed & not scattered
Collimator Group	• Light is collimated
Beam Splitter	• Prism transmits & reflects along axis
SHWS	• MLA is located at pupil conjugate • SHWS can process the wavefront • Measurements are repeatable
Mask	• Pupil conjugate located at gear rear • Gears allow change in configuration
Reimaging Group	• Focal point is at image detector surface
Imaging Detector	• Image is on detector array

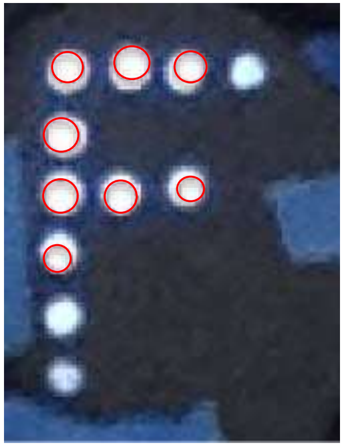
Pupil Conjugate Testing

- Assembly and alignment
- Collimated image
- Location of pupil conjugate and image size
- Main distortion is defocus





Raw data

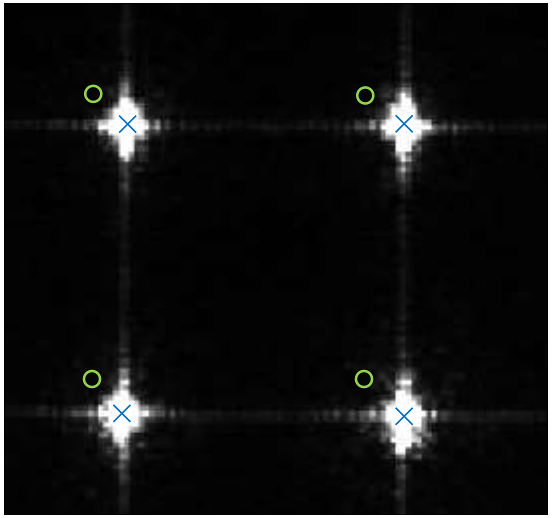


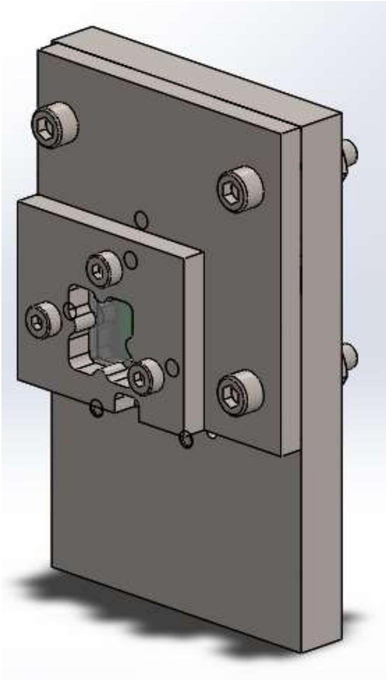
Processed data superimposed on actual image

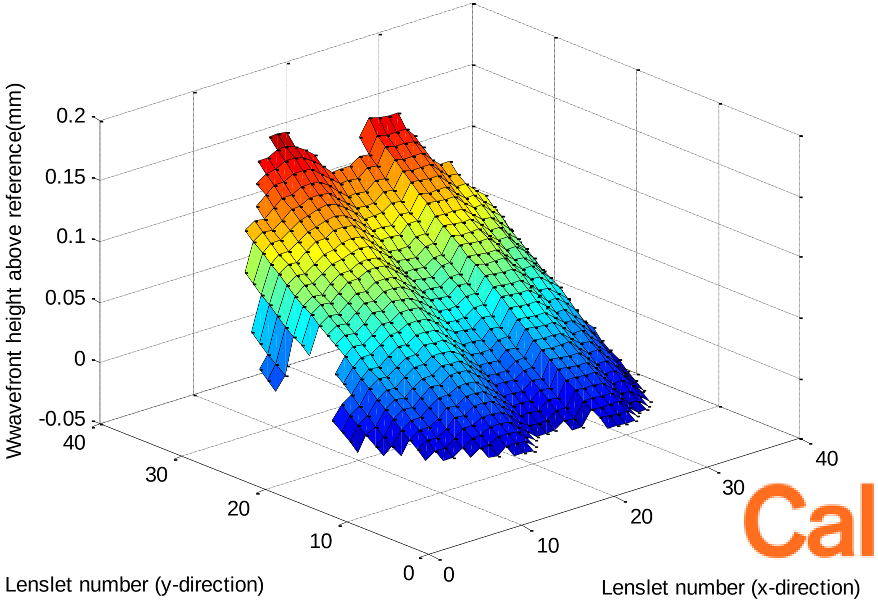
Caltech

SHWS Alignment

- Extract spot locations (x)
- Compare them to reference grid (o)
- Compute slope from the difference between the locations



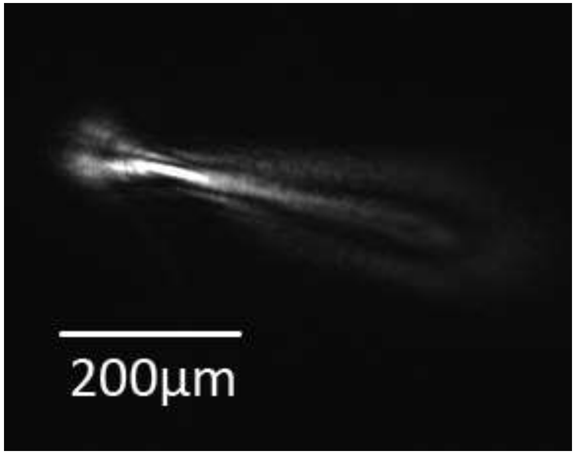




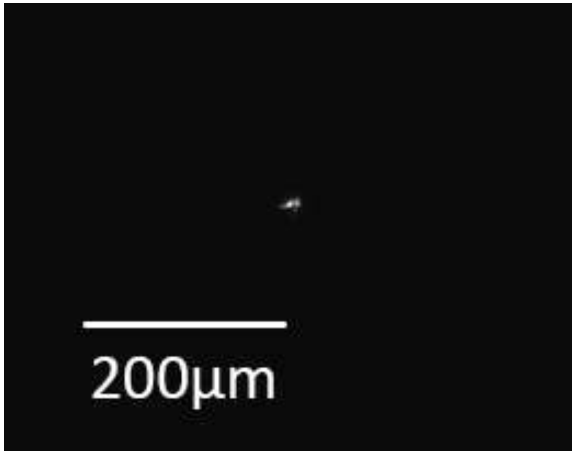
Caltech

Image Detector Testing

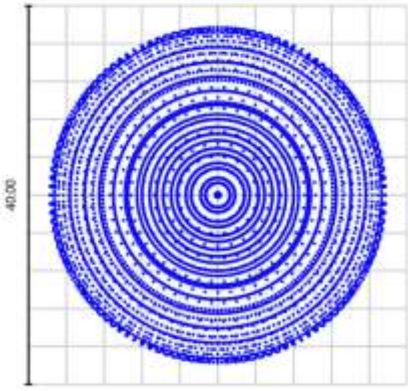
- Imaged with point source in test bed
- Deformations in resulting image:
  - Astigmatism due to misalignment in the full testbed
  - Coma due to off-axis spherical mirrors
- Placing point source at prime focus resulted in expected spot size (36 µm)



Full Testbed Set-Up



Point Source at Prime Focus



Predicted spot size = 36 µm

	Pass
	In-Progress
	Fail

Results

Component	Criteria	Status
ALL	• Light unobstructed & not scattered	
Collimator Group	• Light is collimated	
Beam Splitter	• Prism transmits & reflects along axis	
SHWS	• MLA is located at pupil conjugate • SHWS can process the wavefront • Measurements are repeatable	
Mask	• Pupil conjugate located at gear rear • Gears allow change in configuration	
Reimaging Group	• Focal point is at image detector surface	
Imaging Detector	• Image is on detector array	

Conclusion

Progress

- ✓ Re-designed existing CAD for manufacturability
- ✓ Fabricated & assembled camera prototype
- ✓ Developed a test plan for both prototype & flight
- ✓ Initiated component level testing

Future Work

- ❑ Complete prototype testing
- ❑ Integrate stepper motor
- ❑ Integrate electronics
- ❑ Integrate light shielding
- ❑ Finalize external interfaces
- ❑ Conduct environmental testing

Questions?

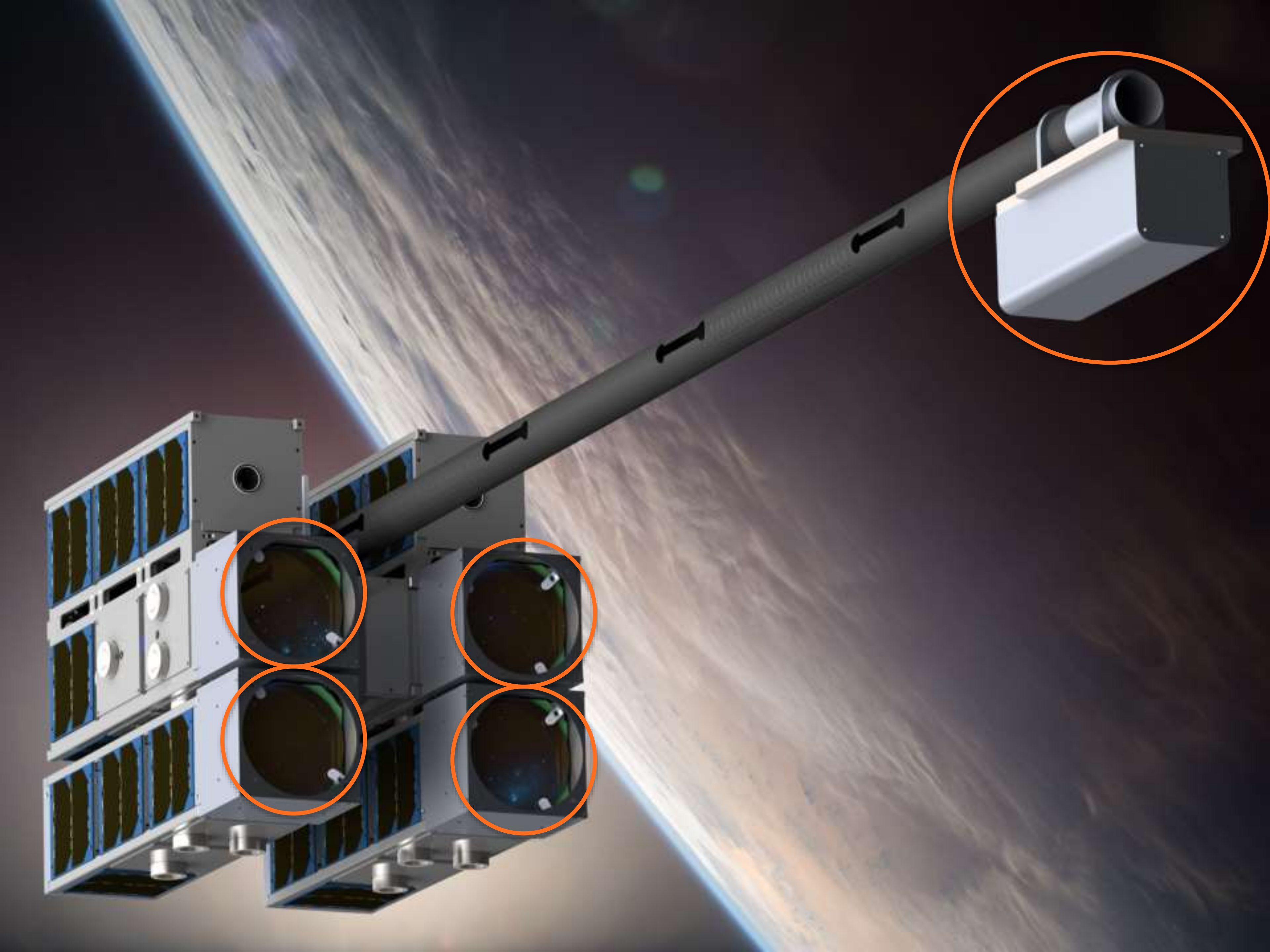
Mirror Calibration Algorithms

Joseph Bowkett

Greg Phlipot

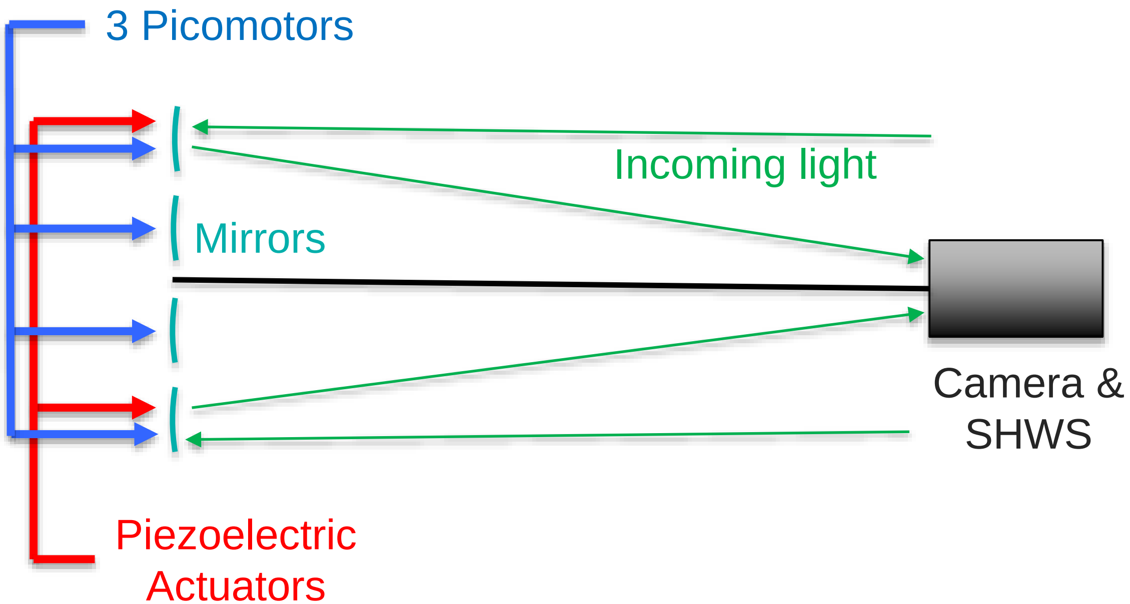
Mentor: Melanie Delapierre,

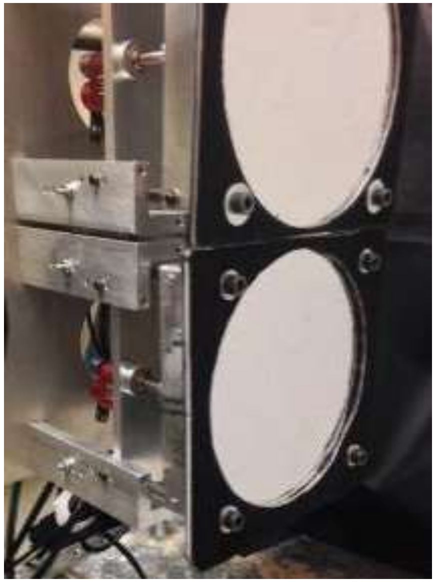
Thibaud Talon

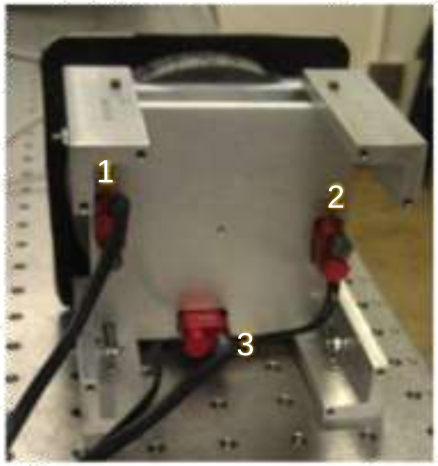


Overview

- Point, center, and focus four mirrors in reasonable time
- Wavefront error correction
- Implementation and experimental testing



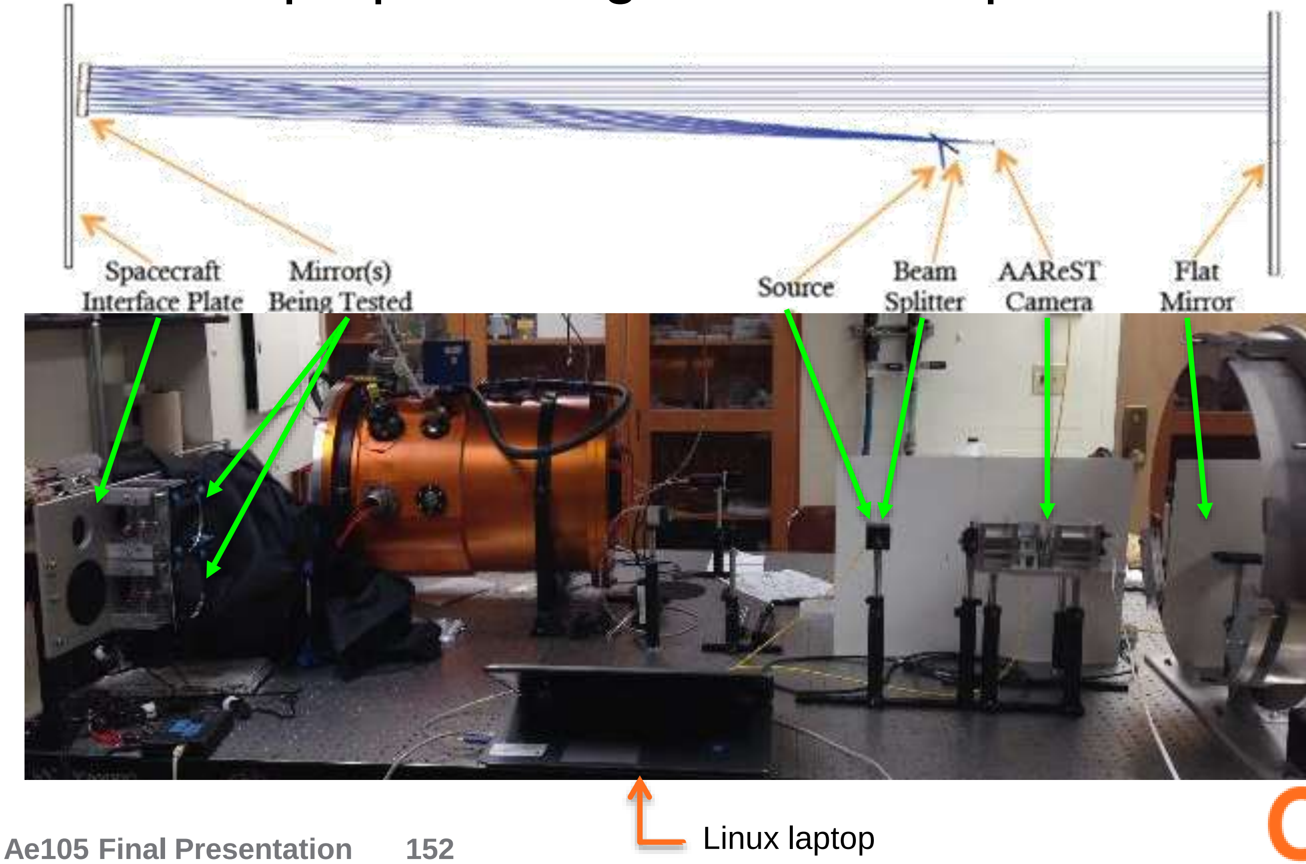




Caltech

Telescope Testbed

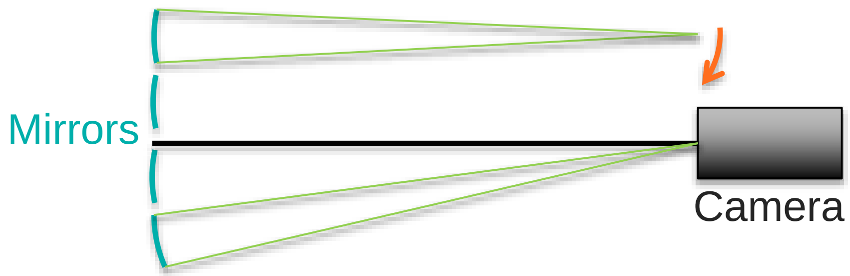
- 2 rigid mirrors with three picomotors each
- Autocollimated light represents distant star
- Linux laptop with flight CPU compatible libraries



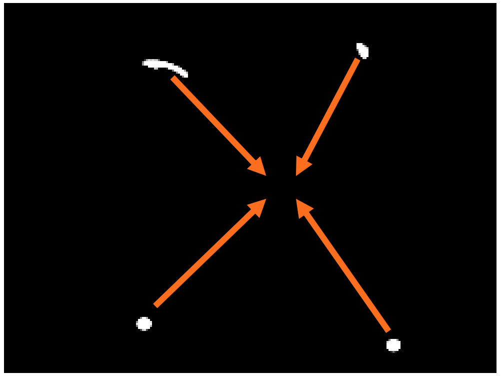
Caltech

Algorithm sequence

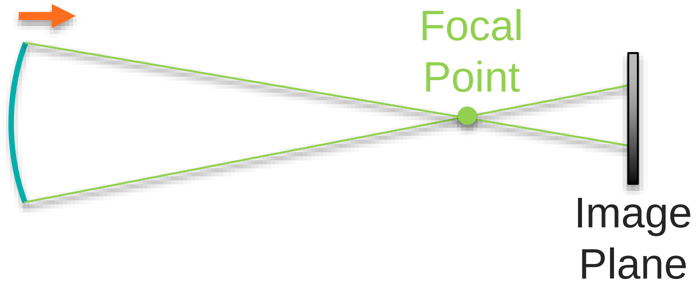
1. Blind search



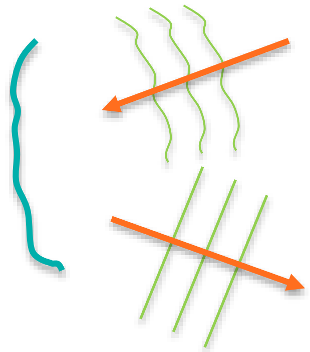
2. Centering



3. Focusing



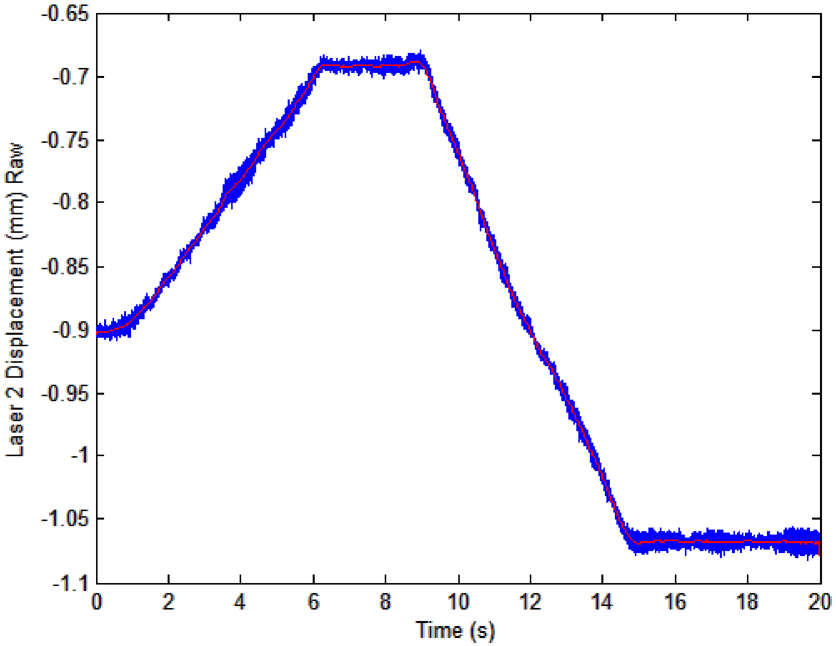
4. Shape correction



Caltech

Picomotor Characterization

- Need consistent actuation for open loop control
- Forward and reverse directions different

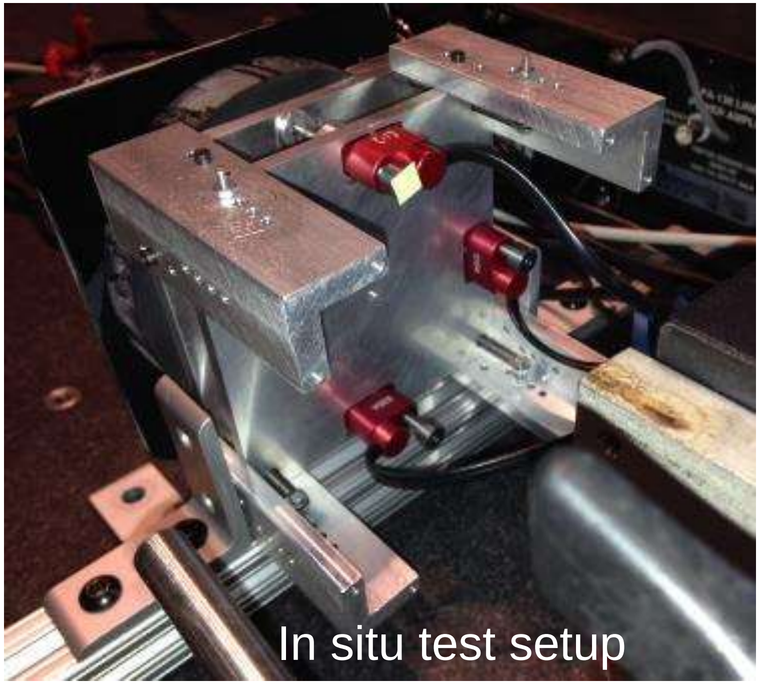


Caltech

Picomotor Characterization

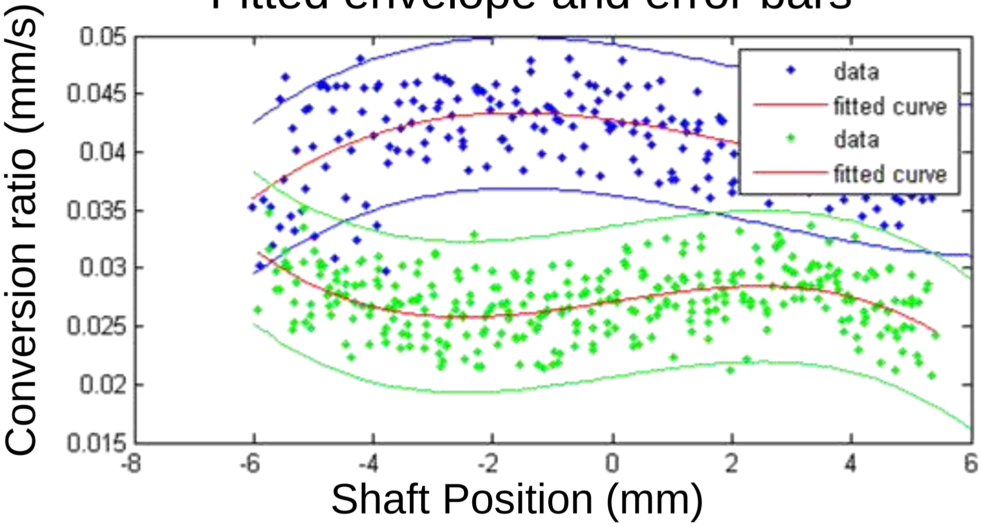
- Non-linear axial spring force causes change along stroke
- Curve can be used but still has significant variance

$$\frac{\sigma_{std\ dev}}{\mu_{mean}} \approx 0.1$$



In situ test setup

Fitted envelope and error bars



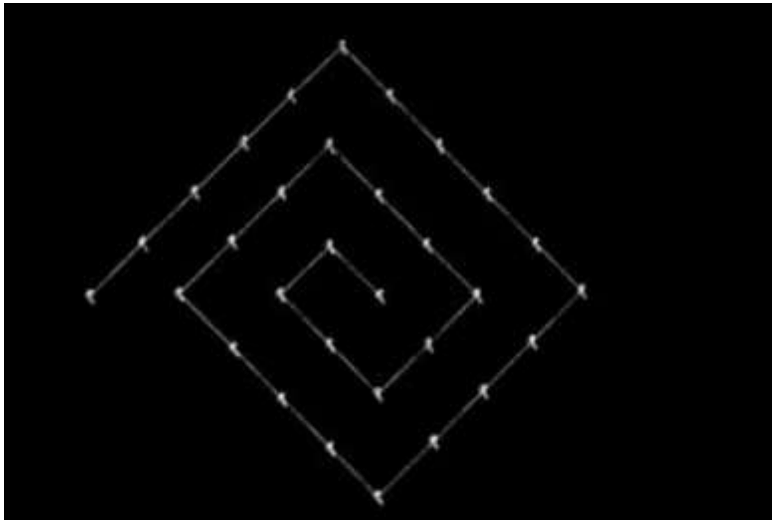
Caltech

Blind Search

- Used to point mirrors toward image detector
- No sensor data, literally shooting in the dark
- Previously used 2 picomotors

<u>Our Tasks</u>

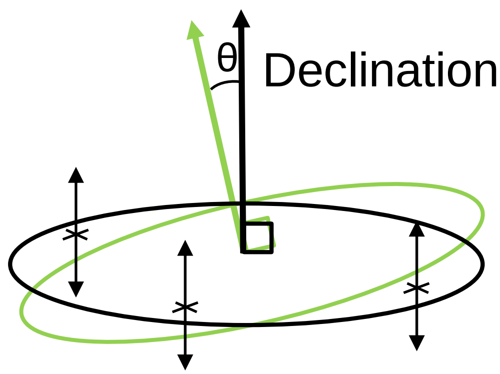
- Extend to 3 picomotors
- Investigate repeatability

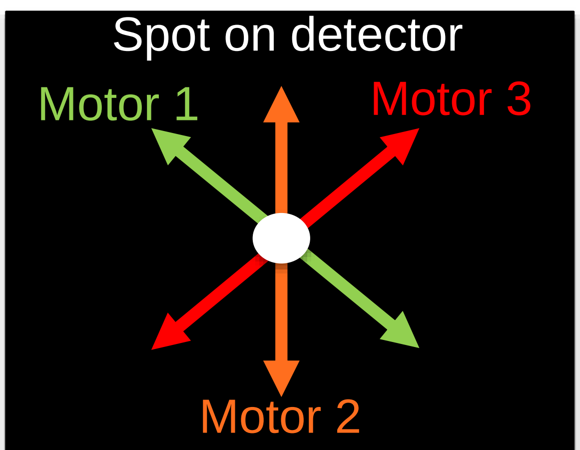


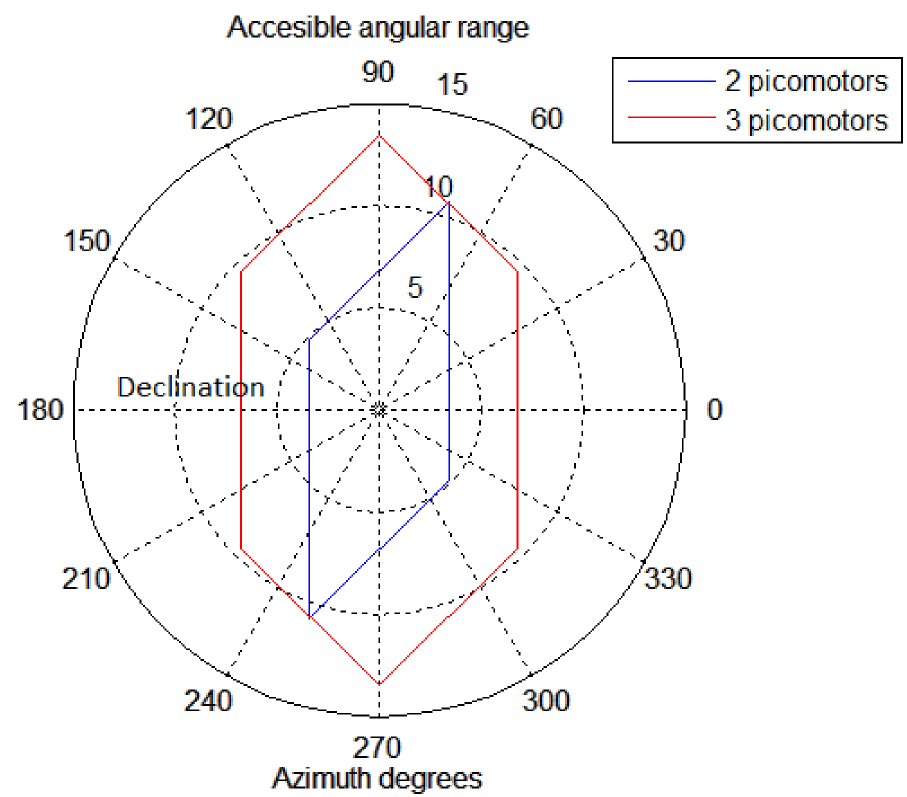
2-picomotor search pattern

Blind Search

- Added a degree of freedom to search pattern

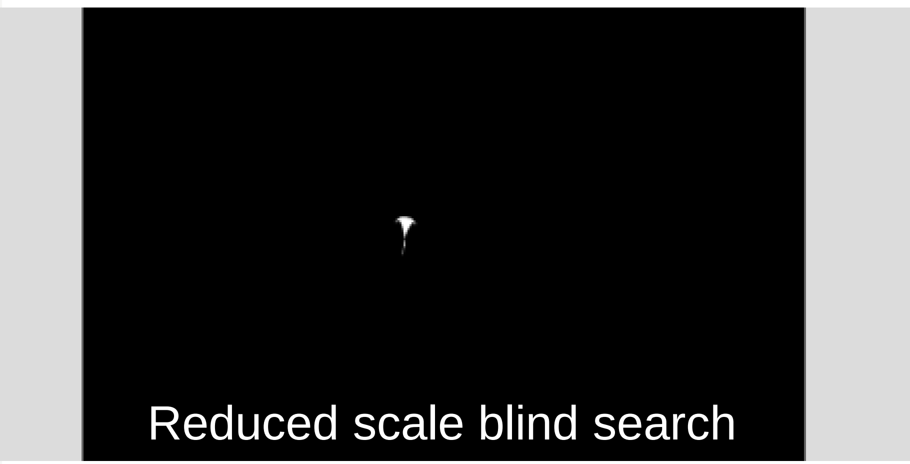


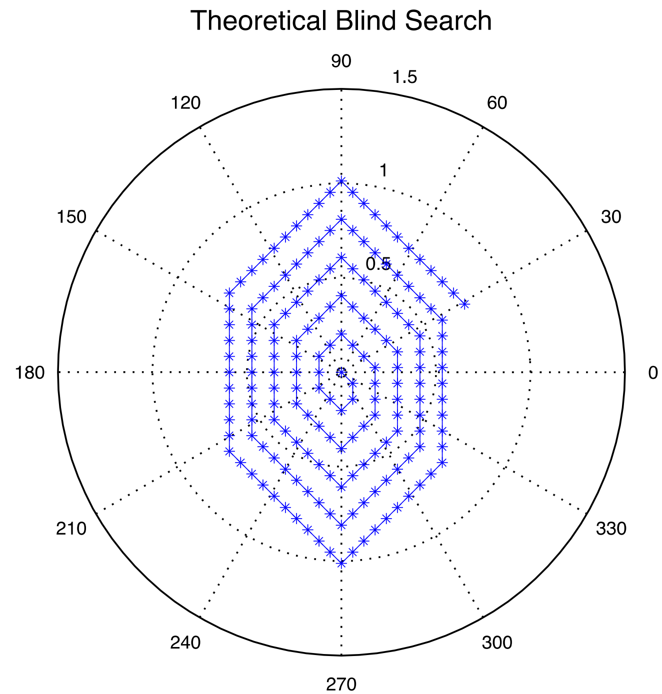




Blind Search

- Actuation variance can cause search to miss detector



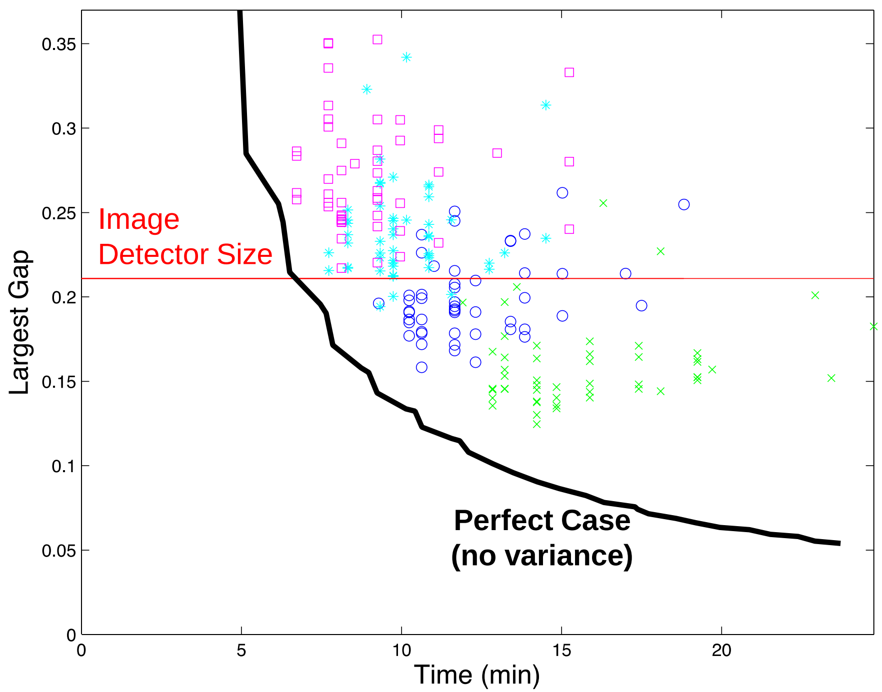


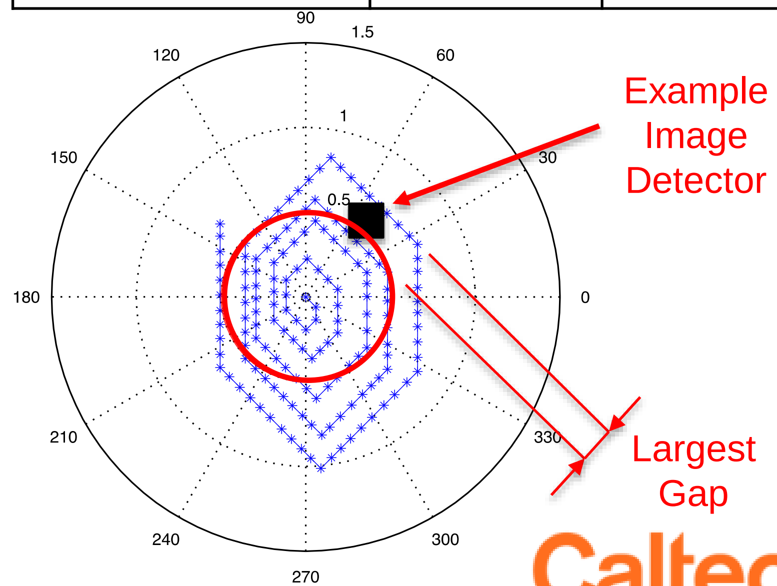
Perfect Search Pattern

Blind Search

- Simulation shows success rate by step size for 0.5 degrees
- Needs to be considerably less than ½ orbit (45 min)

Step Size (mm/step)	Success %	Avg Time (min)
0.052	94%	15.9
0.069	74%	12.2
0.086	12%	10.0
0.104	0%	9.1

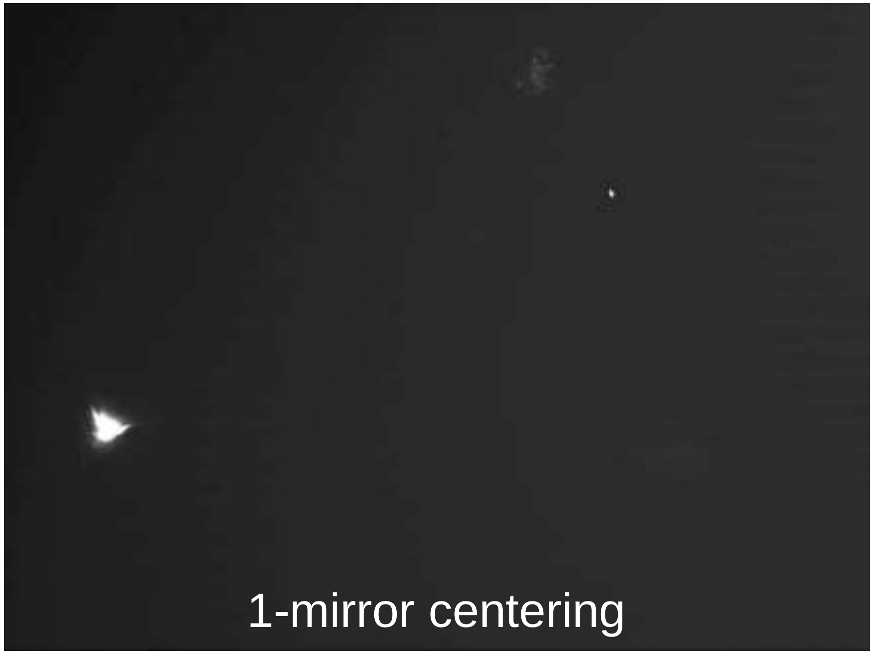




Caltech

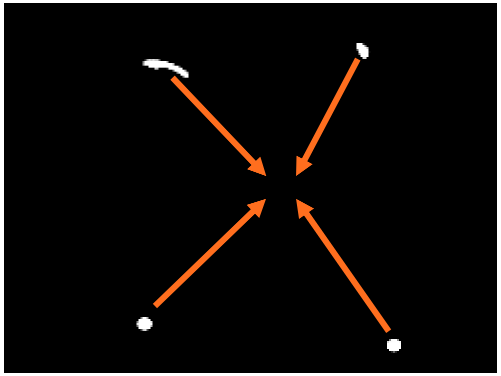
Centering

- Places spots corresponding to all mirrors in center of image detector
- Previously written for 1 spot



Our Tasks

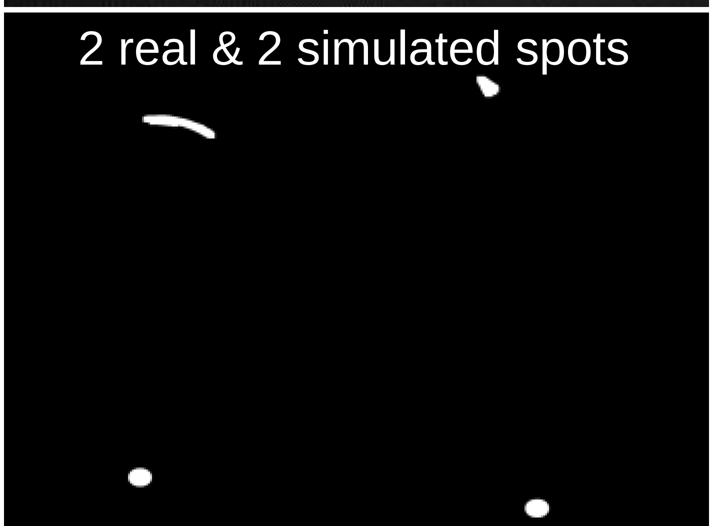
- Extend to multiple spots
- Improve robustness



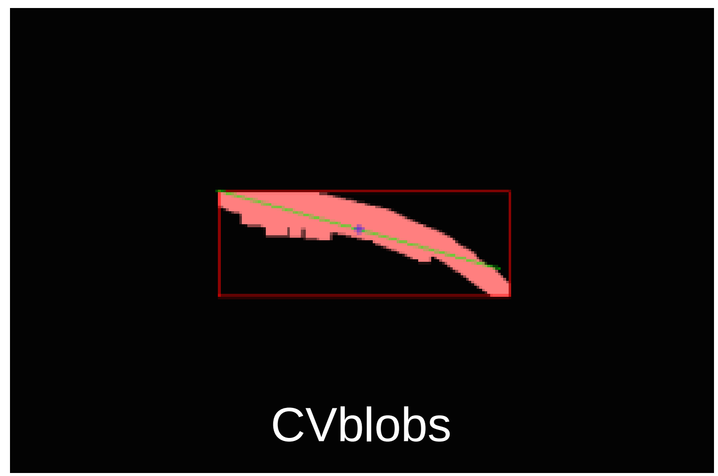
Caltech

Centering: Image Processing


Raw image with ghost spot

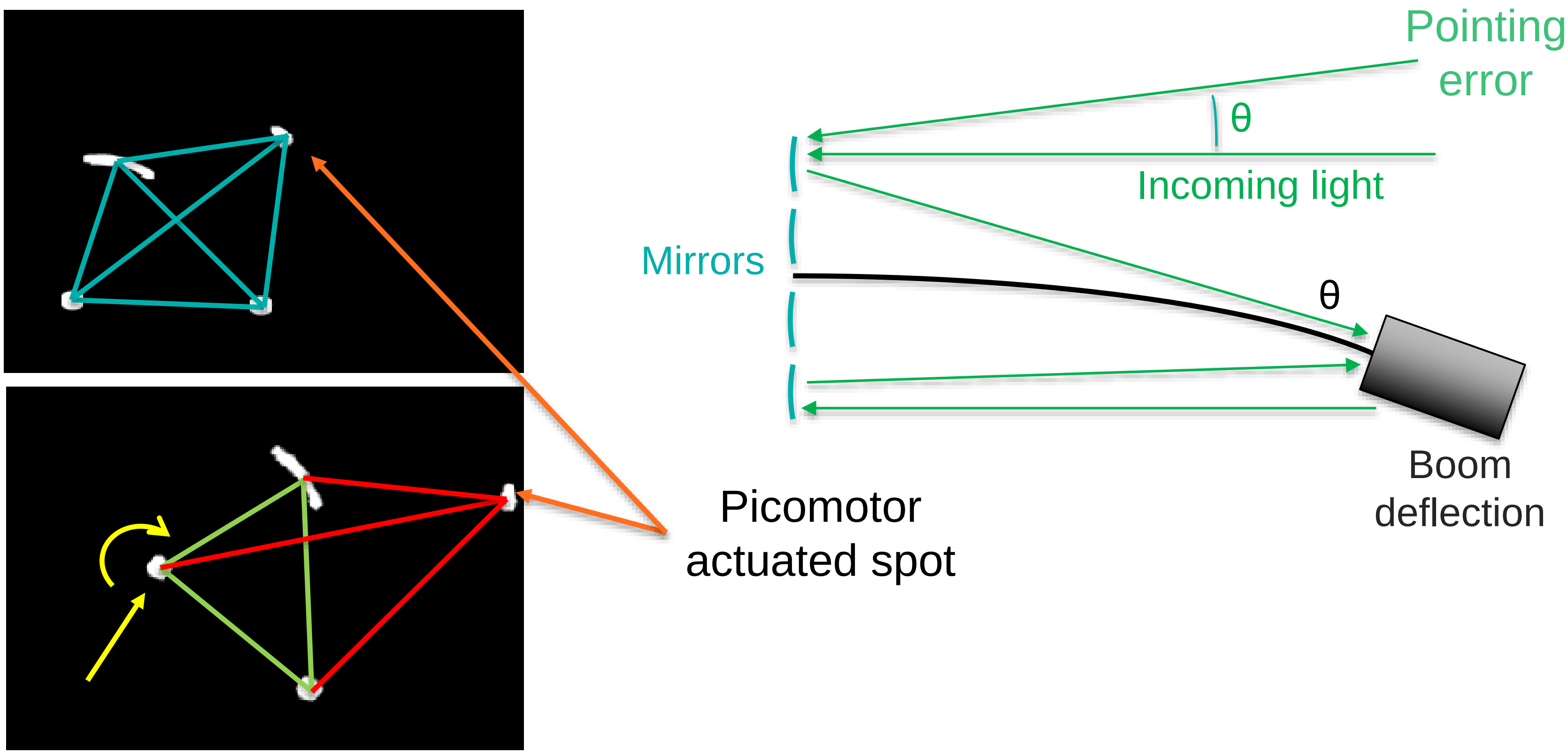

2 real & 2 simulated spots

- Eliminate ghost images
- Simulate additional 2 spots
- Centroid and area detection


CVblobs

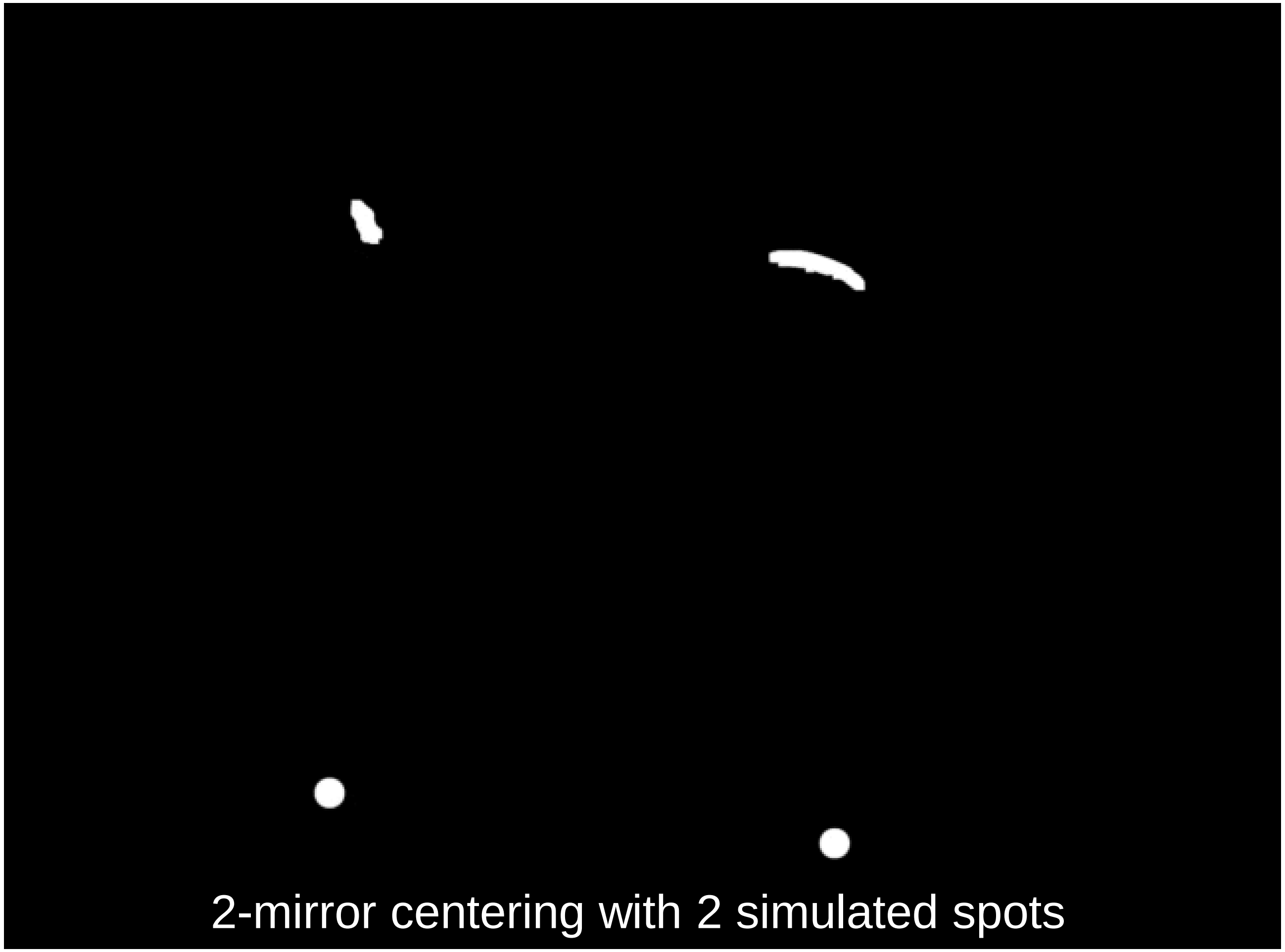
Centering: Rigid Body Motion

- Rigid body motion of all spots from transverse or torsional boom deflection & pointing error



Caltech

Centering



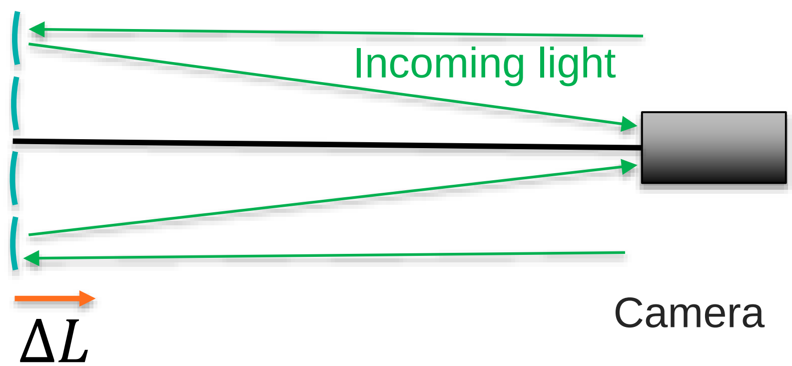
2-mirror centering with 2 simulated spots

Caltech

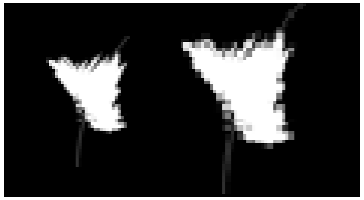
Focusing

- Moves mirrors in piston to focus images
- Change in spot size undetectable

$$\Delta d = 1.22 \frac{\lambda \cdot \Delta L}{D}$$



d = spot size
λ = wavelength
L = focal length
D = mirror diameter

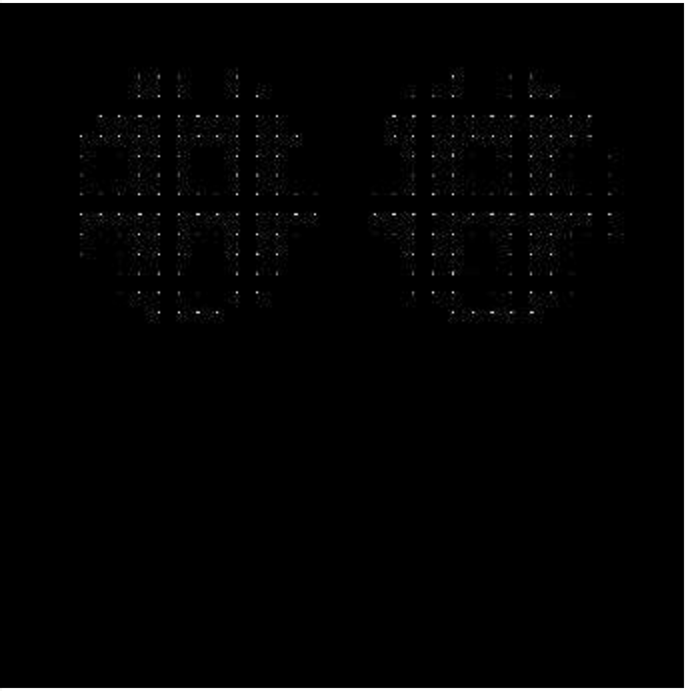


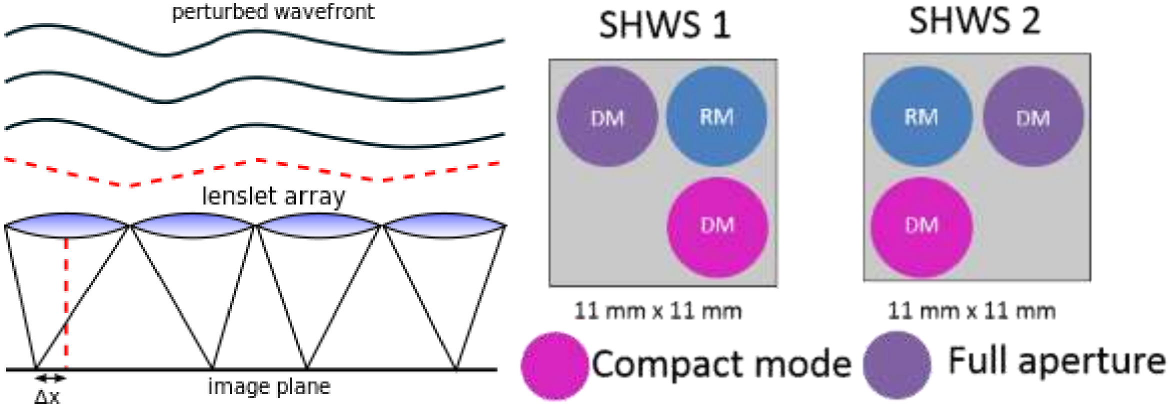
$\Delta d \approx$ 60nm
Pixel size = 2.2μm

Caltech

Shape Correction

- Uses 41 piezoelectric actuators to correct shape of deformable mirrors



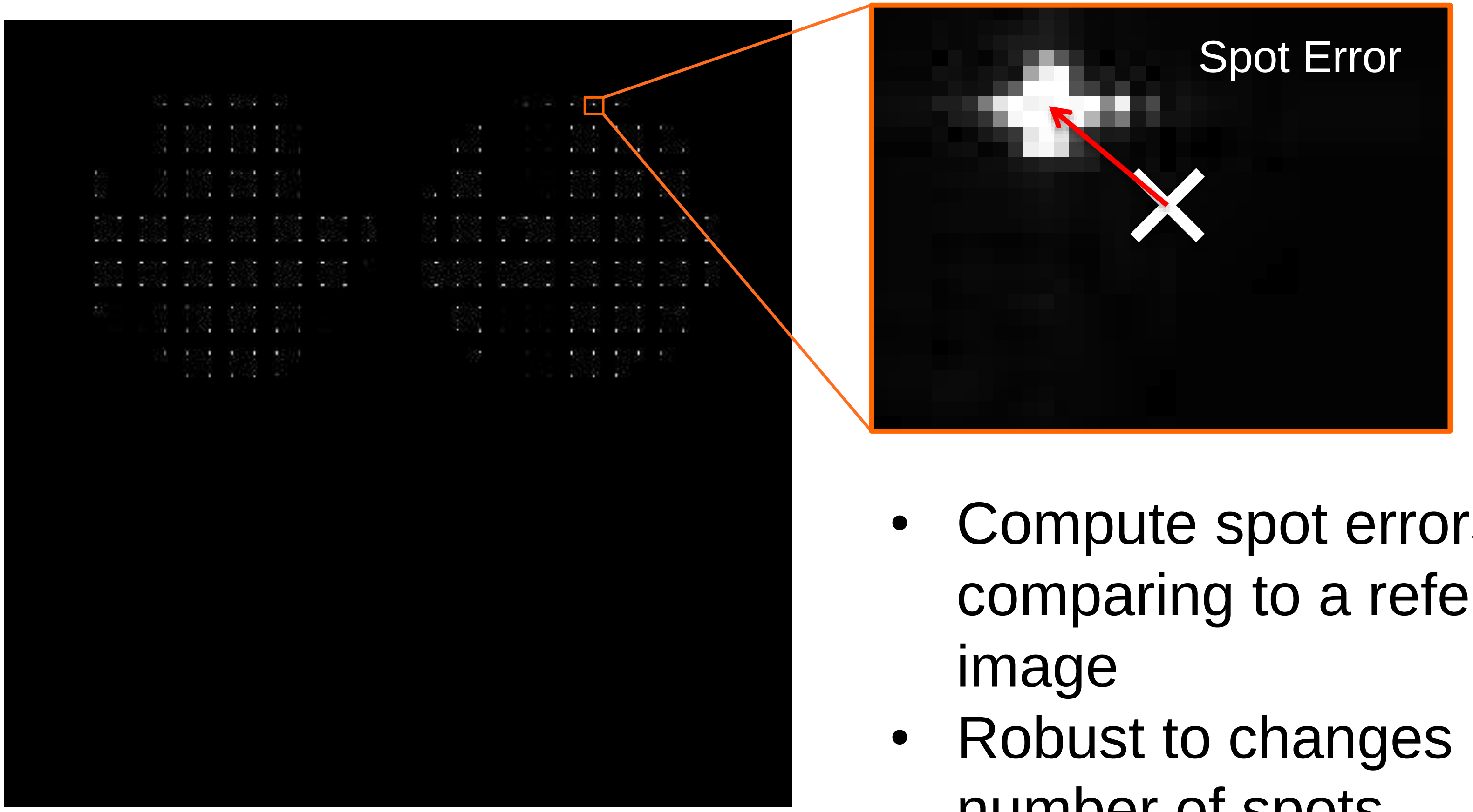


Our Tasks

- SHWS image processing
- Simulation of closed loop control

Caltech

Shape Correction

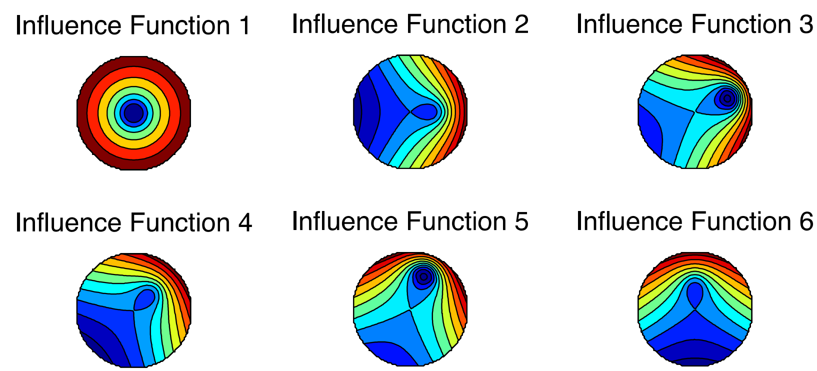


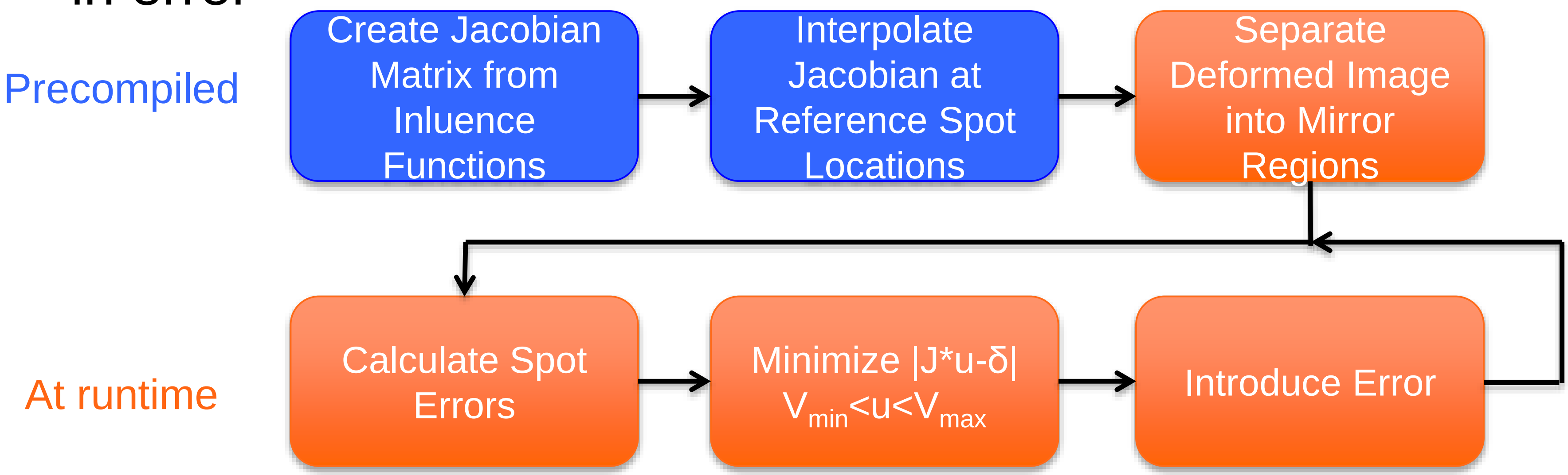
- Compute spot errors by comparing to a reference image
- Robust to changes in number of spots

Caltech

Shape Correction

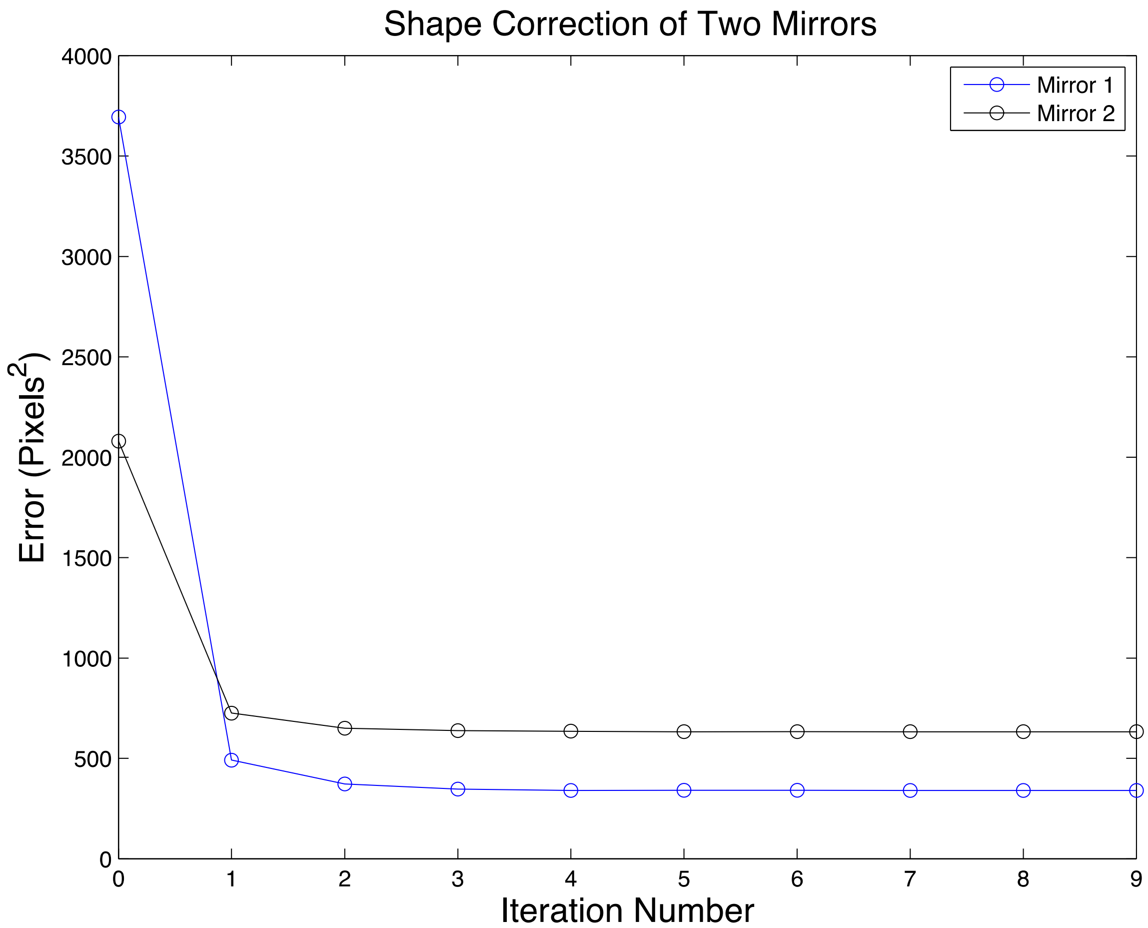
- Constrained least squares minimization
- Simulated nonlinearity in actuators by adding in error





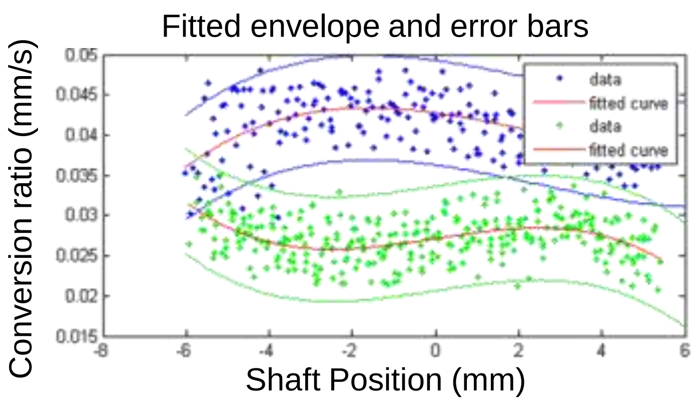
Caltech

Shape Correction

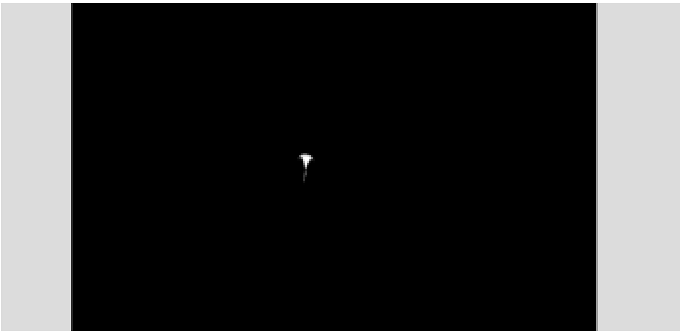


Summary

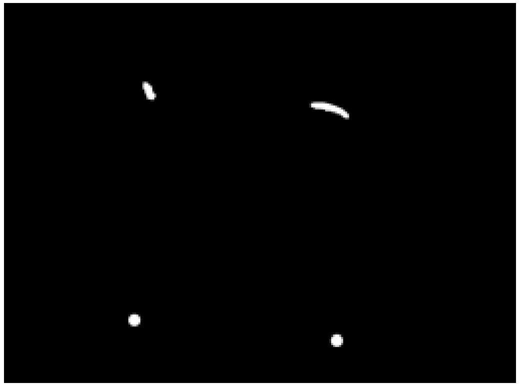
Characterized Picomotors



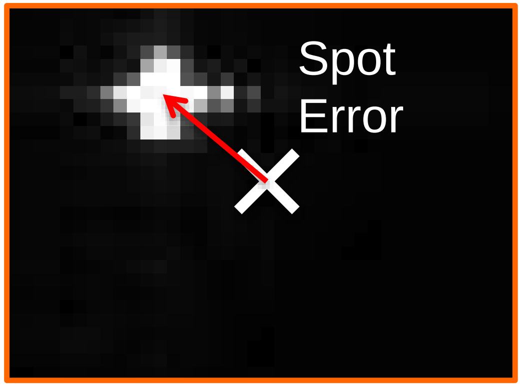
Improved Blind Search



Extended Centering Capabilities



Simulated Deformable Mirrors



Caltech

Future Work

- Test rigid body algorithm on full complement of mirrors
- Test deformable mirror algorithm on telescope testbed
- Adapt focusing to use SHWS data
- Test algorithms on the flight CPU

Questions?

O is for OBSW

Onboard Software

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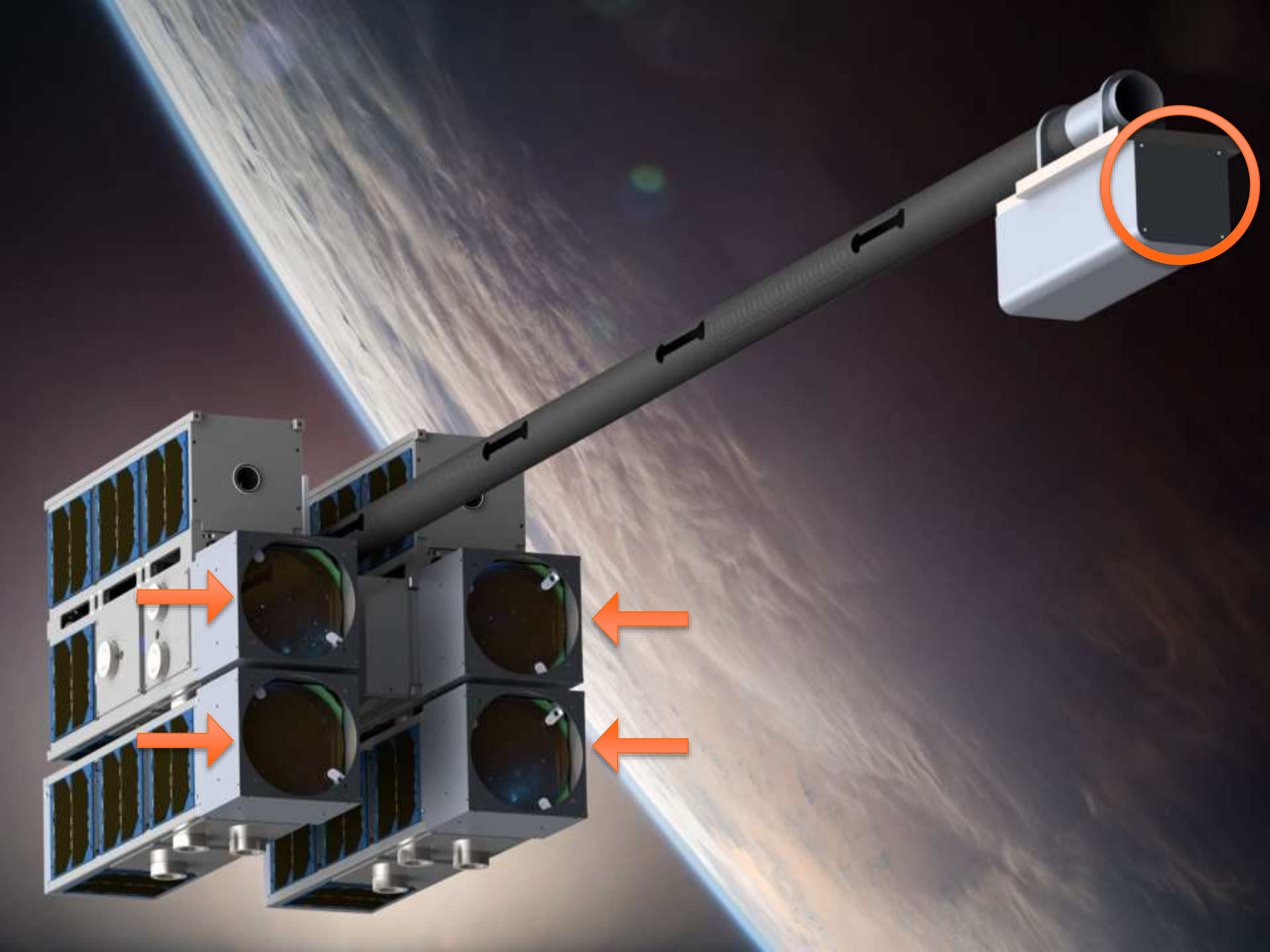

Purpose of On-Board Software

- Controls hardware
- Enables autonomy
- Relays science and engineering data
- Fault detection and recovery

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Overall Group Task

- Analyze mission requirements
- Define an overall software architecture
- Implement design

Achievements

- Performed a detailed mission analysis
- Designed the OBSW framework
- Implemented the OBSW on flight hardware

Detailed Mission Analysis

- Gathered information from other teams
- Mission Requirements Document (MRD)
  - Based on ConOps and team meetings
  - Used James Web Space Telescope MRD as template
- Software Requirements Specification (SRS)
  - Based on MRD
  - Used IEEE 830 standard
  - Used as foundation for system design

SRS

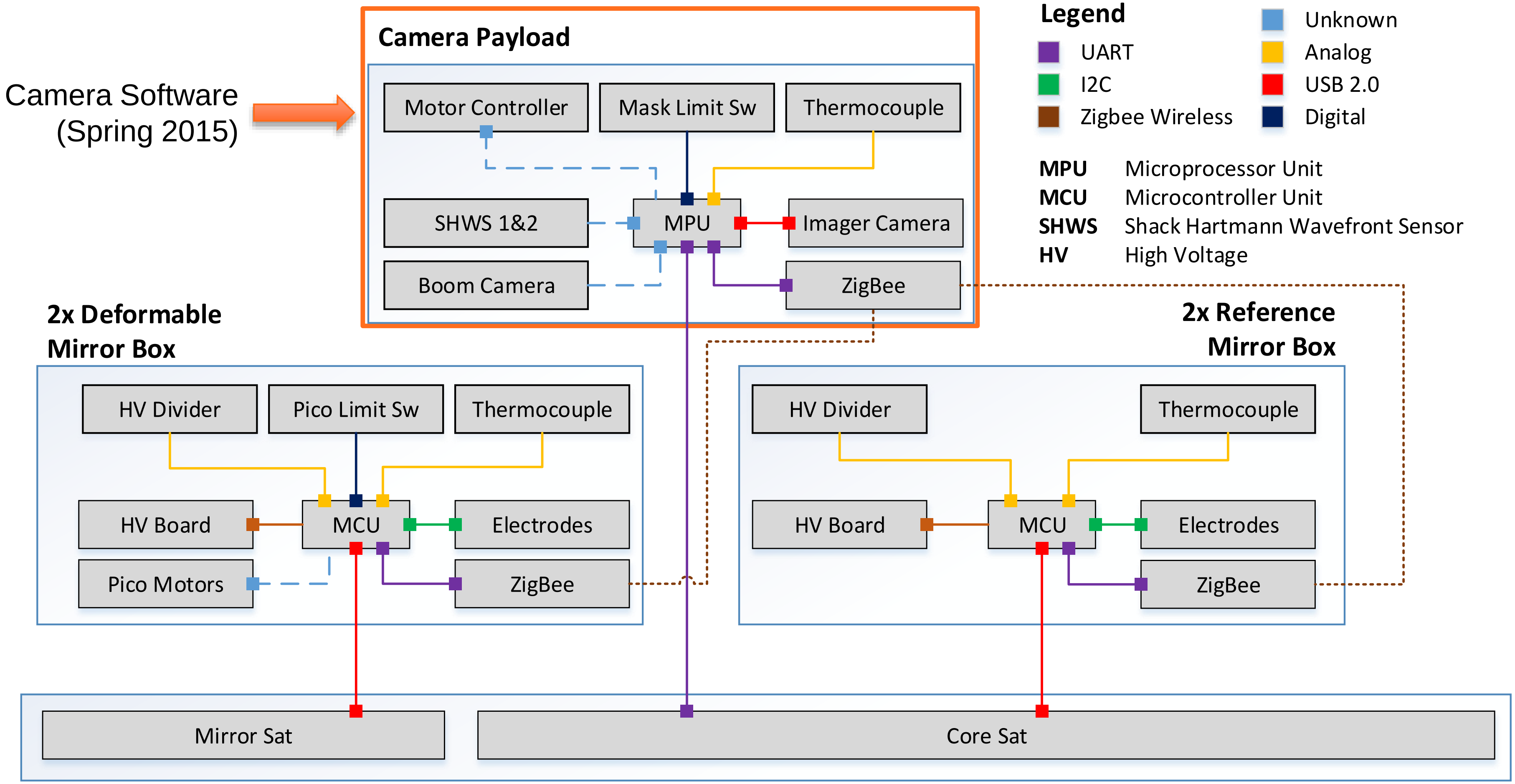
- Software Requirements Specification
  - Functional requirements
  - Non-functional requirements
  - Interface definitions and communication standards

  - Provides traceability
  - Provides testability

System Architecture

- Hardware Design
  - Peripherals and Interfaces
- Operating System
  - Scheduling and Hardware Abstraction
- Software Architecture
  - Control and Logic

Payload Hardware



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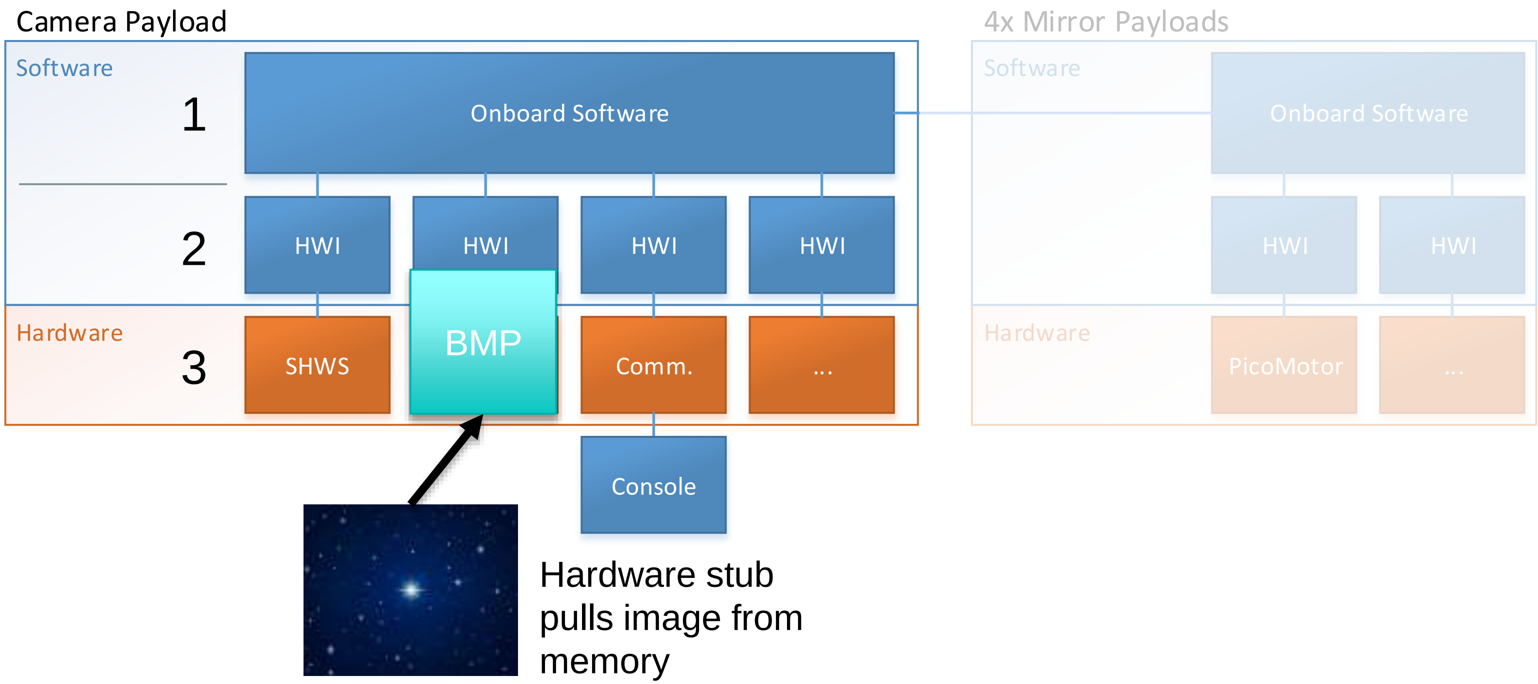
Camera Computer

- Flight computer selected
- Linux AT91 Kernel
  - Issue: Non mainstream kernel
- Challenge: Preemptive scheduling
  - Threads must execute on time
  - Scheduling is currently not defined
  - A patch must be modified

Hardware Abstraction

– 3 layer design



Hardware stub pulls image from memory

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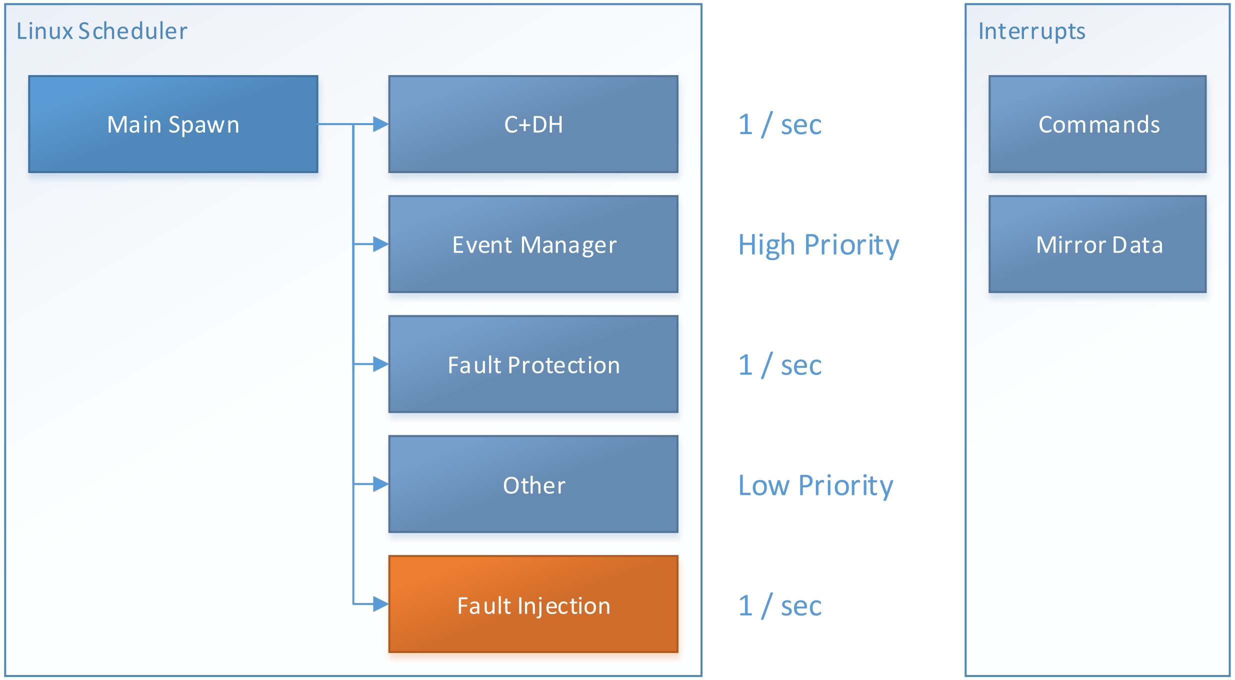
Software Architecture

- Has been implemented in C
  – Demo on Flight Computer will follow



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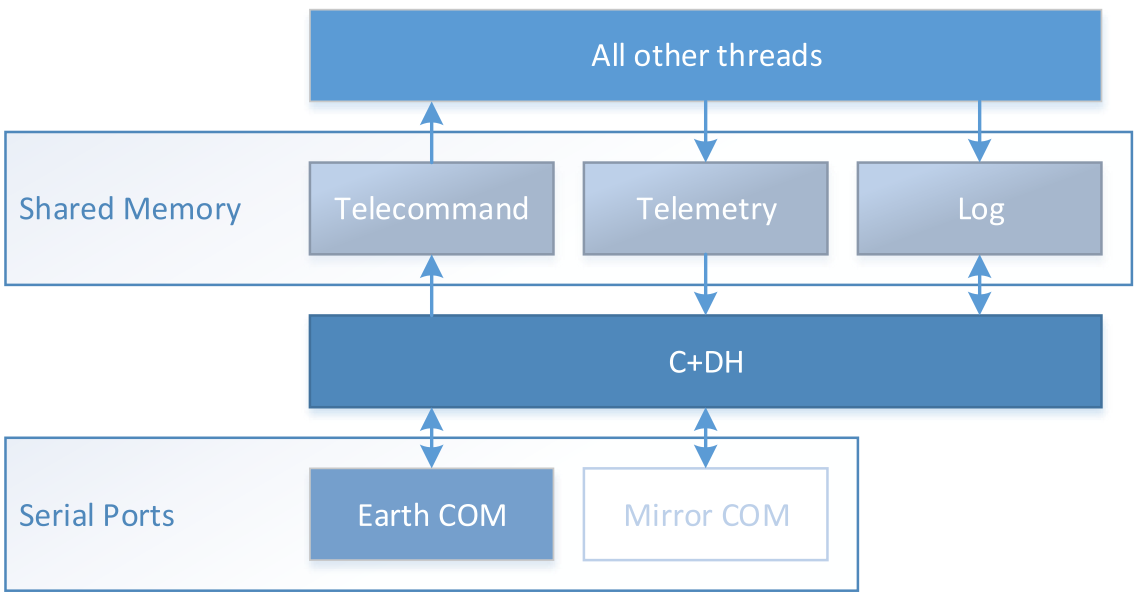
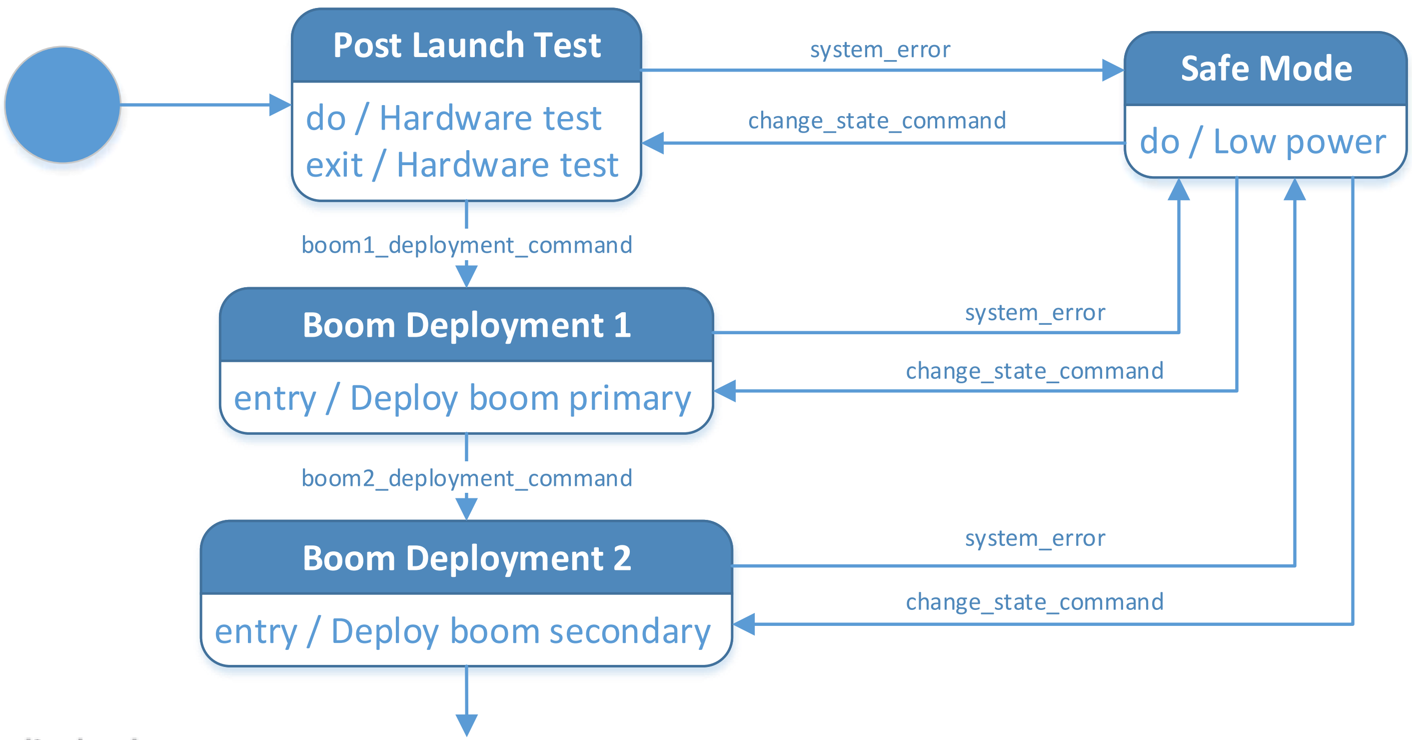
Command and Data Handling

- Handles all external communication



Event Manager

- Executes functions based on
  - Satellite state
  - Events and telecommands



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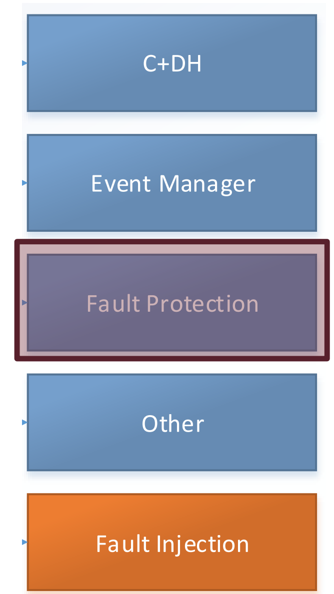
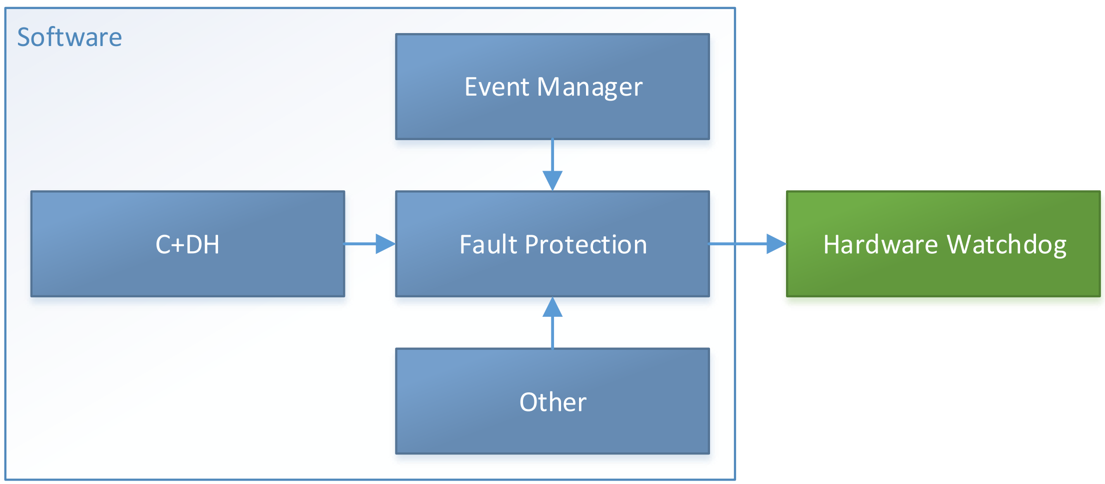
Fault Protection



- Acts as software watchdog



- Monitors engineering data
  - Temperature, Power, …

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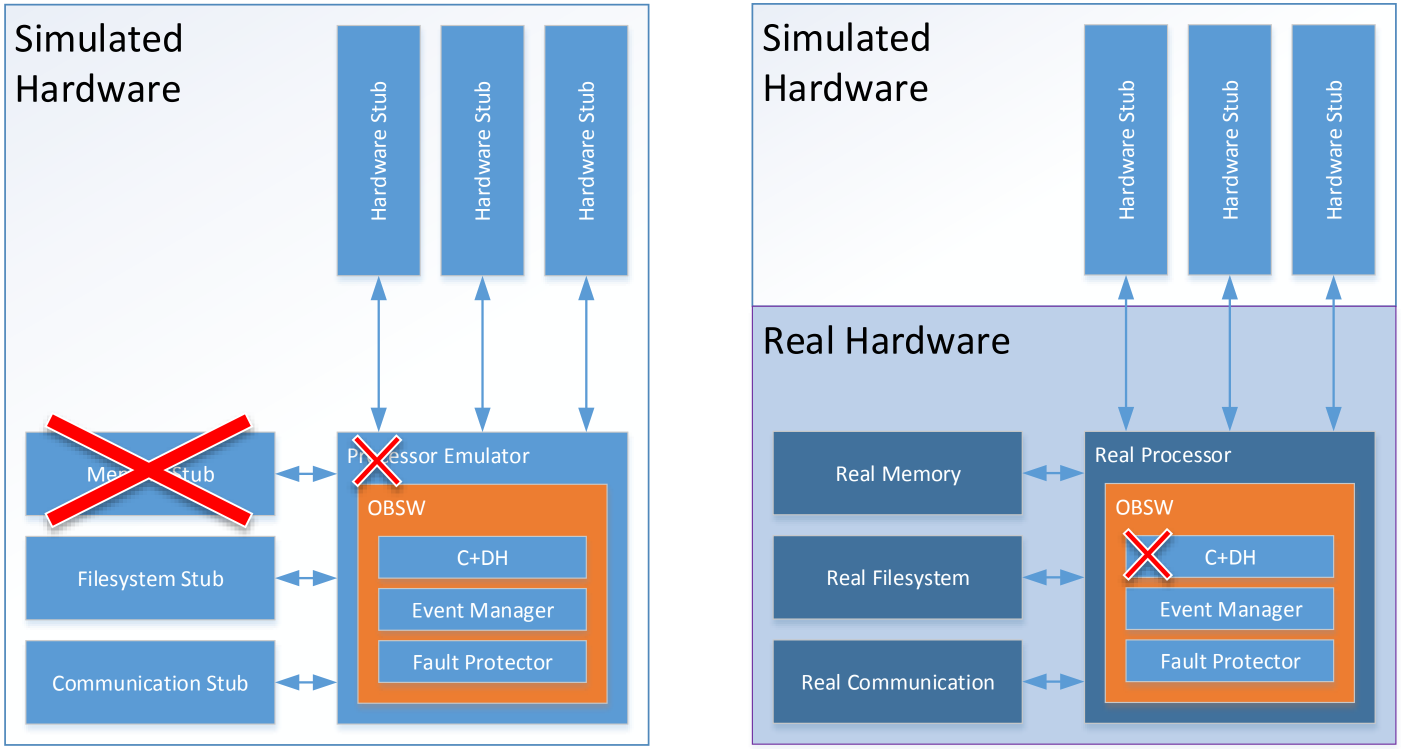
Fault Injection



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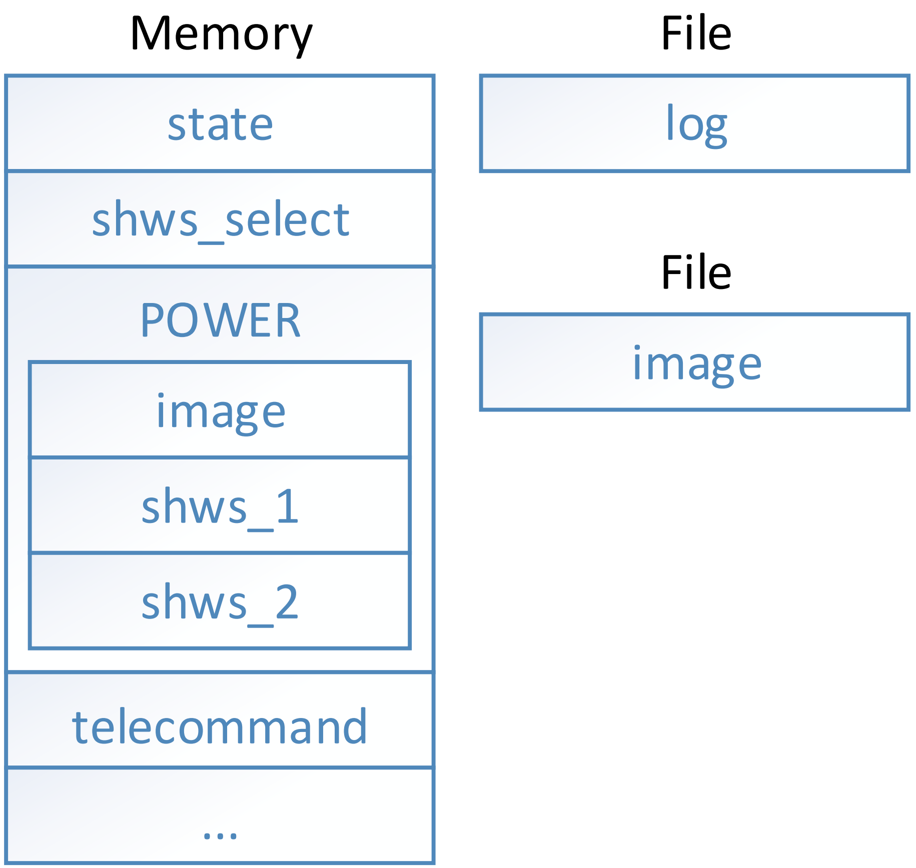
Design Implementation

- Memory
  - Run Time and Long Term
- Communication
  - Uplink and Downlink
- Demo
  - Image Acquisition
  - (Fault Injection)

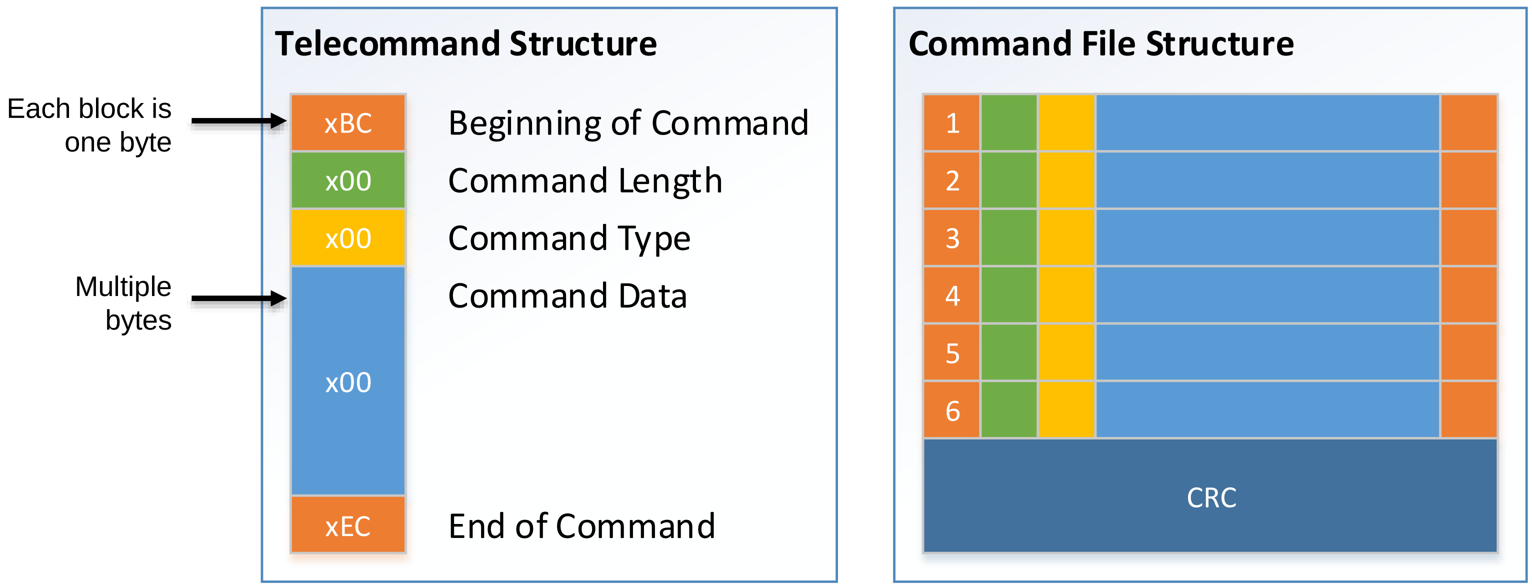
Memory

- Run Time
  - C Struct
  - Easy for memory dump
- Long Term
  - ASCII Files



Uplink Communication

- Telecommands
  - Commands sent as list with CRC



Downlink Communication

- Event Reports
- Telemetry (Science and Engineering)

Event Report Package

xBC	Beginning
x10	Log
x00	Log ID
x00	CRC
xEC	End

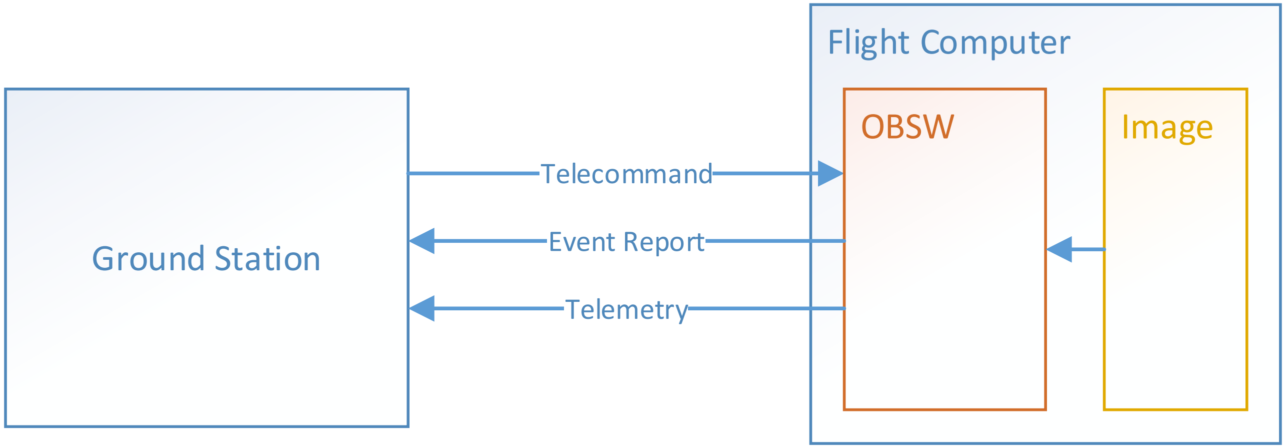
Engineering Telemetry Package

xBC	Beginning
x20	Engineering Telemetry
x00	Data length
x00	Eng. TM ID
x00	Data
x00	CRC
xEC	End

Science Telemetry Package

xBC	Beginning
x30	Science Telemetry
x00	Data length
x00	Sci. TM ID
x00	Data
x00	CRC
xEC	End

Demo Image Acquisition



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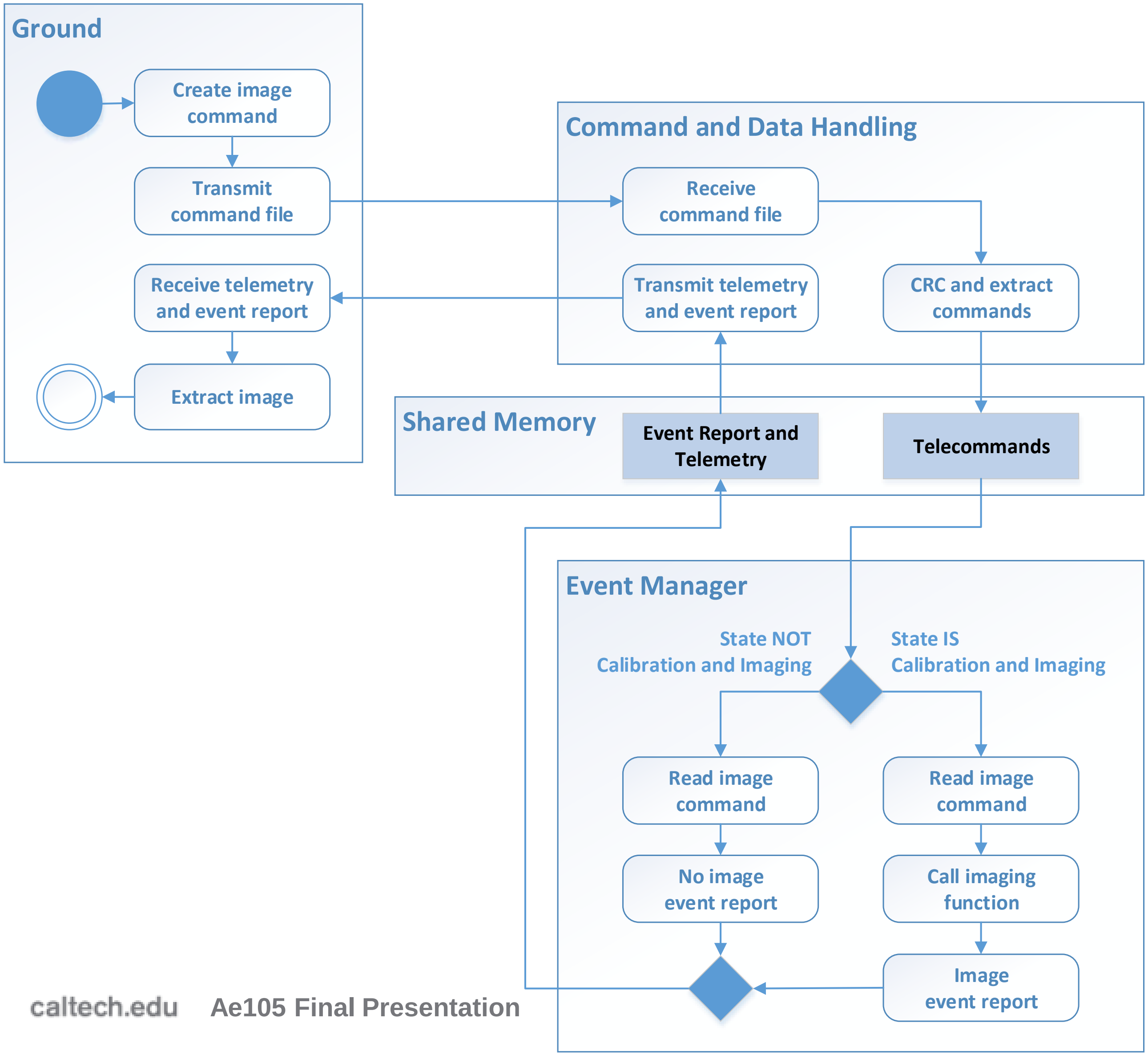
Demo Image Acquisition



OBSW - Future Work

- Improve & extend the functions of telescope software
  - Improve the existing function modules
  - Complete interface layer with camera hardware (SHWS, image detector)
  - Add TC/TM with reference & deformable mirror boxes
- OBSW design for mirror CPU
  - Communication with telescope CPU
  - Operation and failure handling for mirror boxes
- Continue work on software requirements specification
  - Need to specify the TC/TM format with Surrey
- System integration test
  - Unit test for OBSW modules
  - Hardware in the loop test