AAReST
Mission Overview

John Baker

September 9th, 2013

The Vision

Review Objective

Objective:

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

Review Outline

1. Mission Overview (20 mins)
2. Spacecraft Design (60 mins)
3. Telescope Design (160 mins)
    a) Mirrors
    b) Camera
    c) Boom
    d) Telescope System Performance
    e) Test and Calibration
4. System Summary, Launch Vehicle, Project Plan (15 mins)
5. Discussion (15 mins)

Team Responsibilities

UNIVERSITY OF SURREY

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

CALIFORNIA INSTITUTE OF TECHNOLOGY

- Deformable mirrors
- Telescope system
- Optical focus algorithm

UNIVERSITY OF SURREY

System integration & Testing
Mission operations

TBD

Launch

JPL

Class instructors
Manufacturing facilities

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*
- 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.

AAReST Mission Objectives

- Accomplish two key experiments in LEO by demonstrating new technologies for
  1. Autonomous rendezvous and docking with small spacecraft for telescope re-configuration
  2. A low-cost active deformable mirror (one star image with 80% encircled energy)
- Operate as long as necessary to accomplish the objectives (90 days) post commissioning
- Accomplish the mission inexpensively for a 2015 launch
- Gather engineering data that enables the next system development

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.

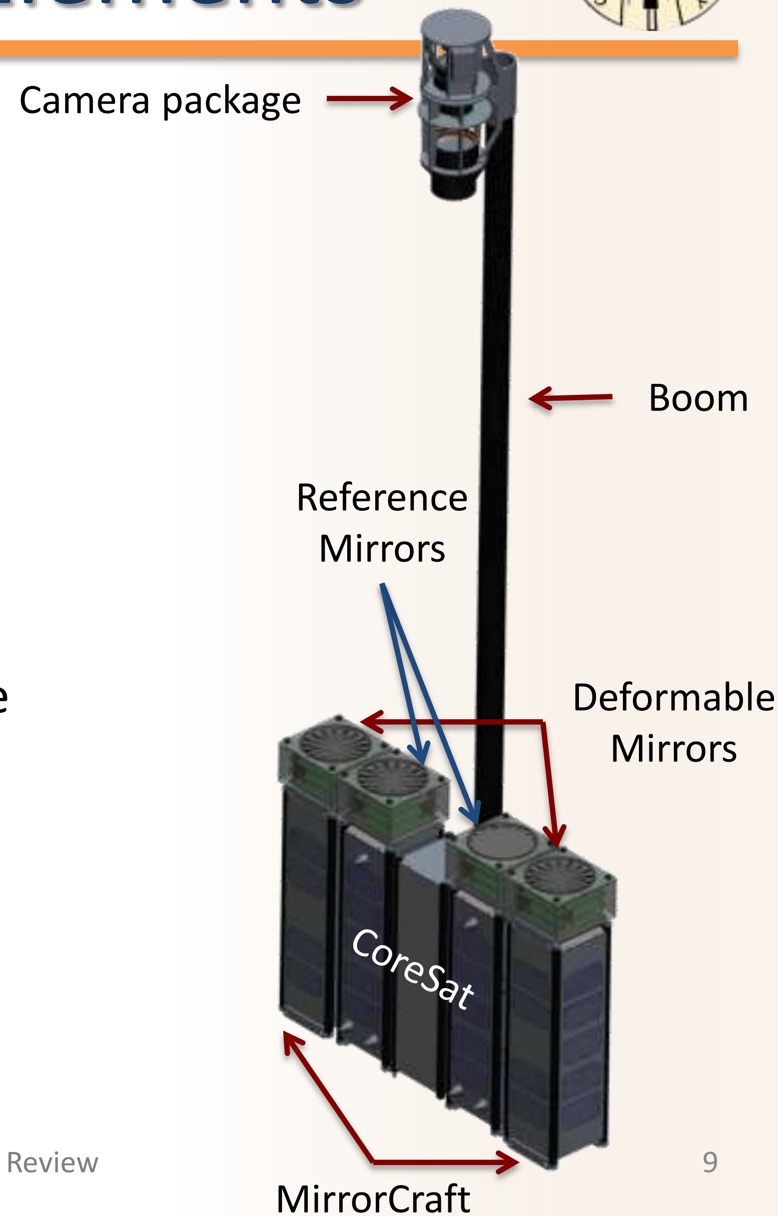
- Requirements flowed down to the subsystem level last year
- Surrey will discuss spacecraft system and subsystem requirements and updates
- Telescope requirements will be discussed in each presentation along with updates.

Spacecraft & Payload Elements

1. MirrorCraft (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

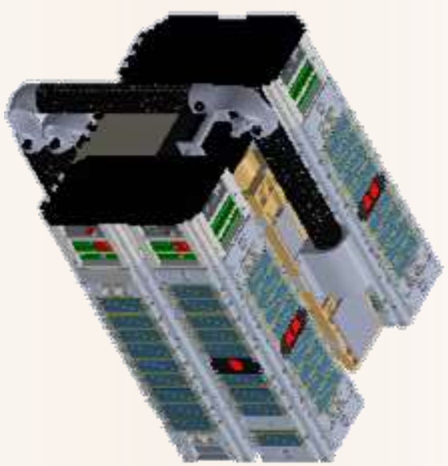


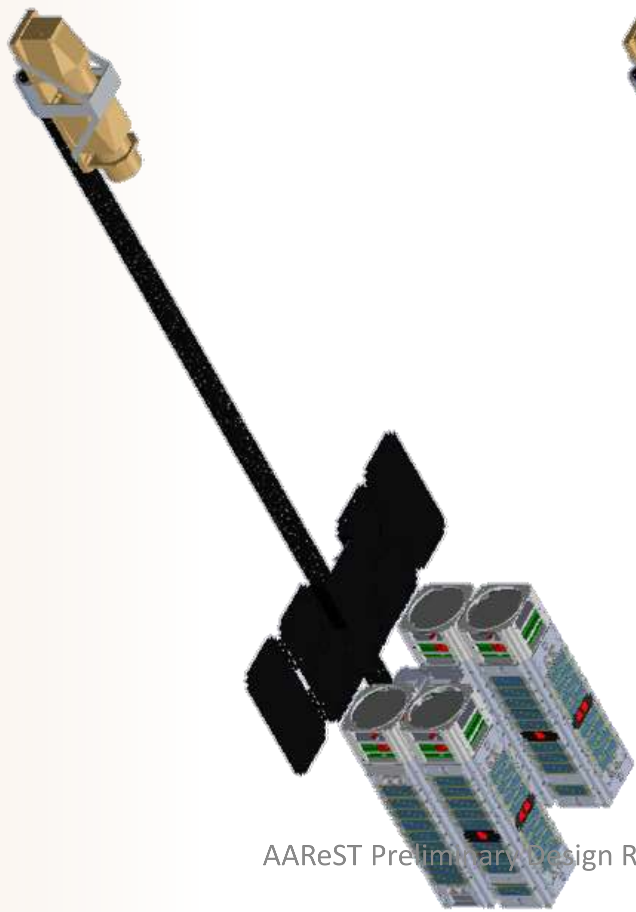
Operation timeline

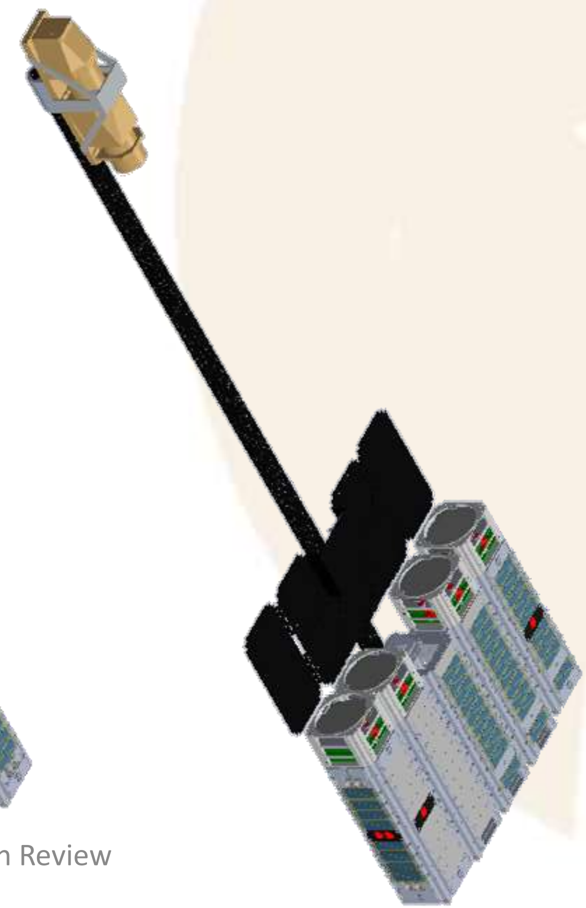
Pre-launch & Launch

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

Desorbit







Deployment

t=0

- Launch
- Detach from launcher & Verify orbit

2 orbits

- Turn on satellite
  - Turn on low voltage then high voltage
  - Switch from battery to solar power

4 orbits

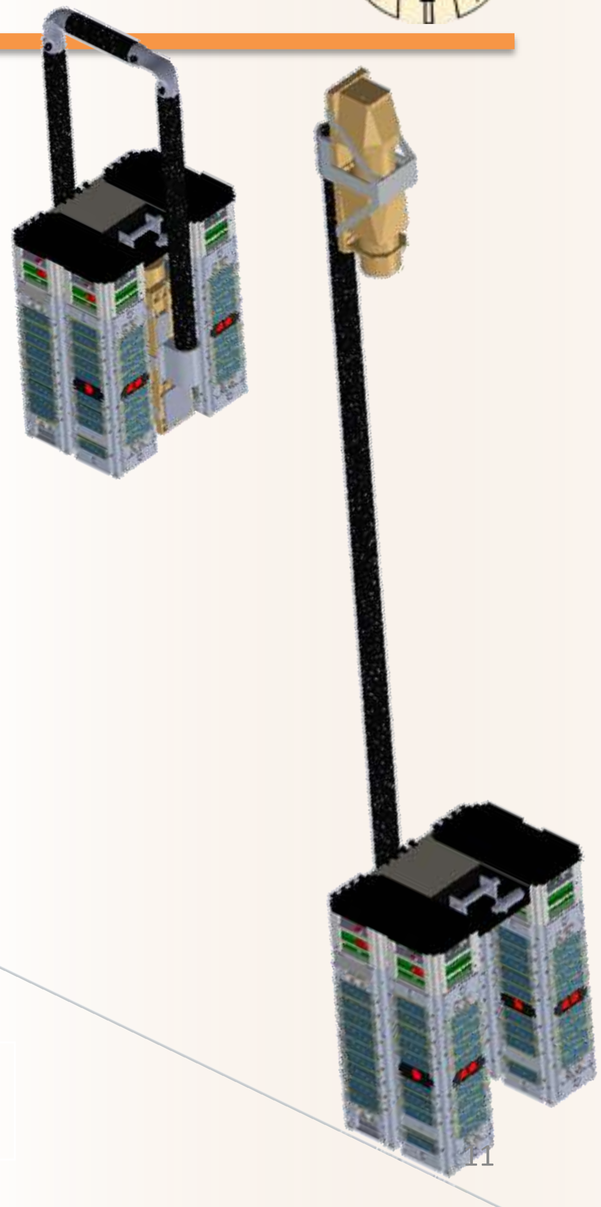
- Verify and stabilize satellite
  - Power, Thrusters, Communications
  - Tumble rate, Temperature, Attitude
  - Camera functioning (dark measurement)

8 orbits

- Telescope deployment
  - 1st stage boom deployment
  - 2nd stage boom deployment (+ camera)
  - Mirror covers deployment
  - Uncage DM1 and DM2

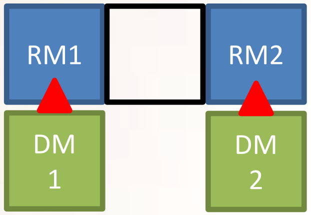
9 orbits

- Adjust and stabilize satellite attitude



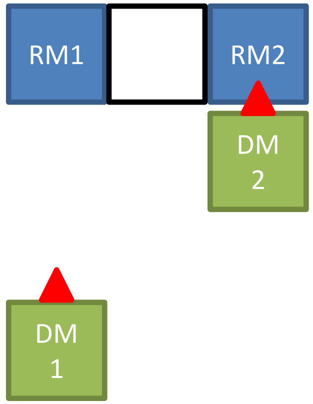
Reconfiguration

1.



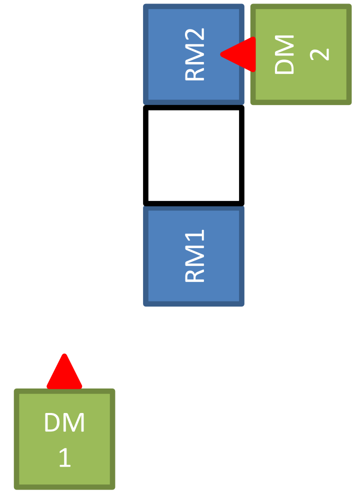
Power up MirrorCraft1
Verify thrusters, T, communication and attitude control

2.



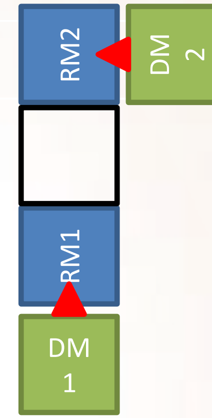
Undock MC1: free-flyer
Check MC1 properties
Move MC1

3.



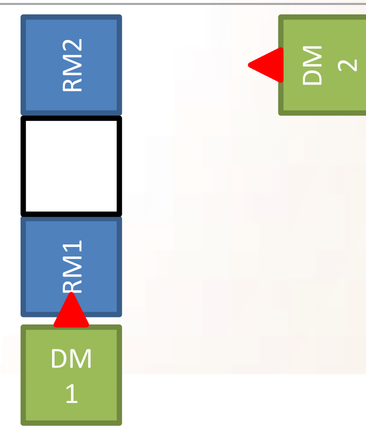
Rotate spacecraft

4.



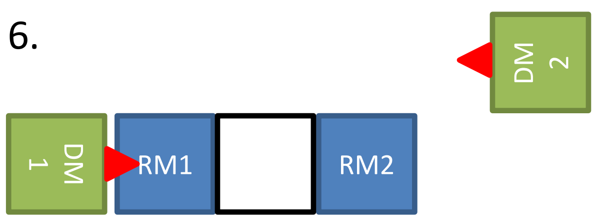
Capture and lock MC1
Check spacecraft
Power up MirrorCraft2
Check MC2 properties

5.



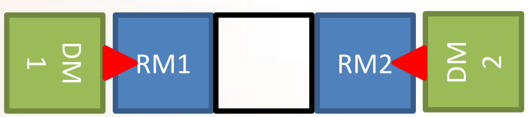
Undock MC2: free-flyer
Move MC2

6.



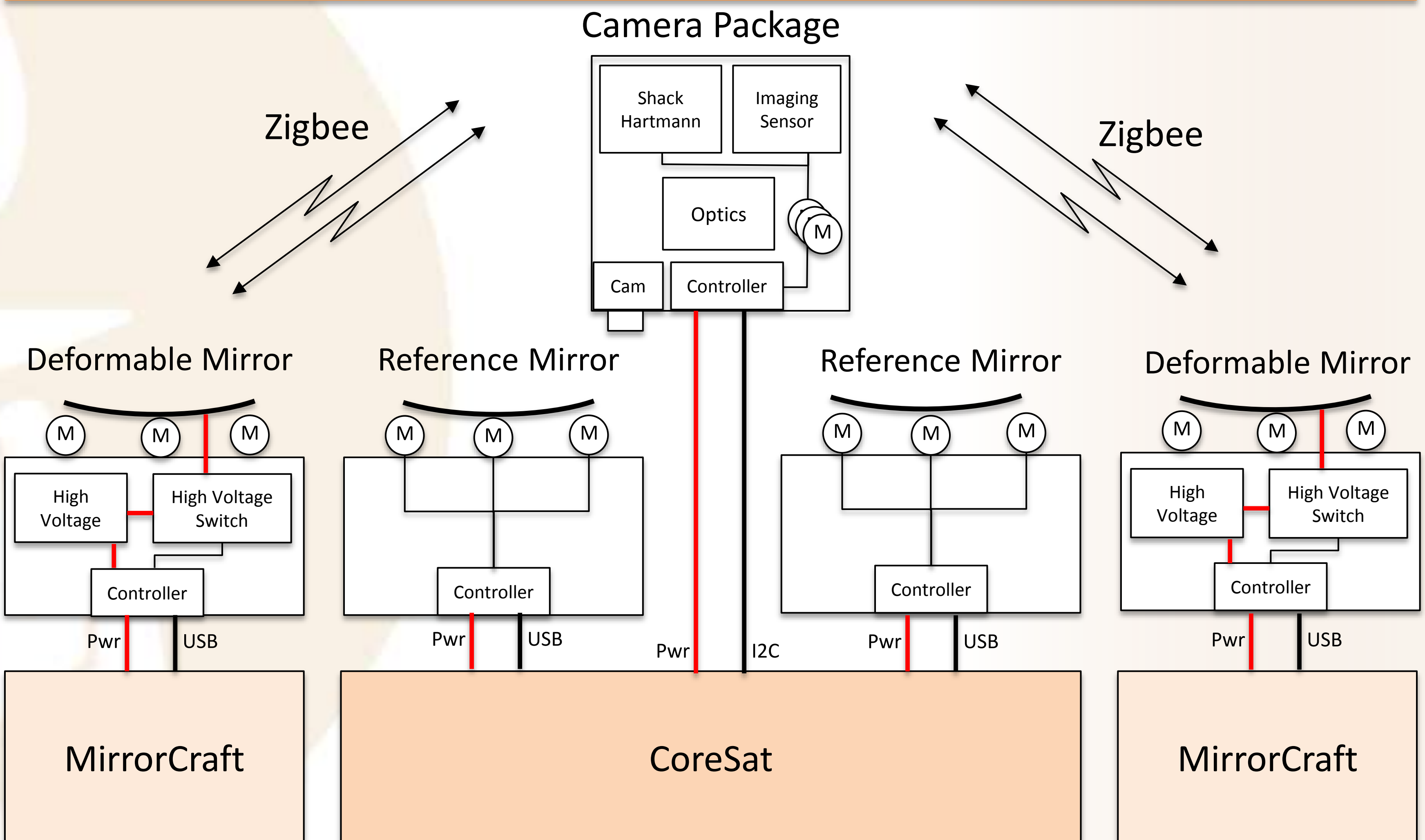
Rotate spacecraft

7.

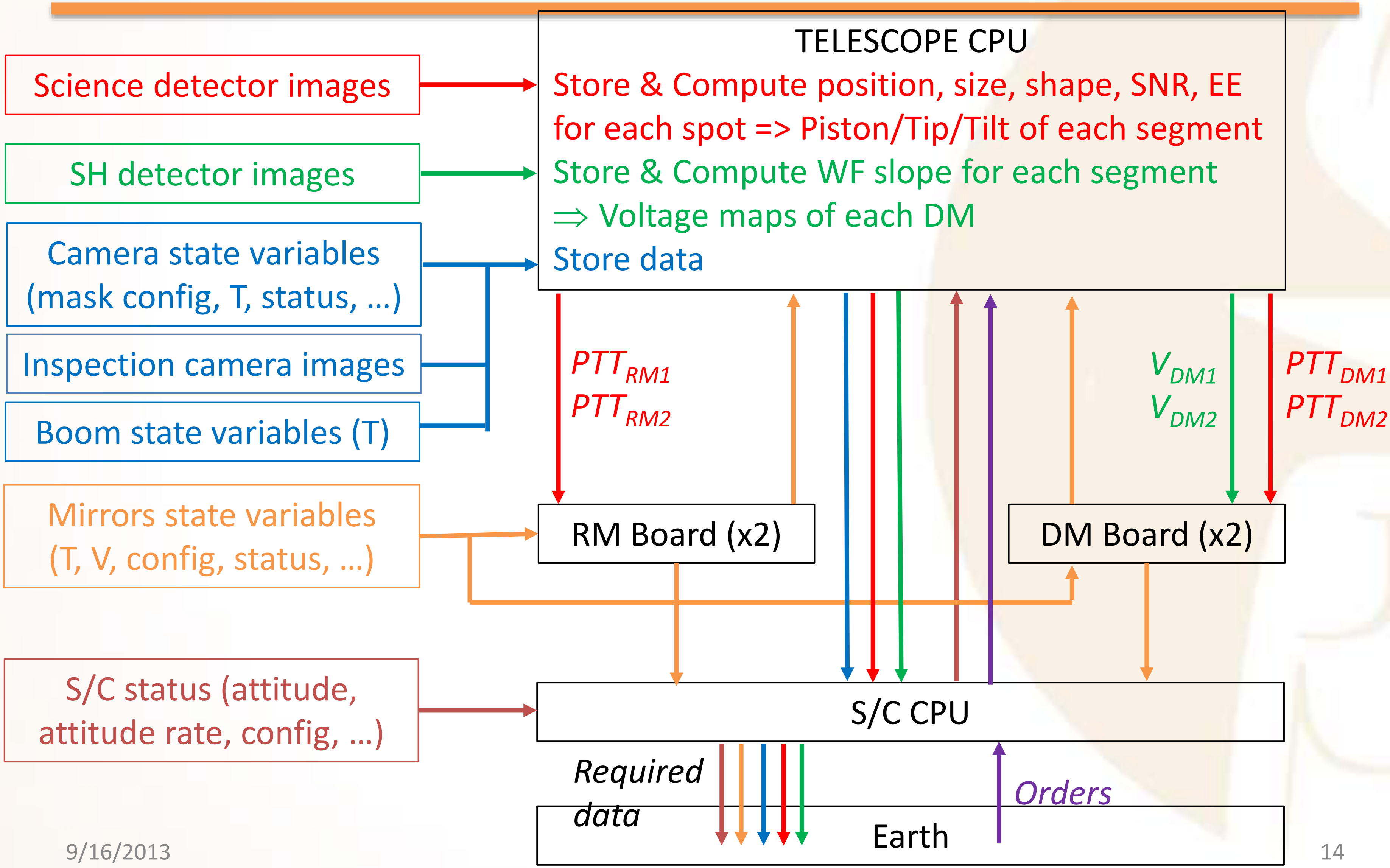


Capture and lock MC2
Check spacecraft

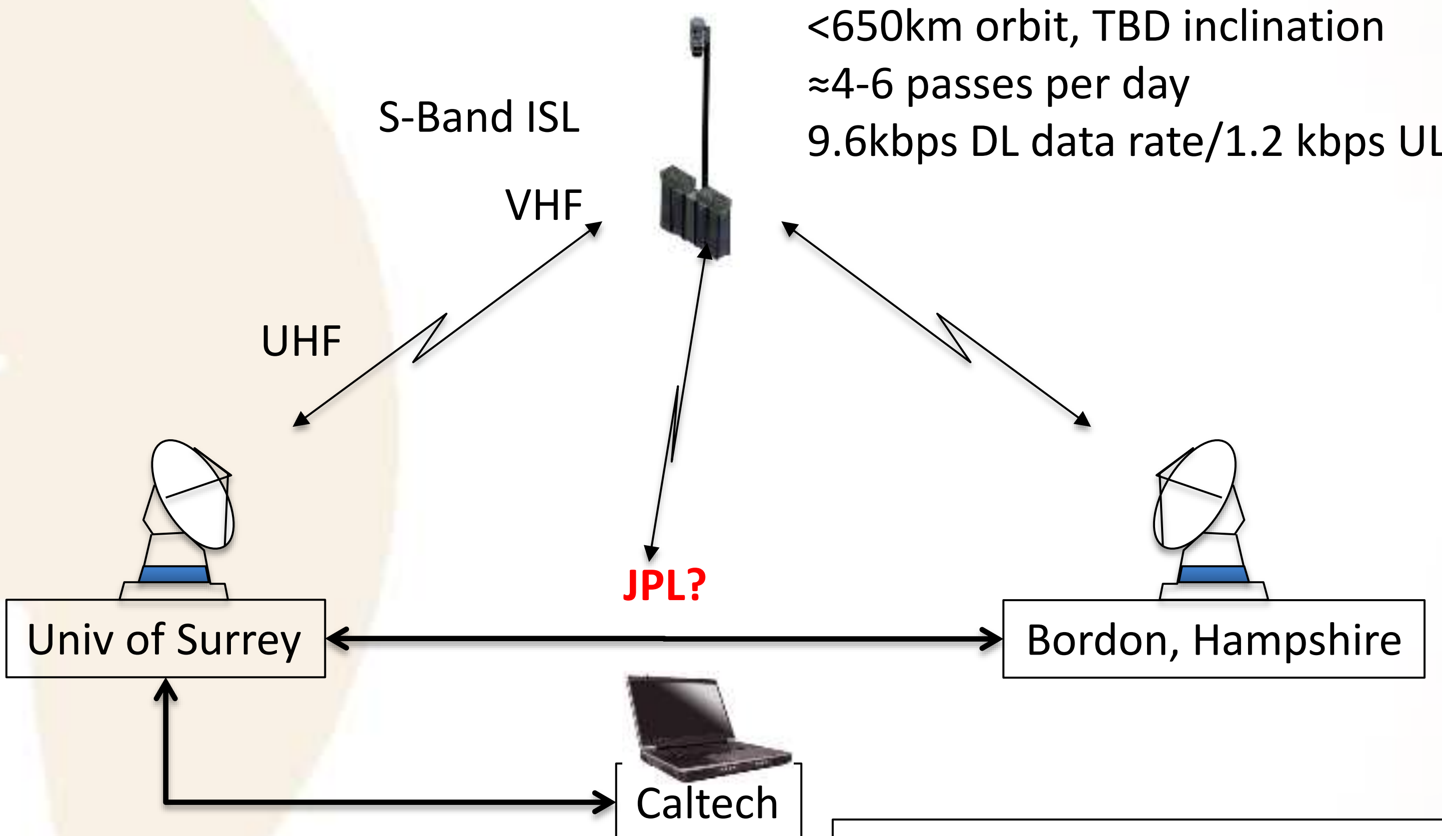
Payload Block Diagram



Spacecraft Communications



Mission Architecture



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

Accomplishments in the Past Year

- Active mirror technology has been further matured in the lab.
- Preliminary spacecraft, telescope and ops concept have been refined
  - Total mass of 40kg is well within secondary launch capability
- 2012-13 AE105 class performed
  - Boom deployment tests and development
  - Refined optical system design
  - Refined Thermal analysis (2 orbit conditions)
- Spacecraft to payload interfaces are simple, with a lot of heritage from STRaND-1 which has flown.

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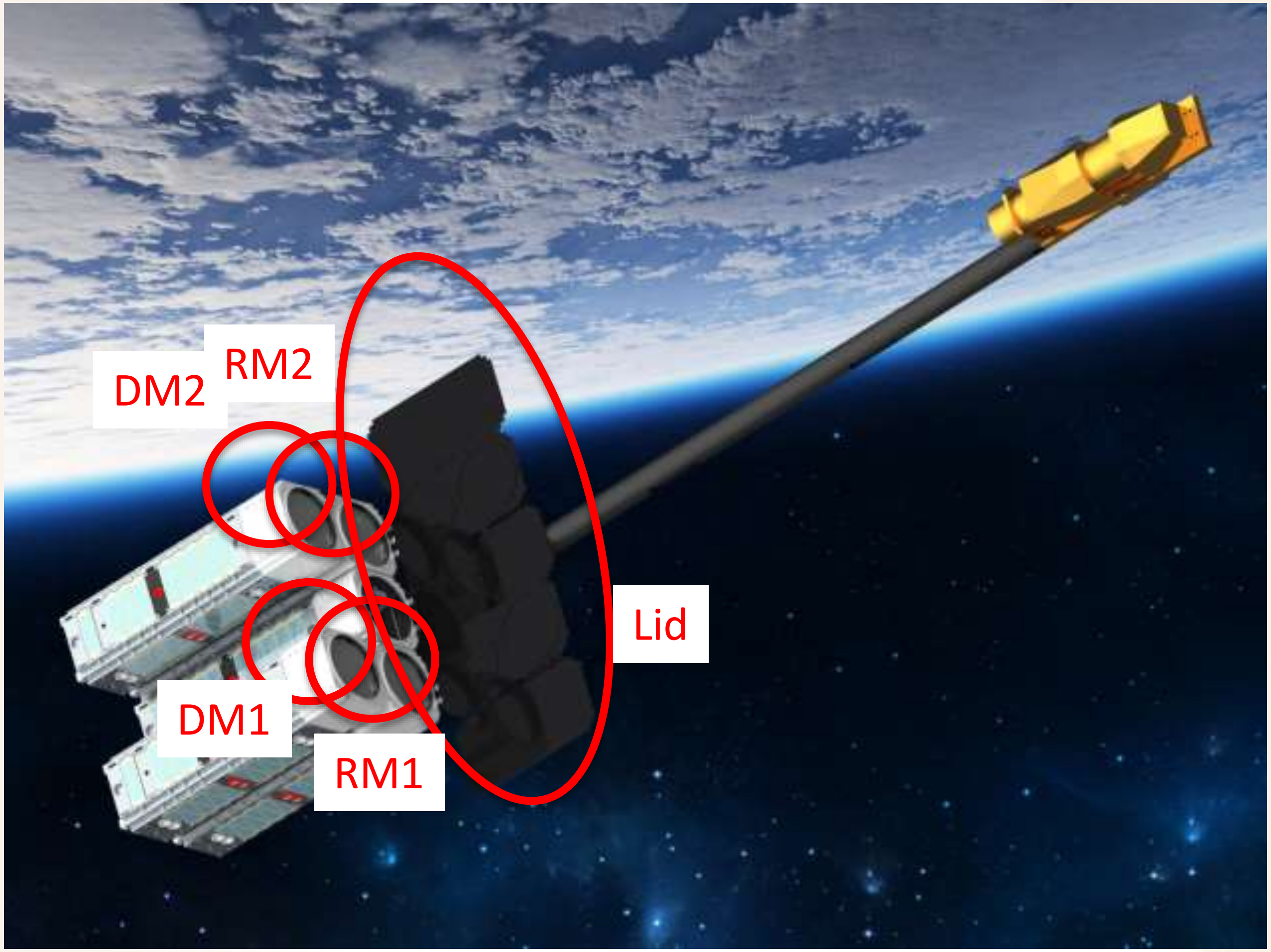
Deformable Mirrors

Keith Patterson (task lead, presenting)
Marie Laslandes (optimization, testing)
Kristina Hogstrom (thermal)
Erin Evans (thermal)

September 9th, 2013

Relevant Assemblies



Problem Description

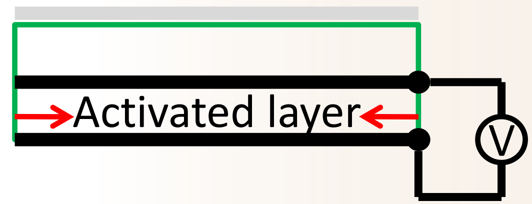
- Develop & design deformable mirror assembly
  - Key Characteristics
    - Thin, flexible, low areal density
    - Identical manufacturing process
    - Actively controlled
  - Key Challenges
    - Large strokes (10’s to 100’s microns)
    - Nanometer precision
    - Volume, power constraints
    - Launch survival

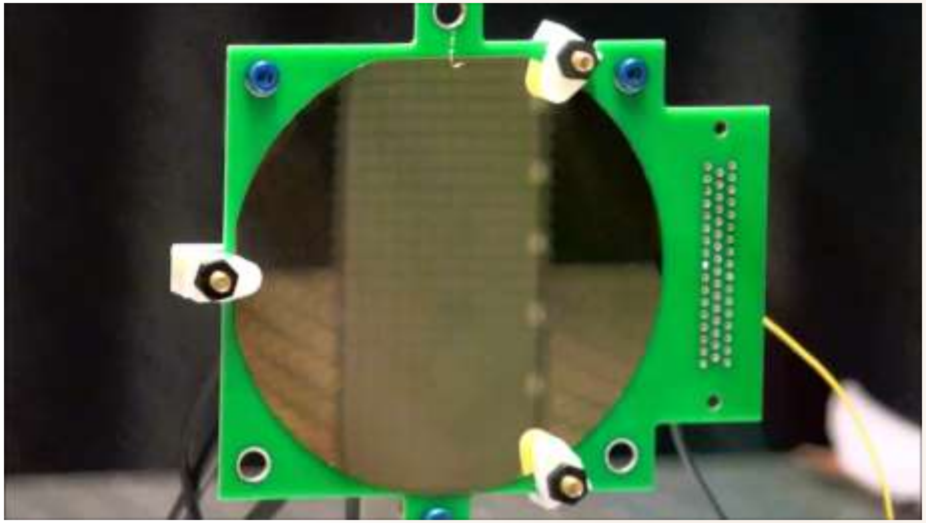
Deformable Mirrors

- Relevant requirements
  - Nominal radius of curvature 2.4 m
  - Deployable mirror cover(s), no debris
  - USB interface to mirrorcraft
  - Zigbee wireless interface to camera
  - 2W power (continuous) for each mirror
  - Functions in both wide and compact configurations
  - Deformation stable long enough for exposures (~50ms)
  - Capable of surviving between -40C and 80C
  - Capable of operating between -20C and 20C
  - Capable of correcting its manufactured shape error (~5 um RMS)
  - Capable of correcting its thermal imbalance (~20 um P-V)
  - Additional OAP stroke (microns RMS surface):
    defocus: 2; astigmatism: 1.2; coma: 0.2
  - Typical reflecting coating roughness < 15nm RMS

General Concept

- Thin laminate
  - Polished glass wafers
  - Piezo polymer coating
- Bimorph actuation
  - In-plane strains create mirror curvature
  - Thin, low areal density
- Actuation patterns
  - Independent regions for fitting of mirror surface shapes

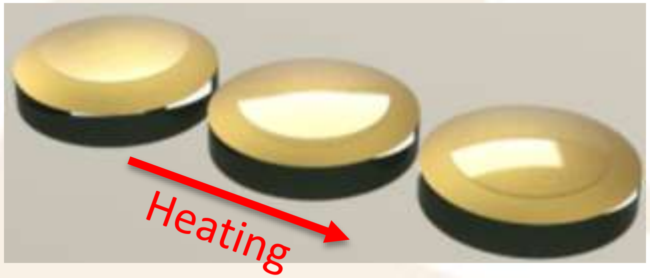


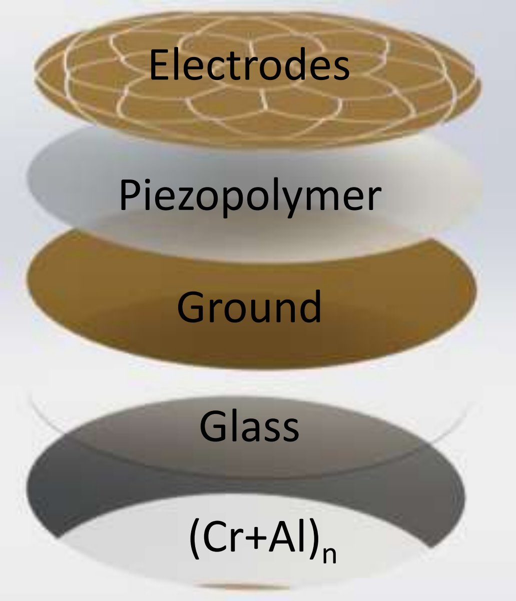


Mirror Fabrication Process

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

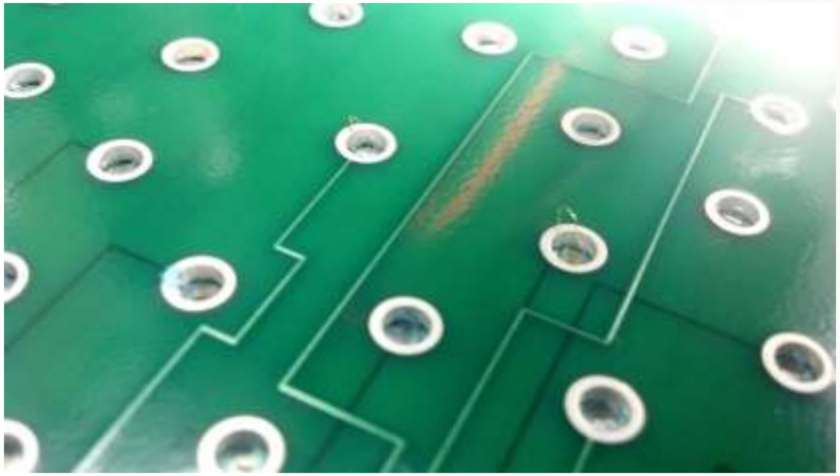


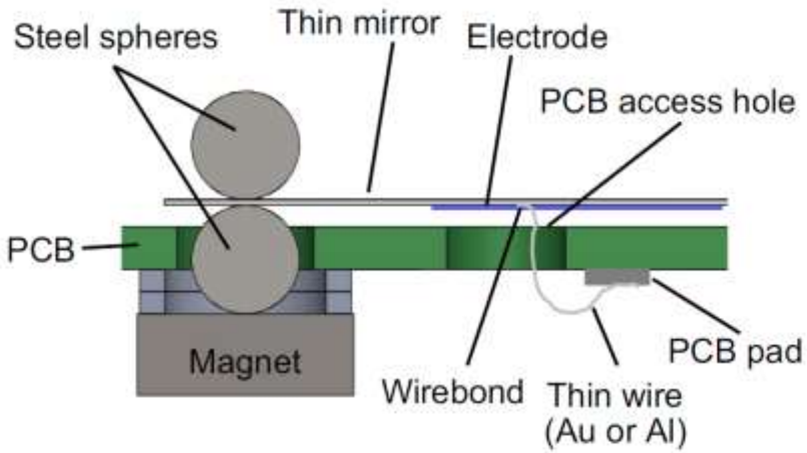


reflective side

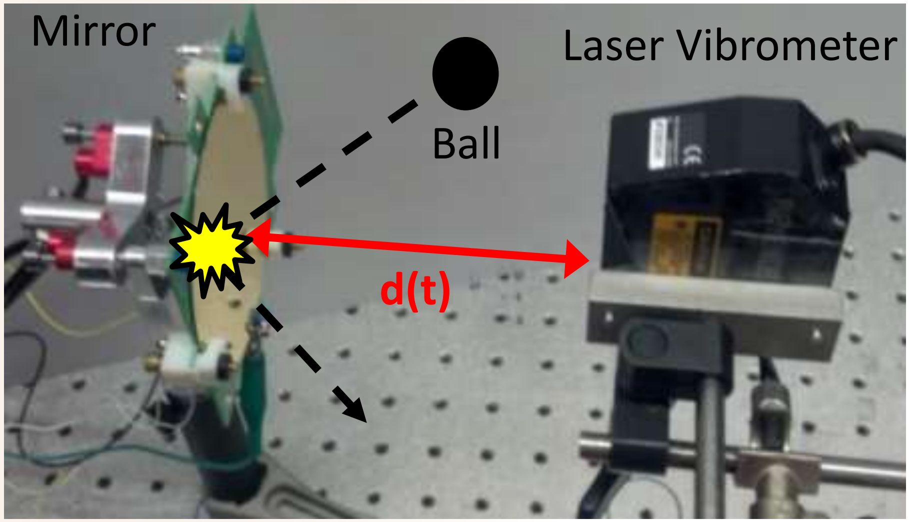
Mirror Mounting

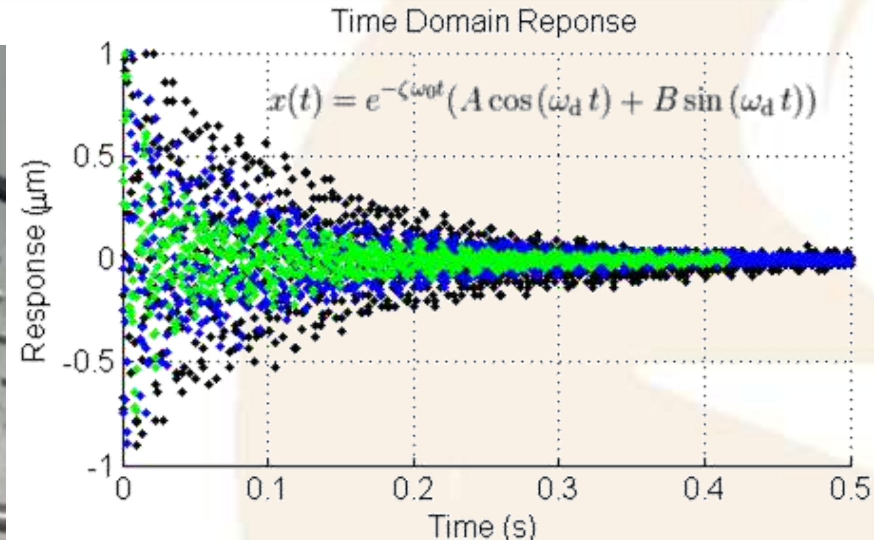
- Tiny Au wirebonds connect mirror electrodes to PCB pads
(via holes)
- Kinematic mounting to PCB
  - Spheres pinch mirror in 3 places, preloaded and aligned using a magnetic field

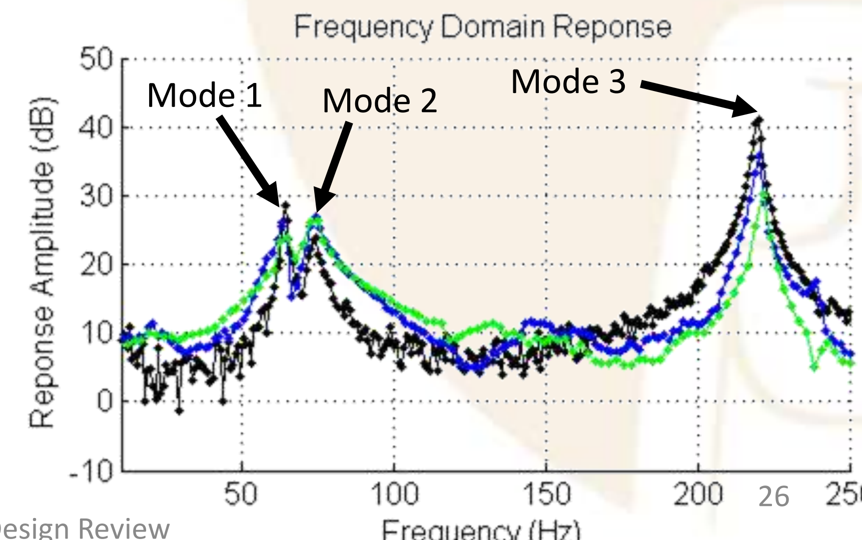




Vibrational Behavior







Substrate: Glass

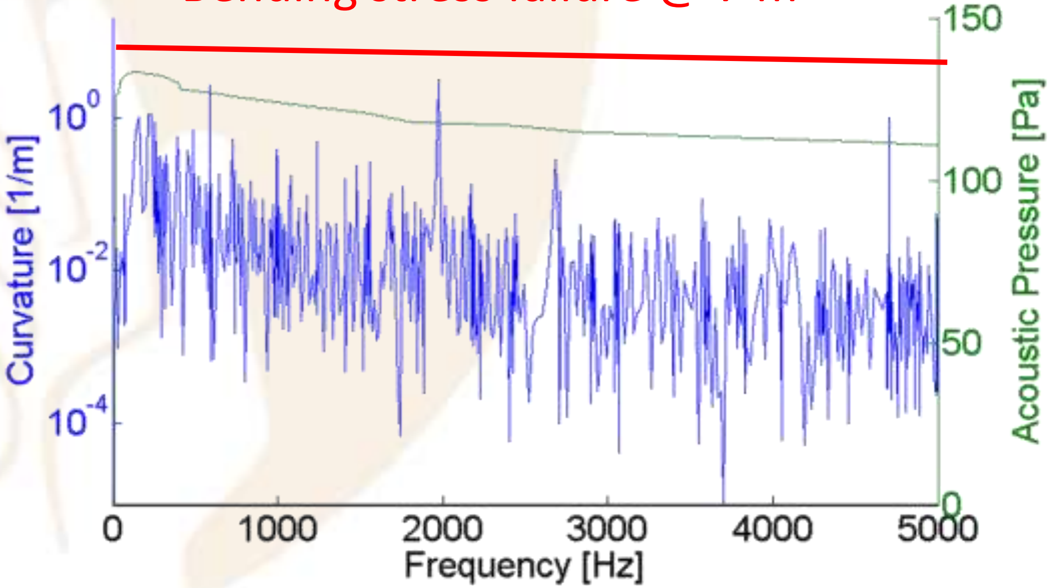
	Experiment	FEM
Damping Ratio, ζ	0.12	(0.12)
Mode 1	63 Hz/3800 RPM	70 Hz
Mode 2	74 HZ/4500 RPM	81 Hz
Mode 3	220 Hz/ 13000 RPM	257 Hz

NOTE: Possible resonances at wheel speeds!

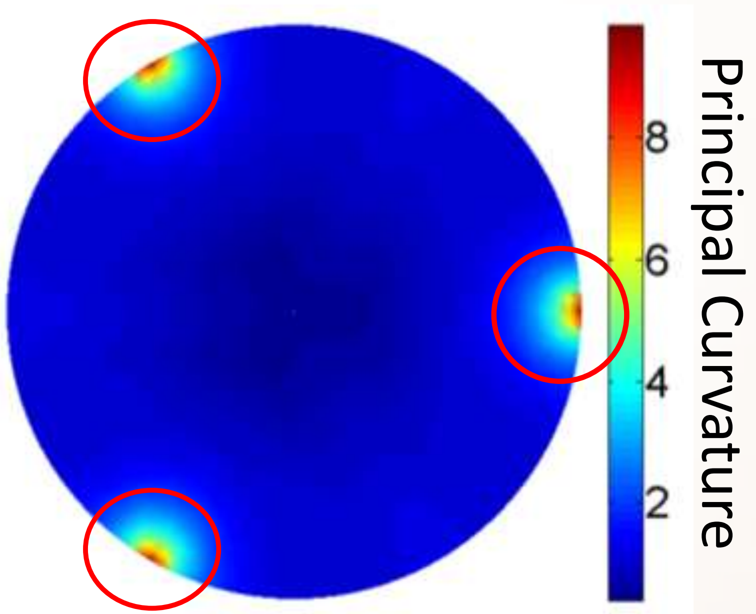
Launch Survival

- Mirror mass is ~4 grams (0.5 kg/m^2)
- Acoustics are most concerning
  - Delta IV-Heavy acoustic loads (conservative case)
  - Clamping points have critical stresses
- **Decision: require mirror launch restraint**

Bending stress failure @ 7 m^{-1}

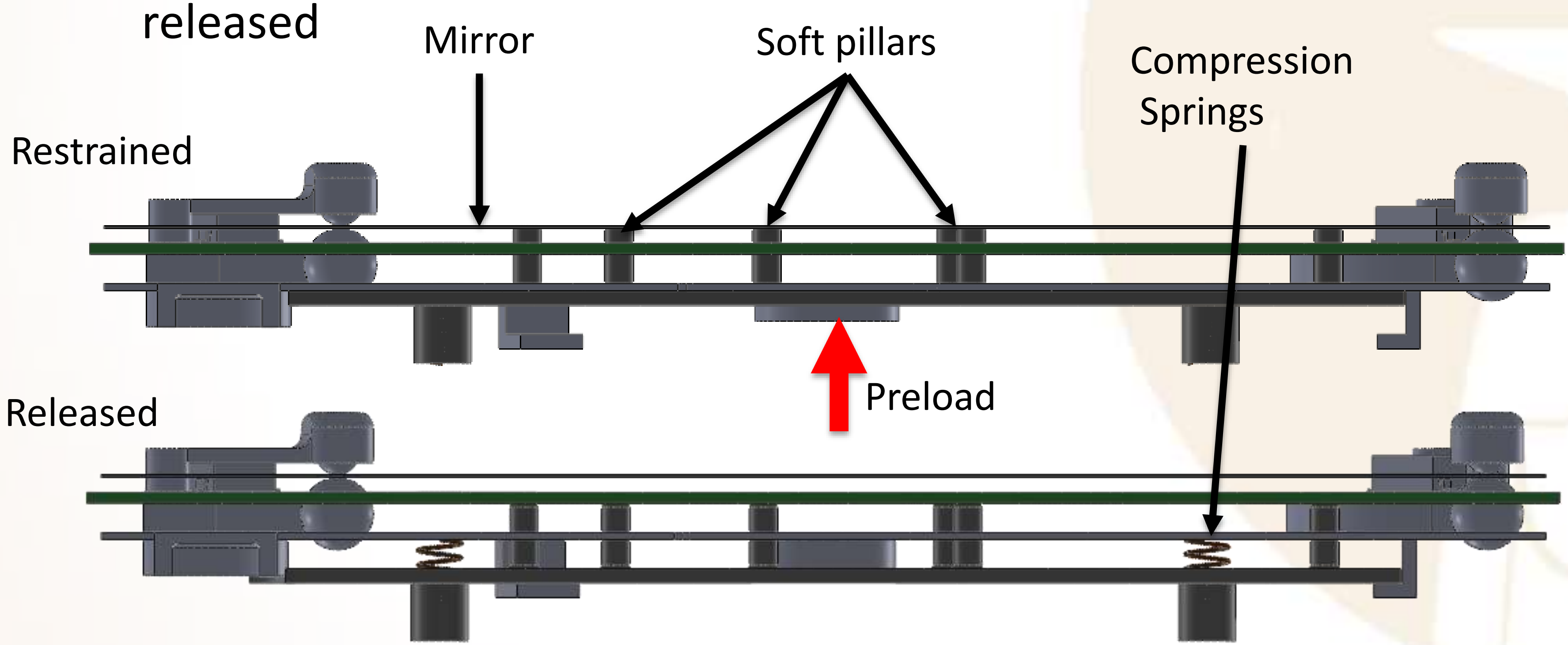


RSS of curvature over all freqs m^{-1}

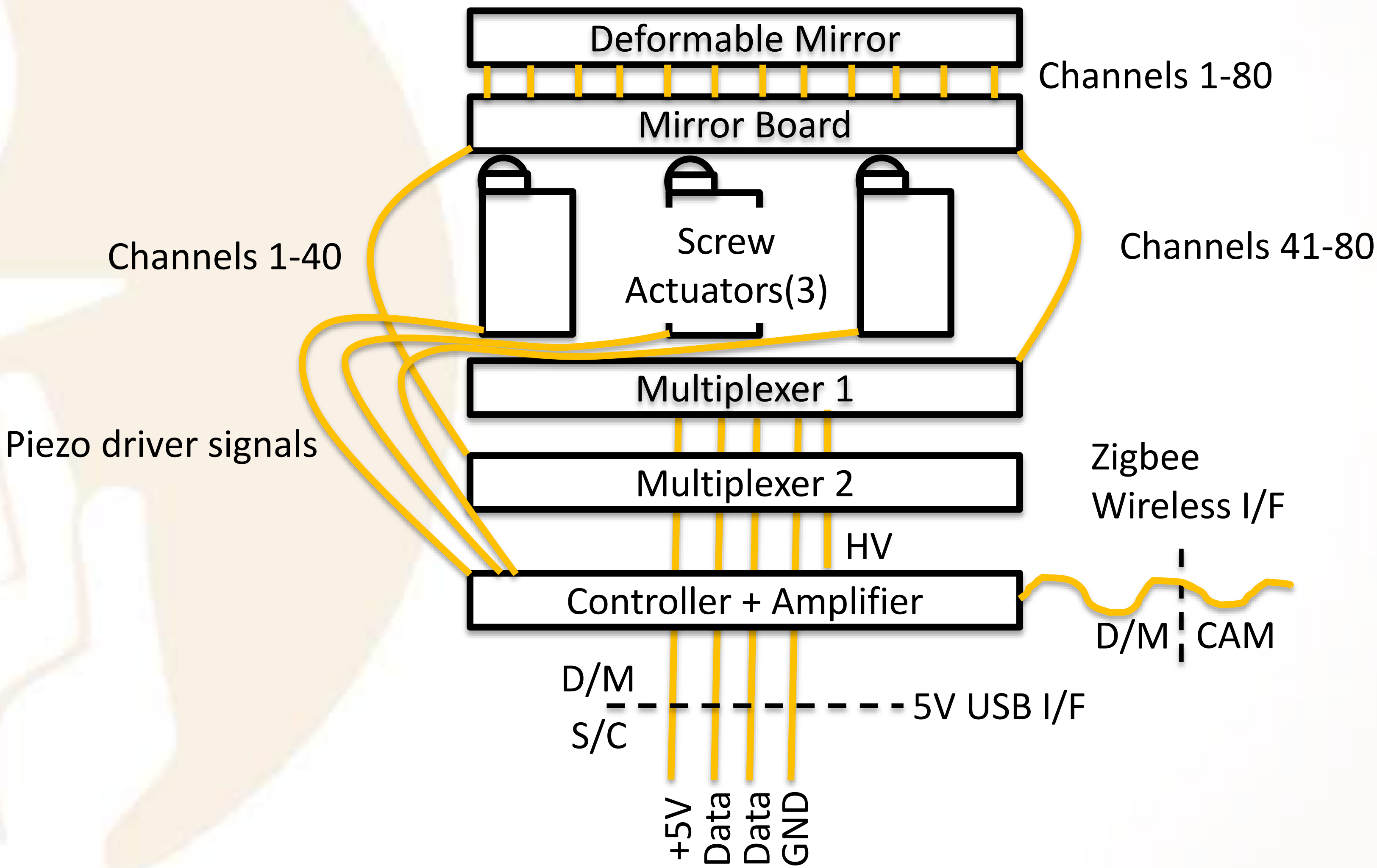


Launch Restraint Concept

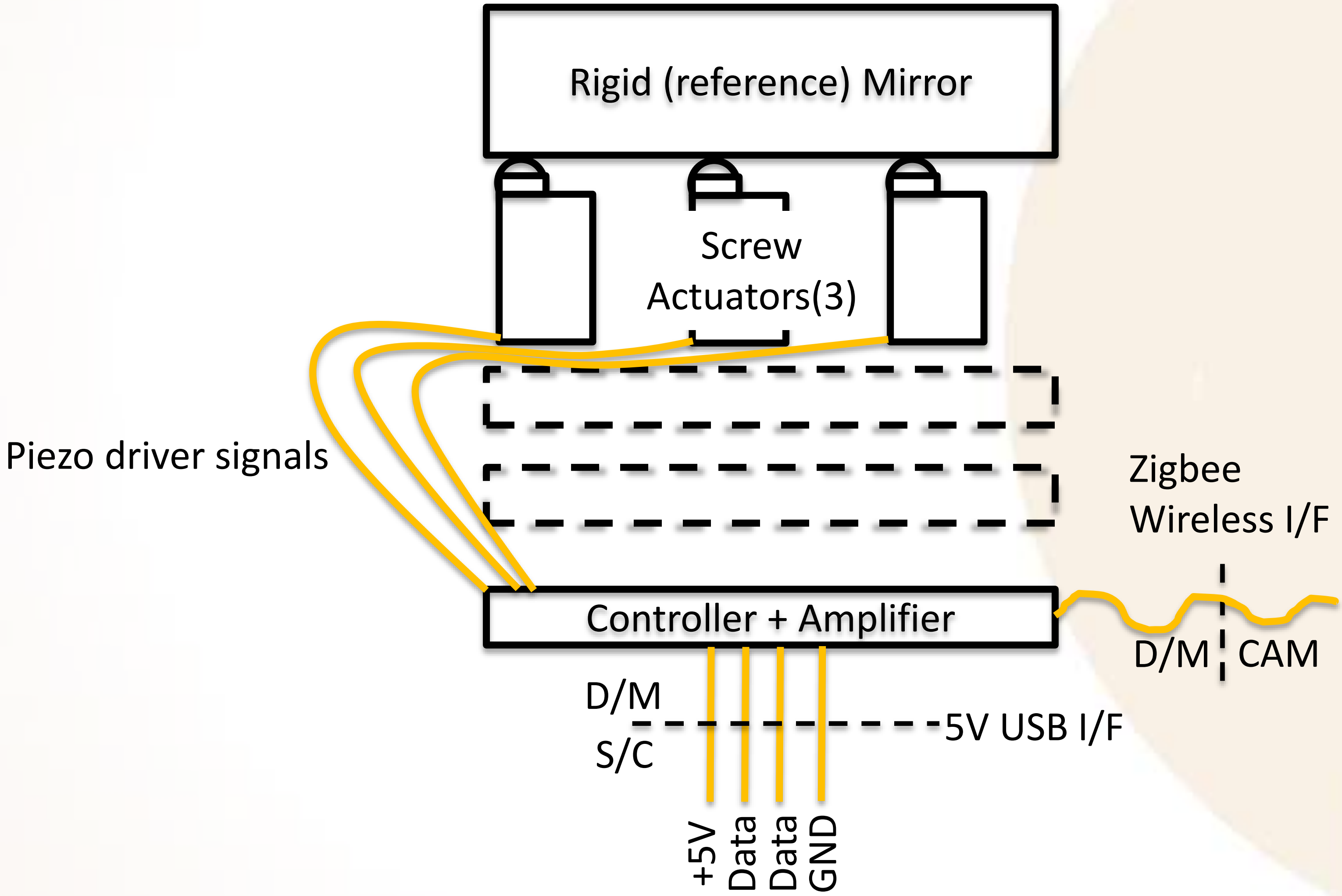
- Screw actuators lower mirror onto spring loaded restraint plate
- Restraint plate has small, soft pillars mounted to it to press on mirror underside
- Closed lid presses down from above with large soft pad (not shown)
- After lid is opened, mirror lifted from pads by actuators, restraint plate released



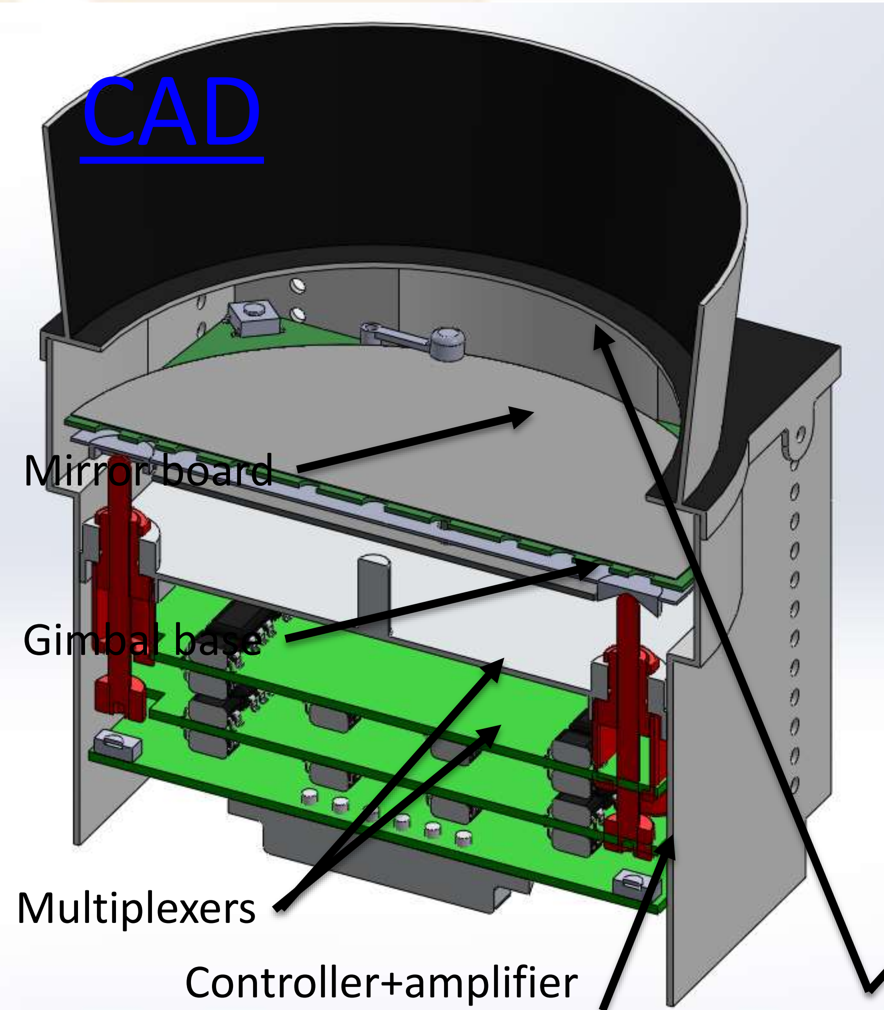
DM Package Block Diagram



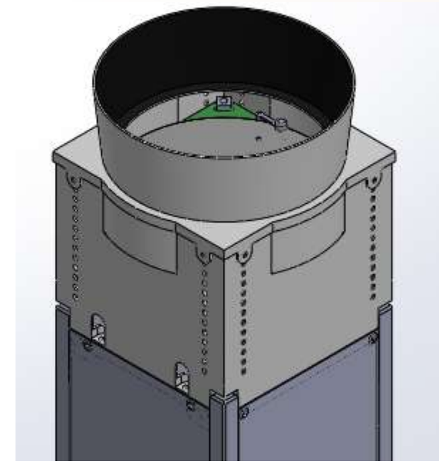
RM Package Block Diagram

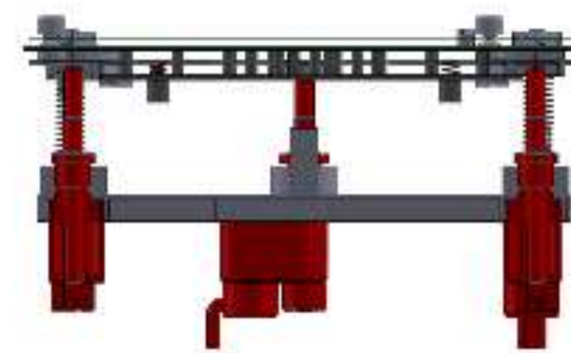


Current Configuration



Mirror casing (white paint)





Sensors and Actuators

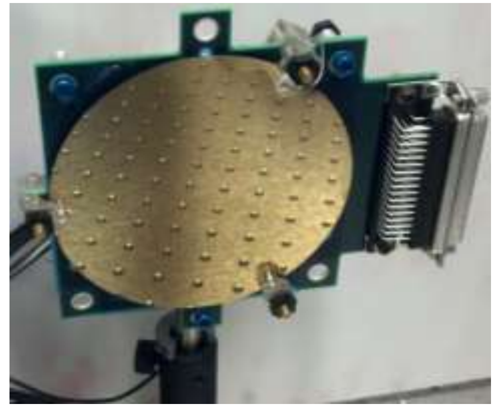
- Sensors
  - Thermopile remote temperature sensors underneath mirror to monitor temperature, TBD locations
  - Thermocouples on PCB's
  - Gimbal limit switches
- Actuators
  - ~40-80 mirror channels
  - 3 piezo screw actuators
  - Optional use of propellant heaters under mirrorbox
  - Gimbal range of motion:

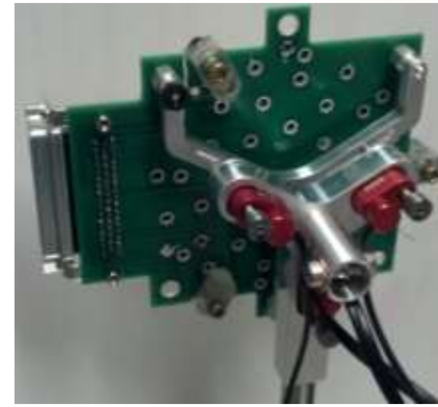
Mirror Position	Relative Piston (mm)	Tip (deg)	Tilt (deg)
Reference	0	2.855	0
Compact	2.9	2.855	2.855
Wide	8.7*	5.695	0

*without step height in wide configuration

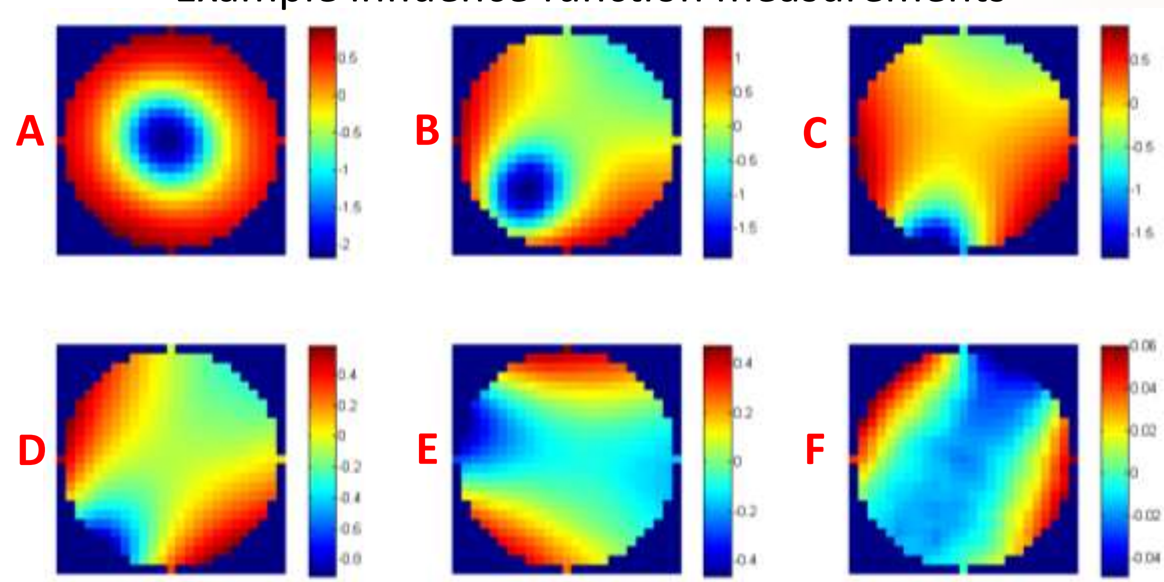
41 Channel Lab Prototype

- Upgrade from previous 16 channel design
- Marie’s optimized “Notre Dame” actuation pattern
- Process improvements still ongoing
  - Reliability
  - Quality



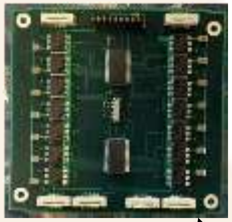


Example influence function measurements



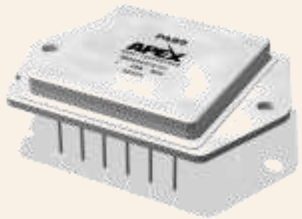
Major Components (Mirror assembly)

- Mirror board
  - Mirror
  - PCB
  - Launch restraint system
- Gimbal
  - 3 Newport Picomotors (8301-UHV)
- Multiplexer boards
  - Panasonic AQV258 PhotoMOS relays (1 per channel)
  - Maxim MAX6956AAX+ LED driver IC's
- Controller board
  - M/C options
    - Rascal micro (Atmel ARM9)
    - MBED M/C (ARM Cortex-M3)
  - Apex/Cirrus HV Opamp (PA89A)
  - EMCO (AH06N-5T, AH06-5T) DC-HV DC converters
  - Zigbee wireless (TI CC2520)



Relays

HV Opamp



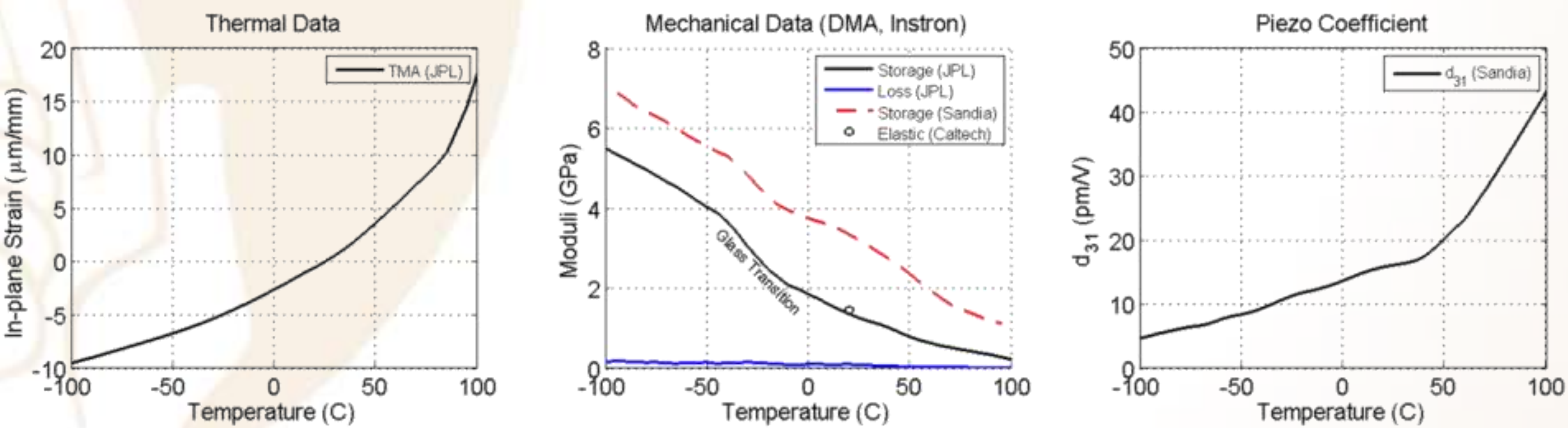
DC->HV DC

M/C's

Zigbee

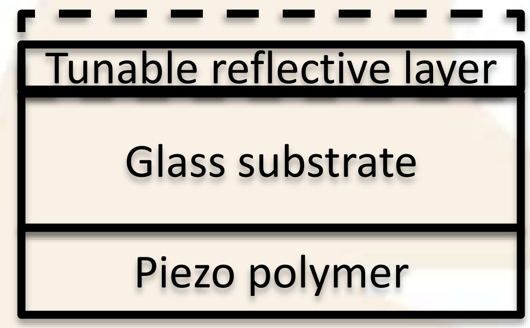
Piezo Polymer Material Data

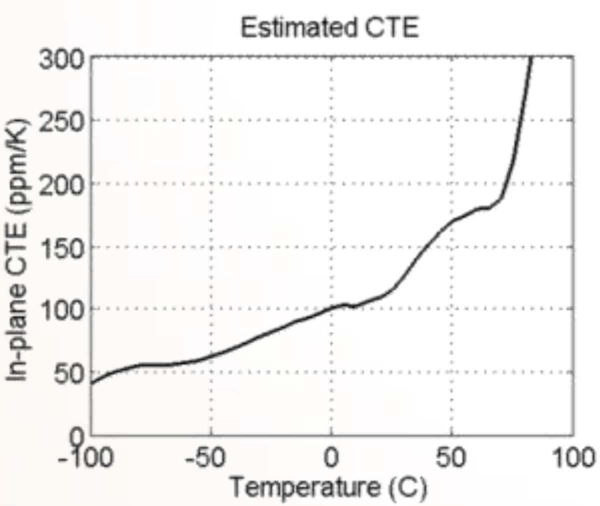
- Material characterization
  - Data from
    - JPL polymer lab (TMA, DMA, DSC, TGA)
    - Caltech material testing (Instron, optical measurements)
    - Sandia report on PVDF in space (DMA, piezo measurement)
  - Large variation in properties across temperatures

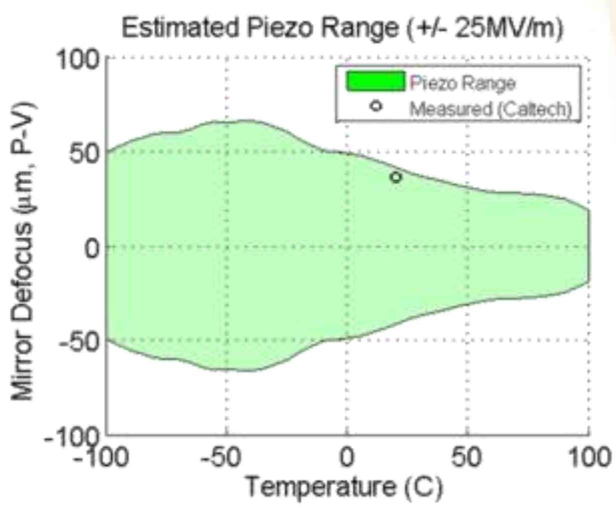


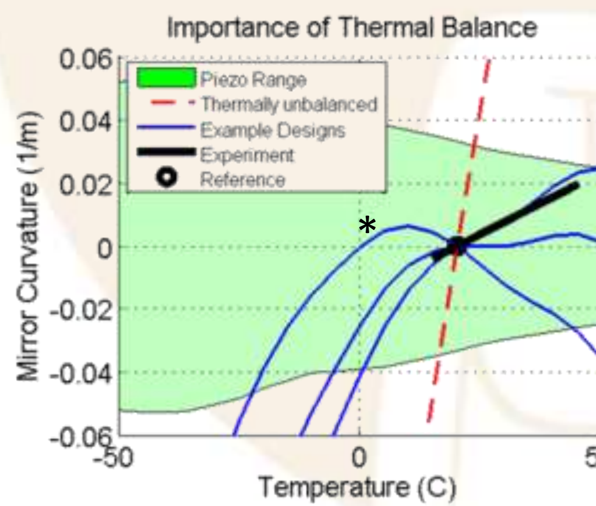
Piezo Polymer Material Data

- 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 (for defocus mode)
  - +/-40 microns at 20C, +/- 60 microns at -40C
- Thermal balance
  - Thermal expansion overrides piezo range in <10C
  - Tuned balancing of mirror can extend operational range
  - Example designs below
  - * indicates curve used for performance analysis



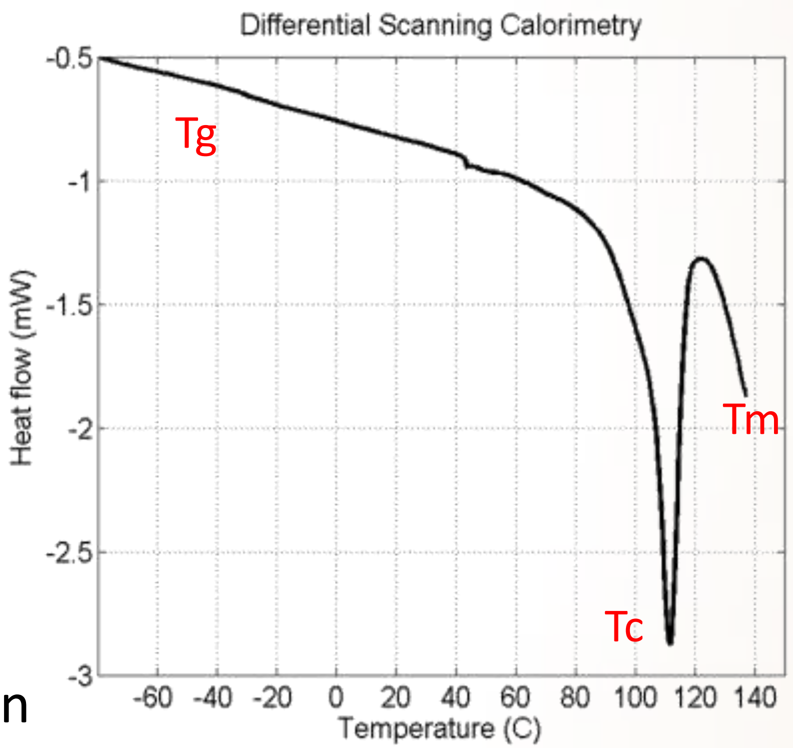






Additional Piezo Polymer Properties

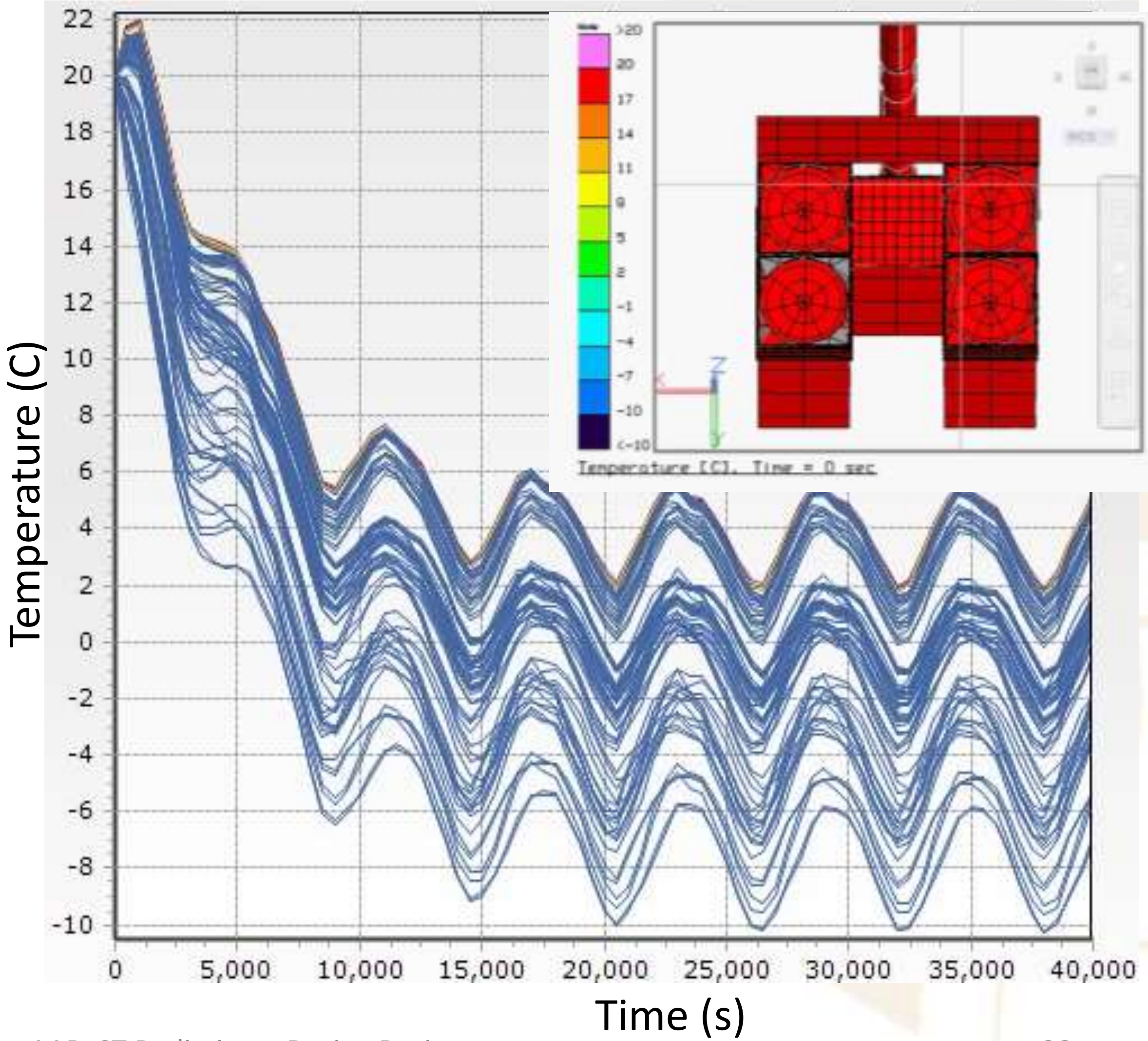
- Critical temperatures
  - Tg: -40C , glass transition (ill-defined)
  - Tc: +110C, Curie
  - Tm: >140C, melting
  - Td: >400C, decomposition
- No moisture absorption (<0.01%)
- Viscoelasticity
  - Stiff for a polymer but still viscoelastic
  - Creep master curve to be measured
  - Good news: glass substrate will dominate shape over time and maintain molded shape



Thermal Traces: 11am/11pm SSO

The Model:

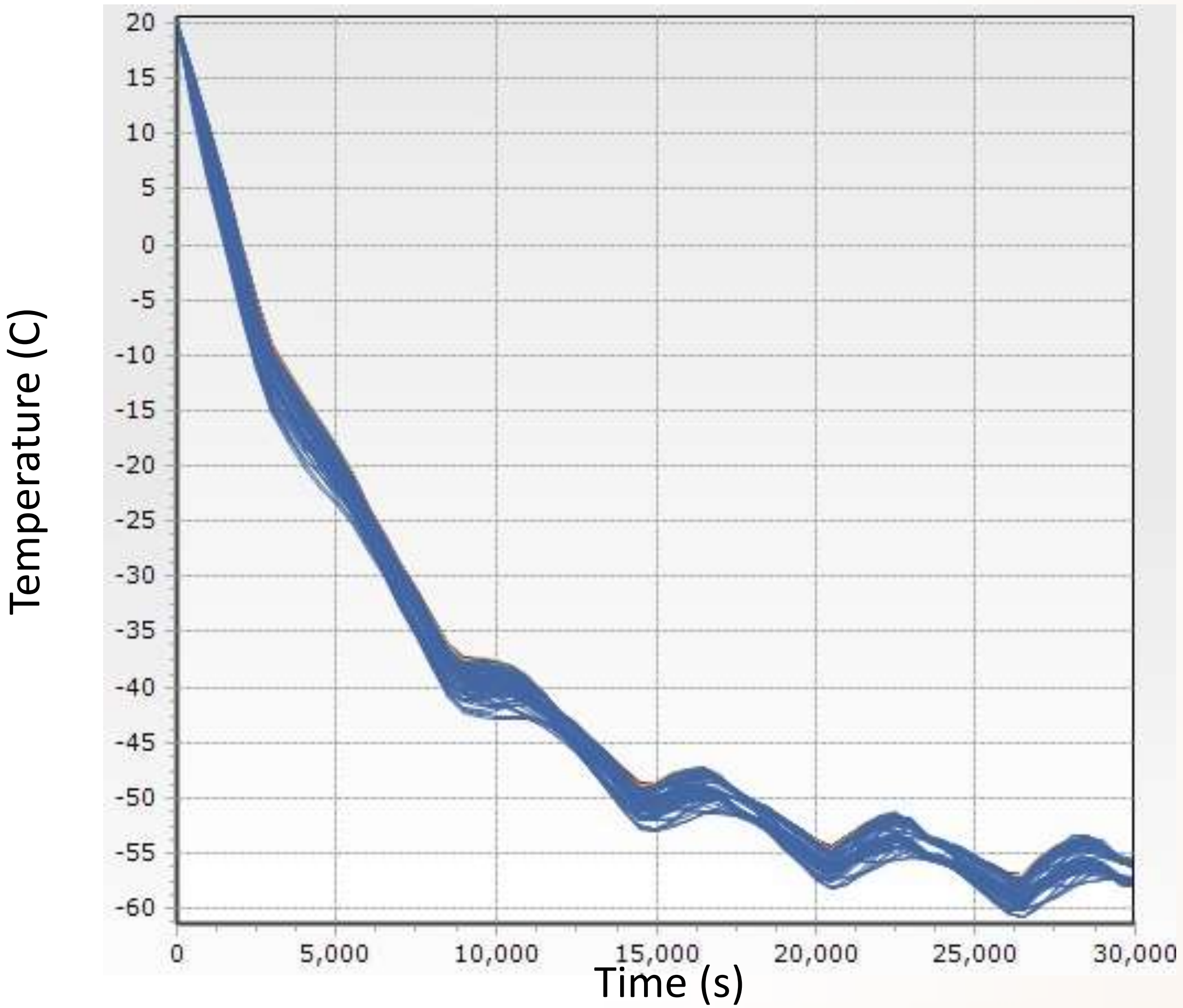
- Planetshine on
- Albedo on
- Sunshield (white paint, black chrome)
- .5 W generated/circuit board
- Temperatures between -10C and +10C
- Some radial thermal gradient present (due to board heat)
- Want surface temperature and emissivity underneath mirrors as uniform as possible to minimize gradients



Cold Case: No Power

The Model:

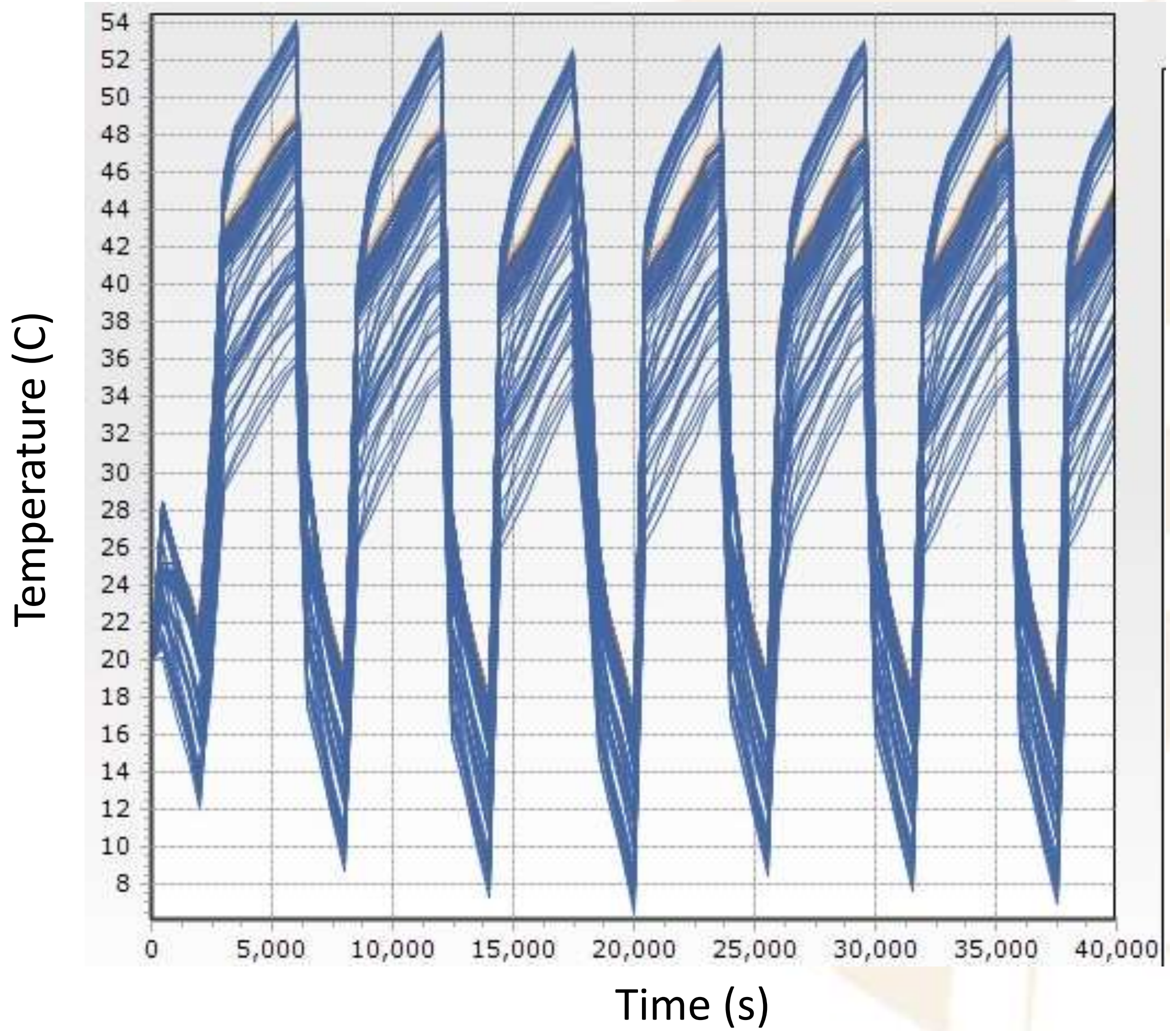
- 11 AM 11 PM Sun-synchronous orbit
- Planetshine on
- Albedo on
- Sunshield (white paint, black chrome)
- 0 W generated/circuit board
- Drops down to -60C
  - Need to ensure mirror survival here
  - Can improve conduction to mirrorcraft
- Minor thermal gradient



Sun Pointed (Lost Control) – "Hot" Case

The Model:

- 11 AM 11 PM Sun-synchronous orbit
- Planetshine on
- Albedo on
- Sunshield (white paint, black chrome)
- .5 W generated/circuit board
- Telescope orbits with mirrors facing the sun
- Mirrors warm but still within survival range
- Solar irradiance may reflect into camera if mirrors are aligned -> BAD

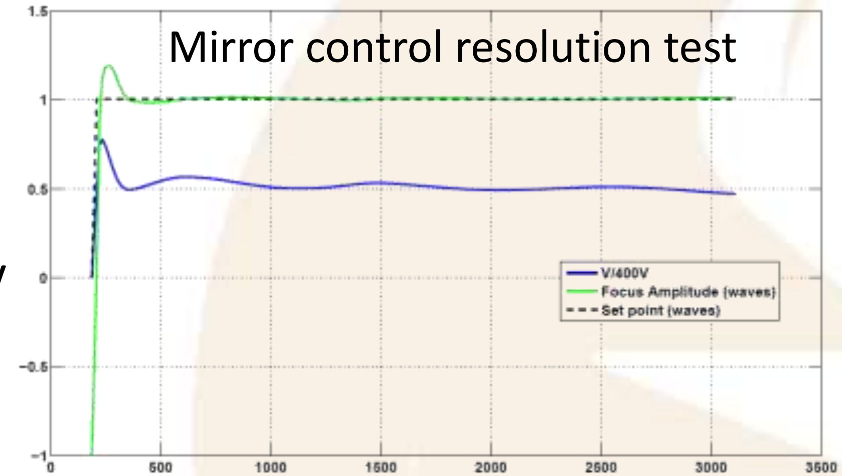


Interfaces

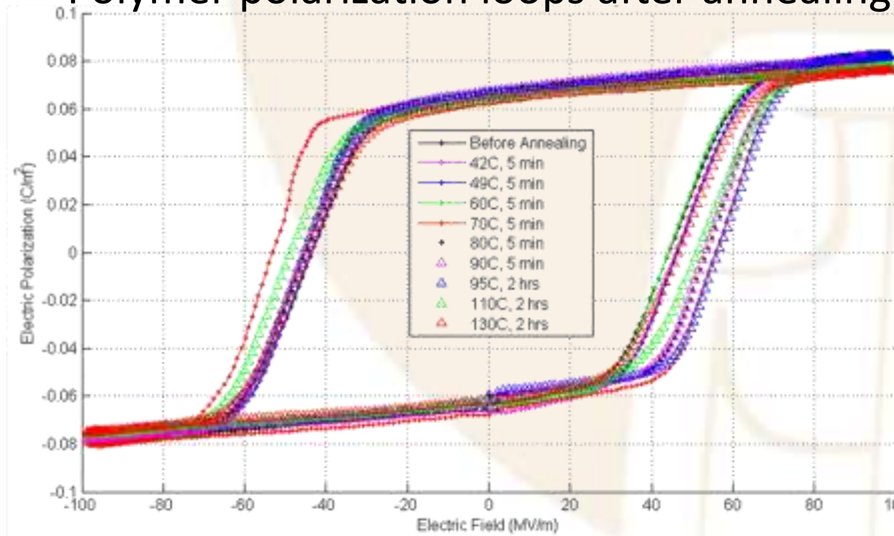
- Mechanical
  - Mirrorbox bolts on top of 3U ISIS structure
- Electrical
  - 5V USB interface to mirrorcraft
  - Zigbee wireless to camera
- Thermal
  - Conductive contact with mirrorcraft
  - TBD survival heaters
  - Shielded from sun by lid/baffle(s)

Development Functional Tests

- Optical
  - Demonstration of 16-channel and 41-channel prototypes
- Electrical
  - Multiplexer prototype tested to +/-500V in air
  - Future: HV boards in partial vacuum
- Thermal
  - Piezopolymer survival (1 hour)
    - retained functionality down to -70C and >90C
  - Future: thermal cycling of mirror package, shape hysteresis/creep
  - Future: thermal cycling of electronics
- Mechanical
  - Future test: launch restraint acoustic testing



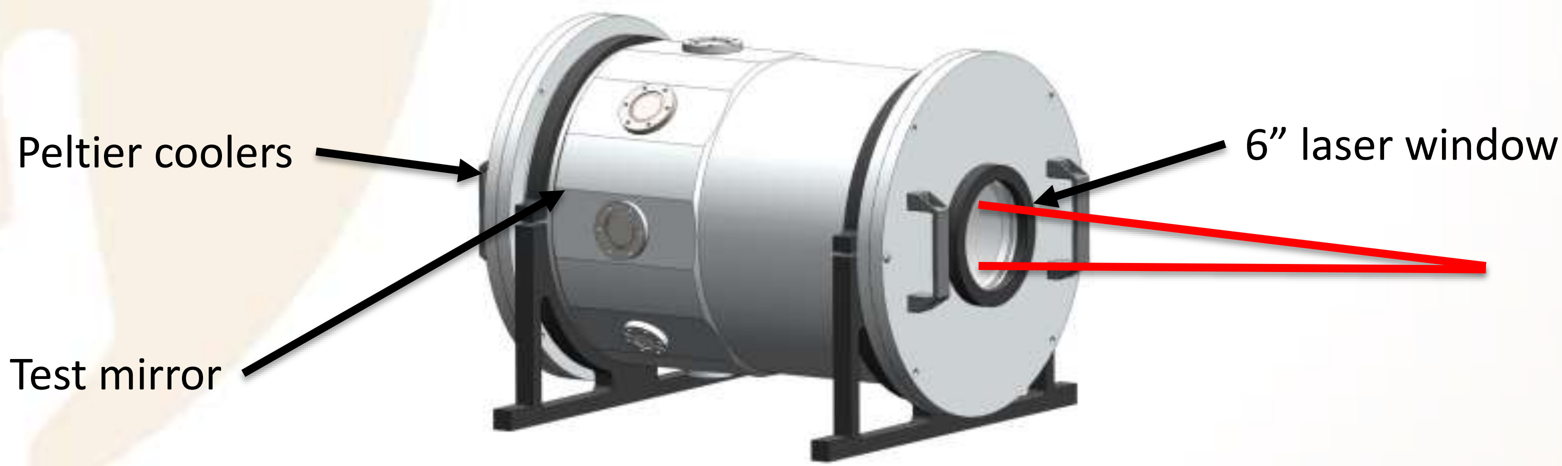
Polymer polarization loops after annealing



Performance Tests

- Optical
  - 16 channel Si prototype
    - Achieved 2 waves RMS error in lab environment
  - 41 channel glass prototype
    - Some shorted channels, testing ongoing
  - Future: demonstrate diffraction-limited reproduction of OAP shapes
- Electrical
  - Future: amplifier power efficiency, peak power
- Thermal
  - Future
    - Mirror thermal shape stability and actuator stroke confirmation

16”x20” Vacuum chamber



Assembly and Integration

- Assembly
  - Critical step is wirebonding mirror to board
  - Boards mount into casing using brackets
  - Wirebonded flat flex cables between boards to minimize cabling volume/weight
- Integration
  - DM/RM individual unit assemblies shipped to Surrey
  - Assemble modules onto M/C and Coresat
  - Test communication to controllers
  - Verify mirror functionality of all channels (visual inspection)
  - Verify gimbal actuation
  - Lower mirror gimbals, clamp lid and restrain mirrors

Functional Library

- Commands:
  - activateGimbal()
  - resetController()
  - standby()
  - setVoltages(voltages)
  - driveActuator(id, cycles, forward_reverse)
- Queries:
  - getTemperatures()
  - getChannelStates()
  - getGimbalStates()

Conclusion

- Mirror box design
  - Packaging scheme laid out
  - Mirror restraint system concept needs testing
  - Design trade on sun shield/baffle needed
- Preliminary analysis and testing completed
  - Vibration work suggests launch restraint needed
    - Concept needs testing
  - Possible mirror resonance at high wheel speeds
  - Thermal numbers look reasonable so far
    - Good mirror thermal balancing is critical to optical performance
    - Mirror survival heater would be good to include
    - Uniform surface temperature below mirror will aid in thermal gradient reduction
- (System performance modeling coming in later slides)
- Mirror prototypes built and performance tested in ambient
  - Have not yet achieved diffraction-limited but getting closer
  - Improvements to glass slumping and piezo coating methods ongoing
  - Mirrors were functional after thermal survival tests (-70C, +90C)
  - Need to test optical performance with thermal cycling (chamber is being built)
- Controller/amplifier electronics needs breadboard testing
  - Power consumption numbers need to be verified
- Electronics/communication interfaces to M/C and Camera need more definition

Acknowledgements

- John Steeves, Jim Breckinridge (Caltech)
- Namiko Yamamoto, Risaku Toda, Victor White, Harish Manohara, Andrew Shapiro, Bill Warner (JPL)
- Past Ae105 classes

Review Outline

1. Mission Overview (20 mins)
2. Spacecraft Design (60 mins)
3. Telescope Design (160 mins)
   a) Mirrors
   b) Camera
   c) Boom
   d) Telescope System Performance
   e) Test and Calibration
4. System Summary, Launch Vehicle, Project Plan (15 mins)
5. Discussion (15 mins)

Camera

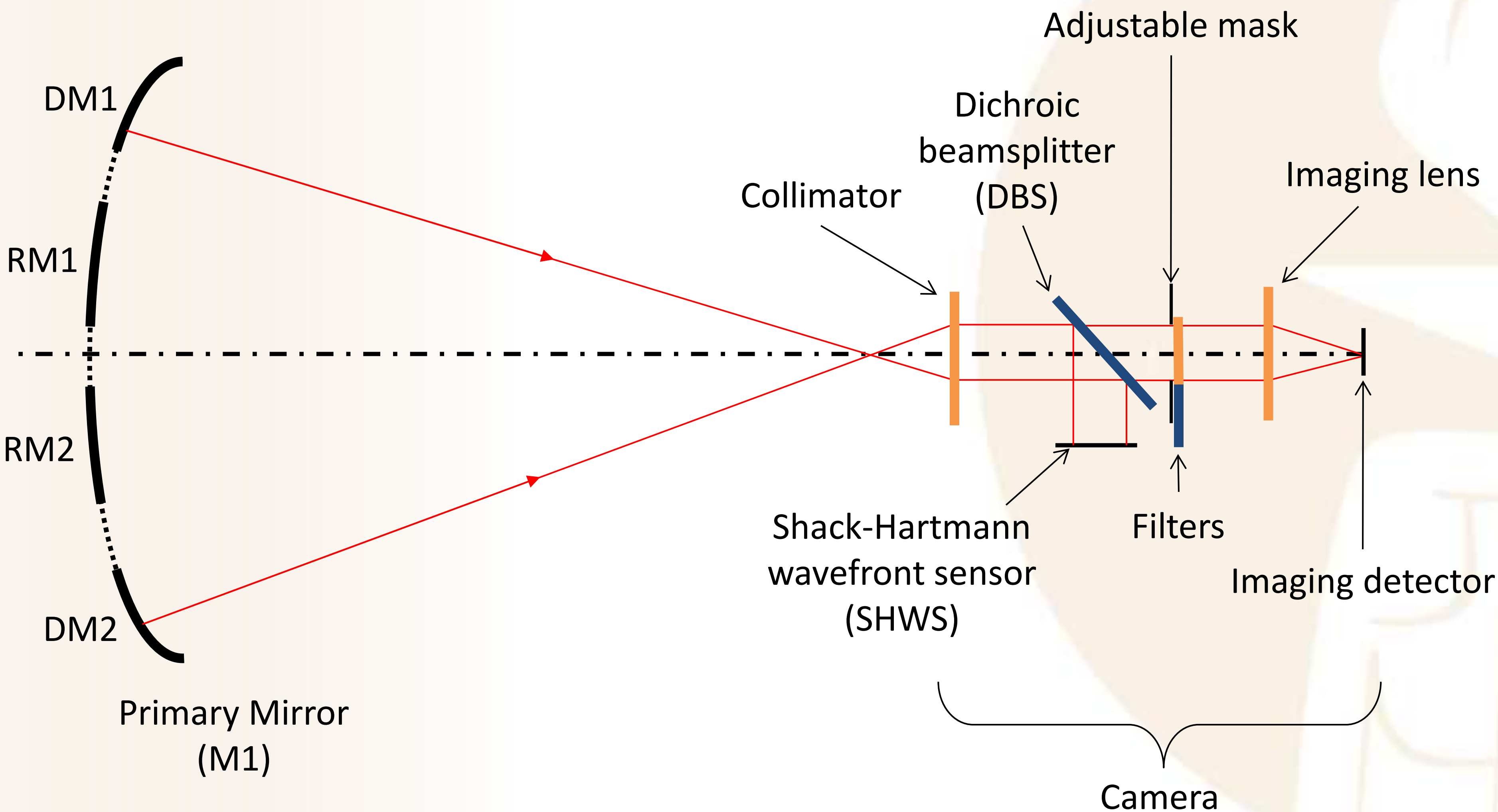
Manan Arya

September 9th, 2013

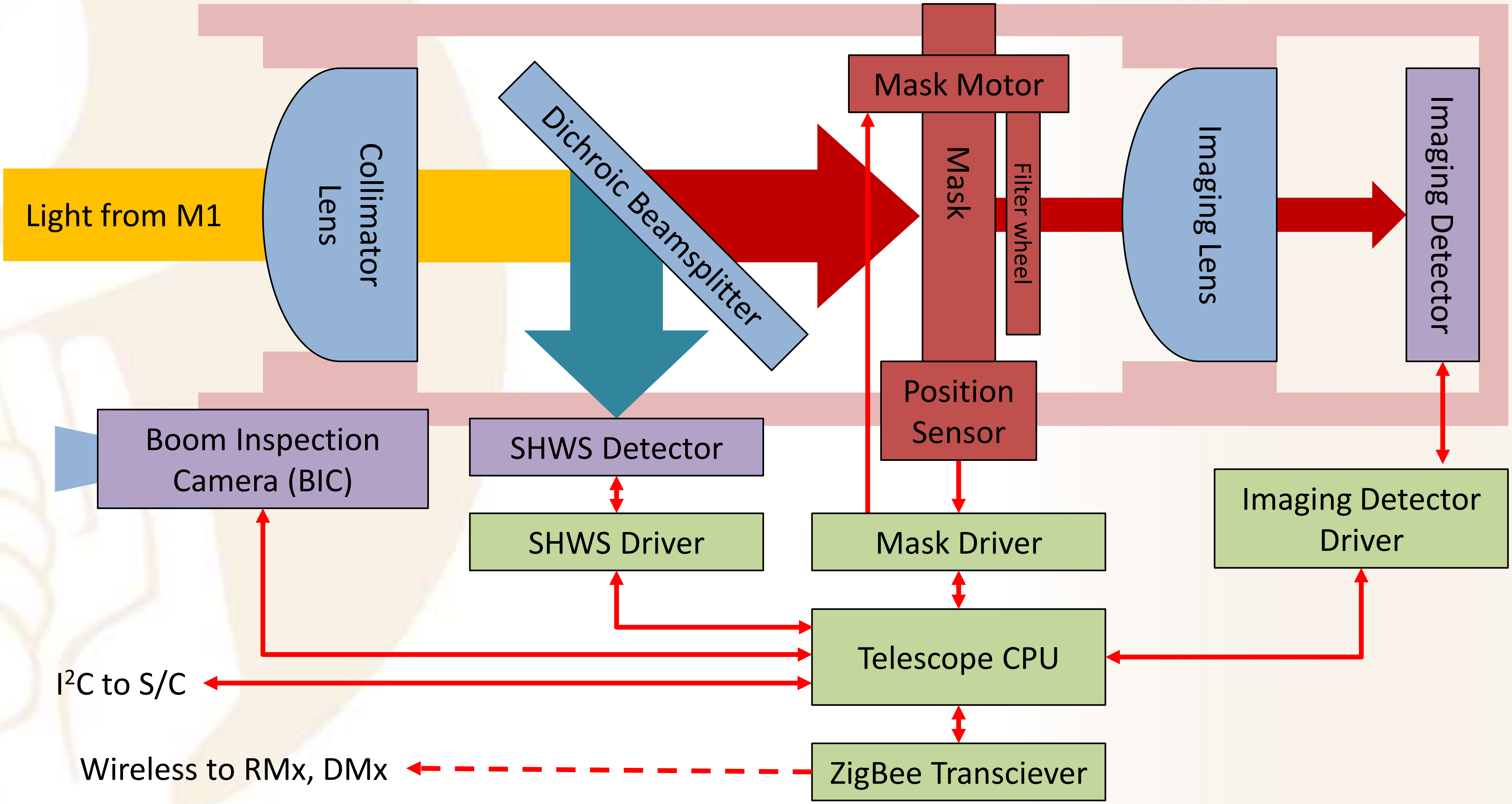
Camera Requirements

- Functional
  - Work with 1.16m focal length segmented primary mirror
  - Provide feedback during primary mirror calibration
    - Deformable mirror (DM1 & DM2) shape
    - Primary mirror segment positions (tip and tilt)
  - Science imaging
- Performance
  - 80% encircled energy radius < 90% diffraction-limited EE radius
  - 0.3° (18 arcmin) full field-of-view
  - SNR > 100
- Constraints
  - Mass < 4kg
  - Volume (excluding boom interface) < 10cm × 10cm × 35cm
  - Power < 5W

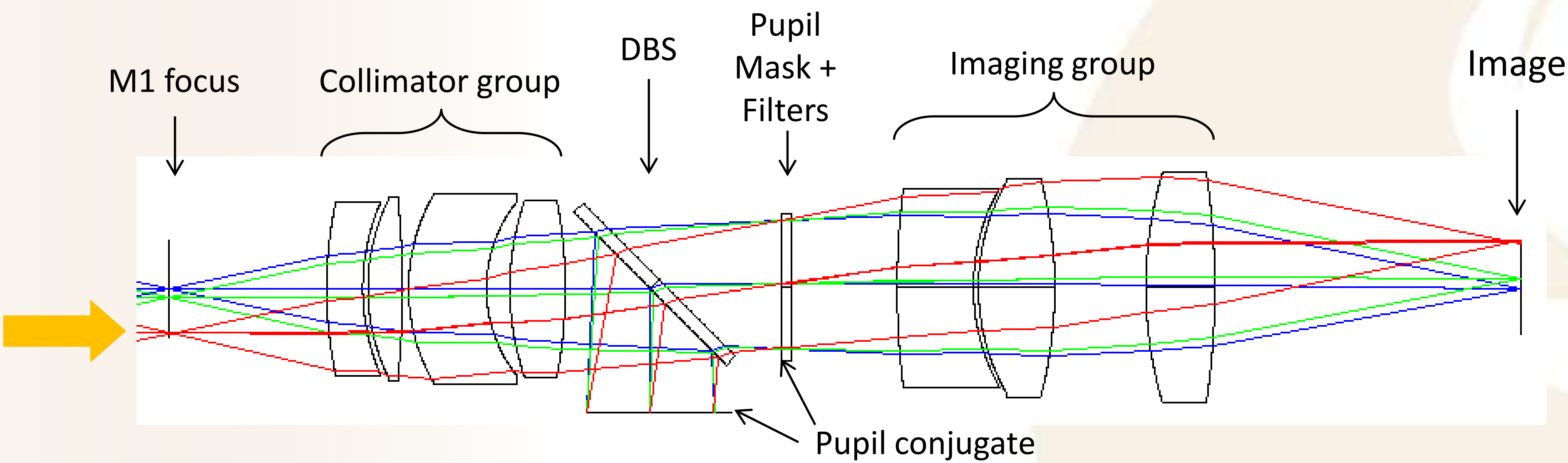
Configuration



Block Diagram

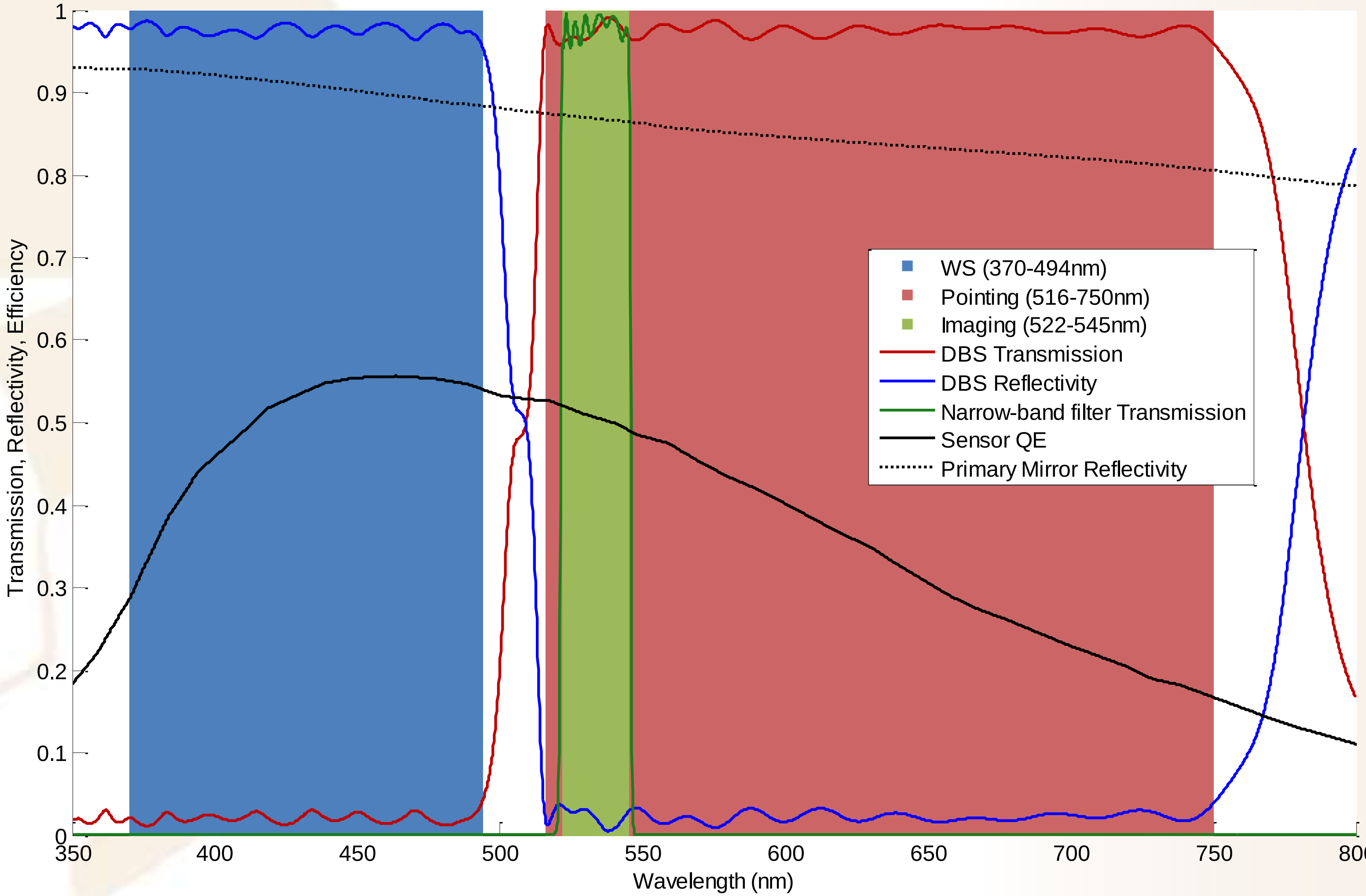


Optical Configuration

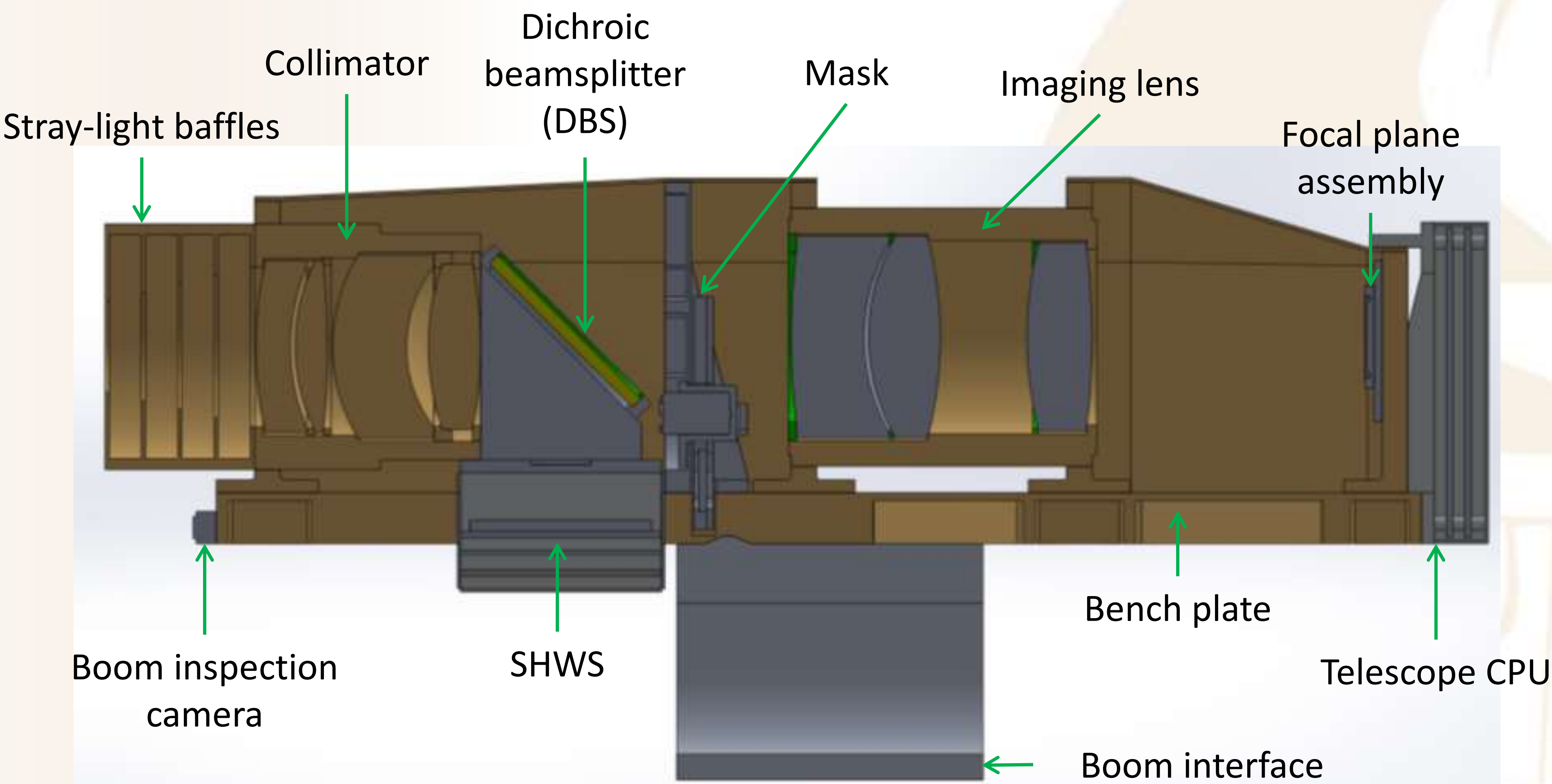


- Designed using Zemax to minimize spot radius at image and wavefront error at pupil conjugate
- Designed for manufacturability
  - Cheaply available Schott glasses
  - Minimum RoC = 32mm
  - No cemented doublets for thermal performance

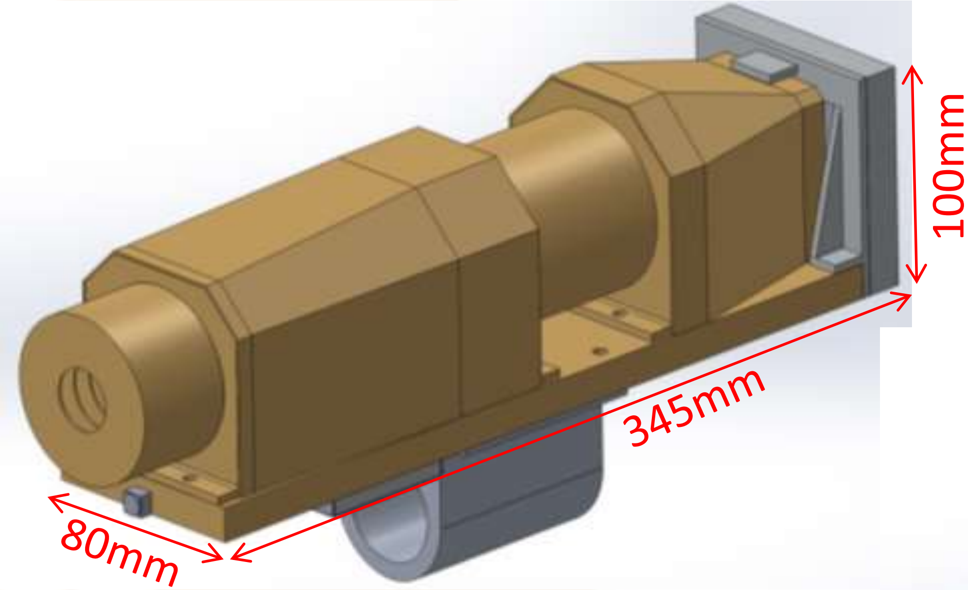
Optical Bandpass



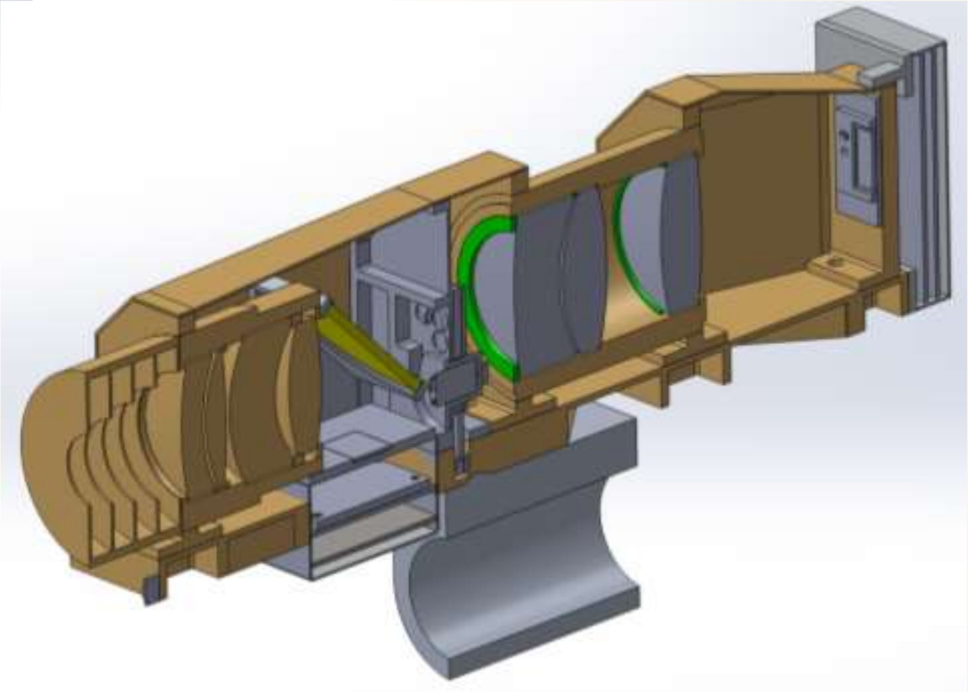
Mechanical Configuration



Mechanical Configuration

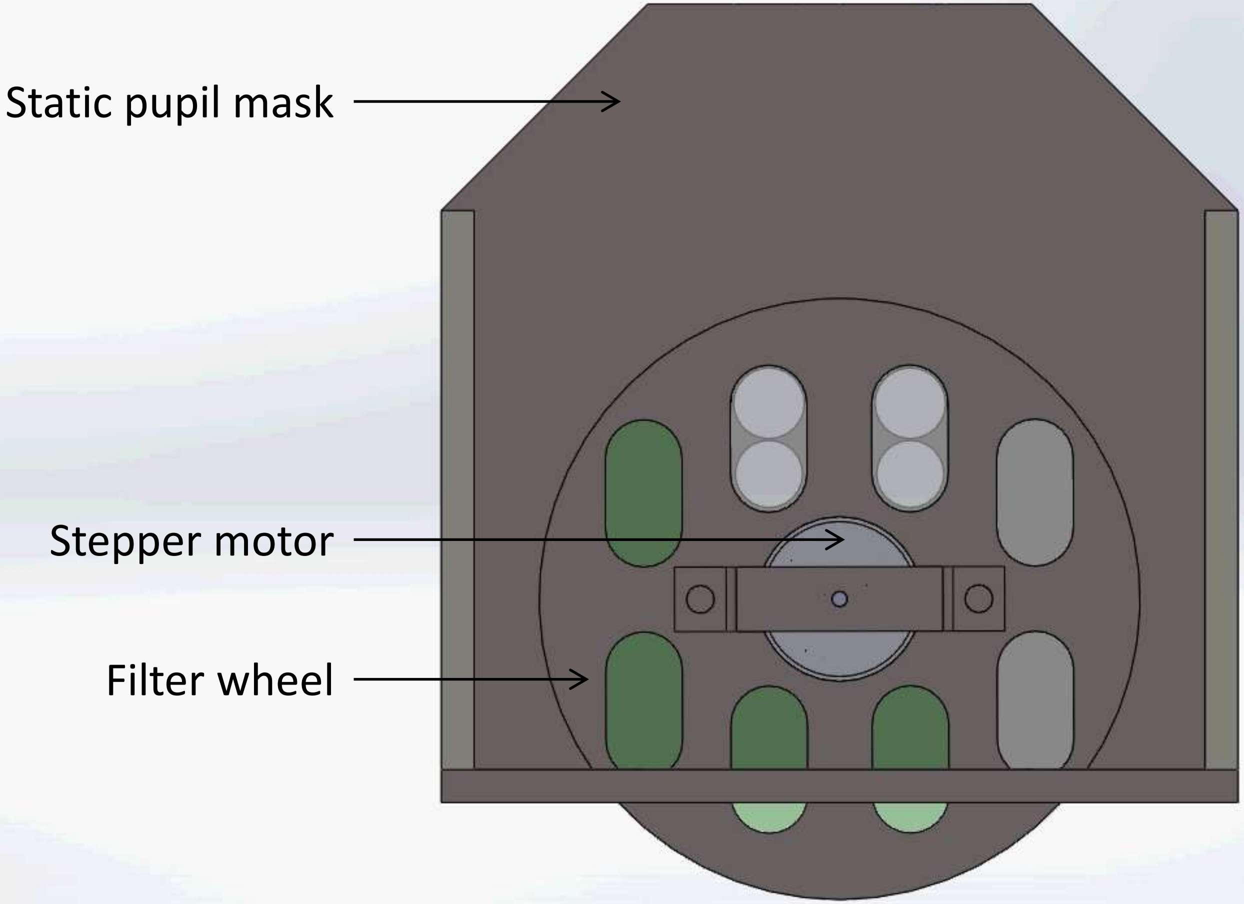


- The exterior will be wrapped in MLI for thermal stability
- The electronics box will be painted white



- Dimensions exclude the boom mount

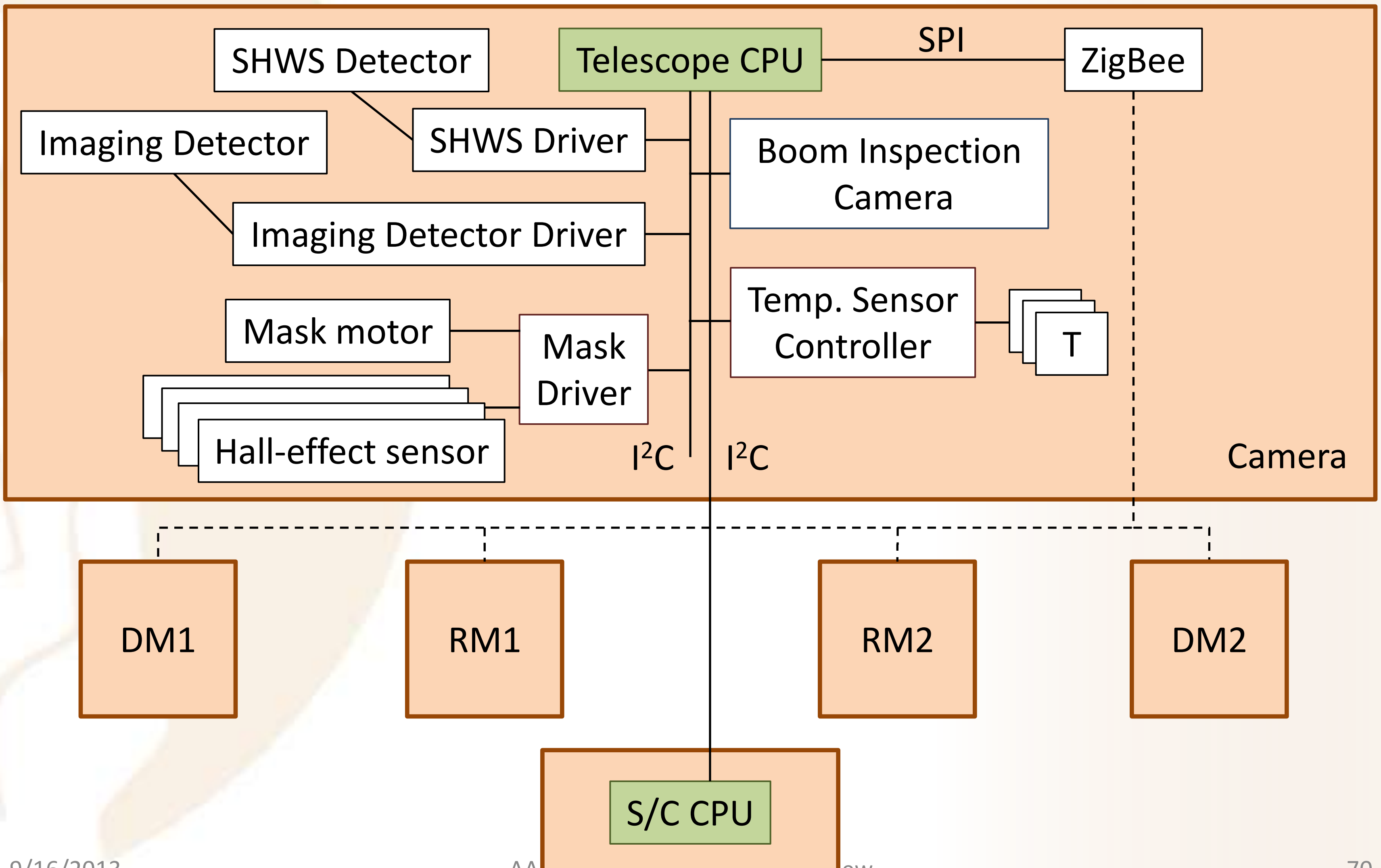
Mask Configuration



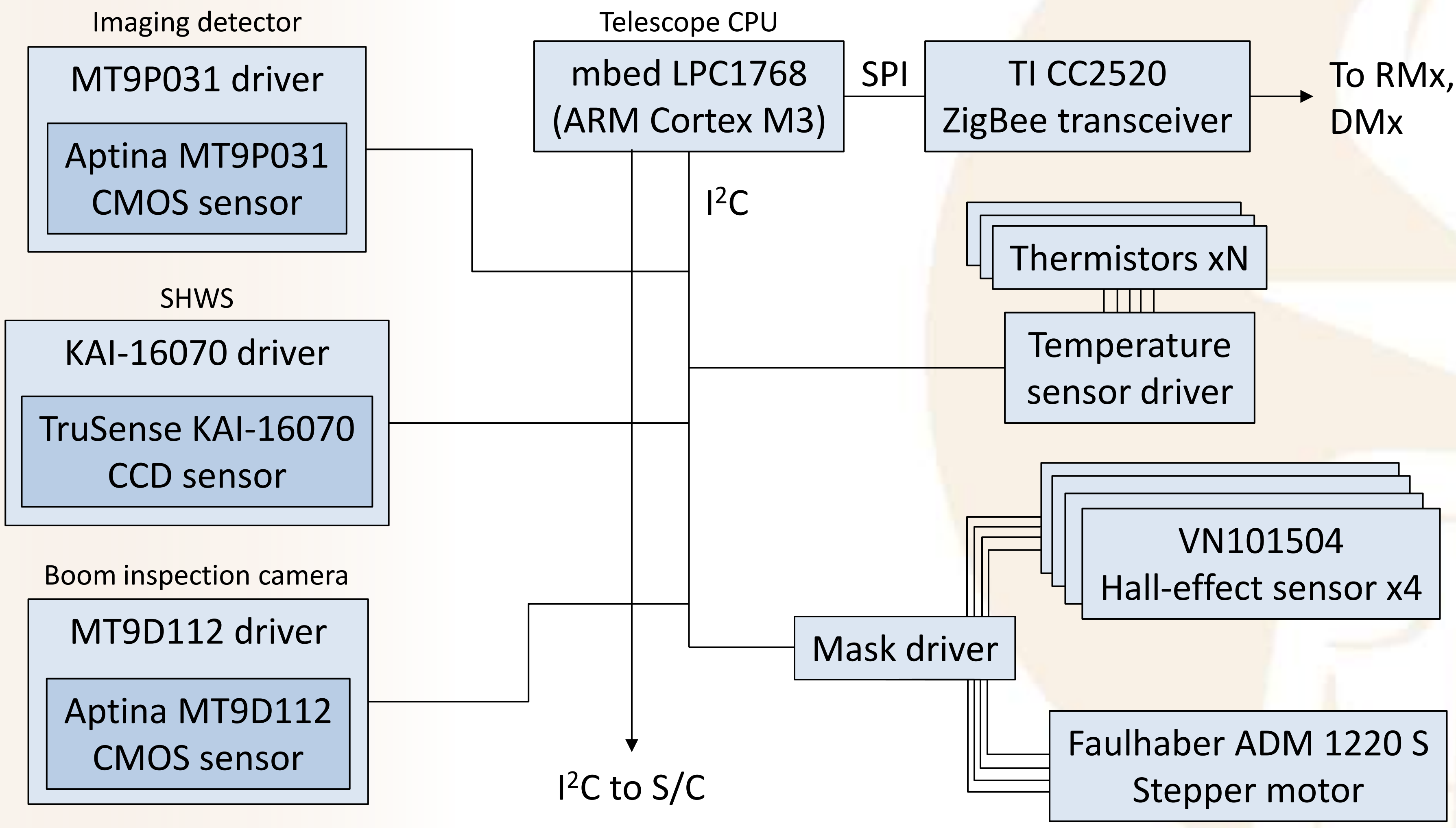
Extended pupil,
Wideband

Compact pupil,
Narrowband

Command Architecture



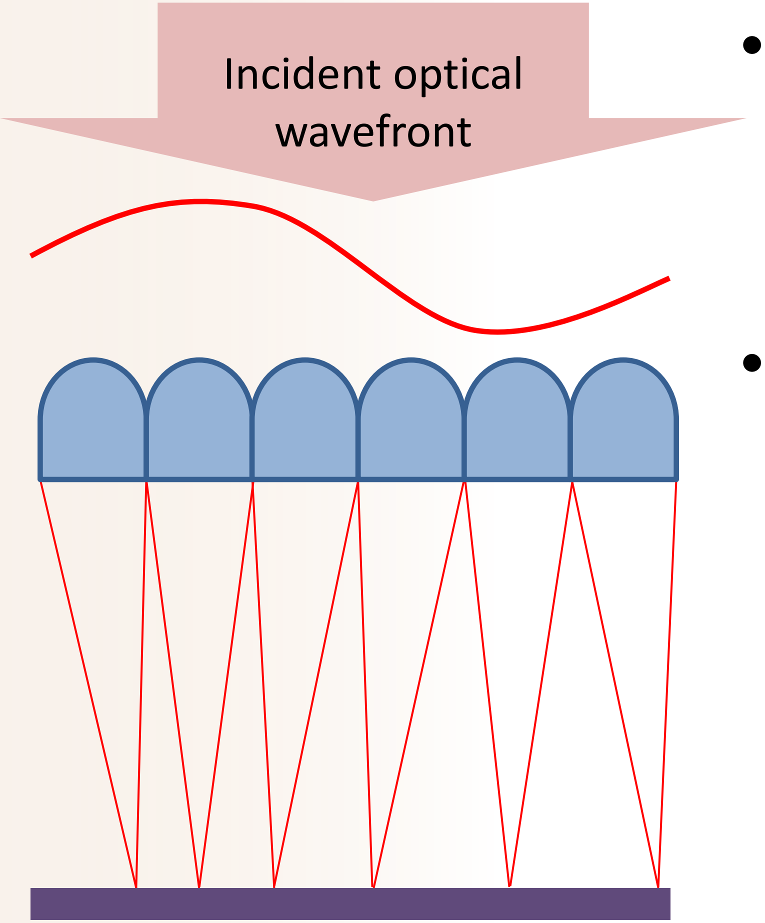
Camera Electronics



Camera Electronics

- Camera receives 5V power from S/C
  - Hardware limited to 5W max draw
- External I^2C connection to S/C
- Internal I^2C bus
  - Master: Telescope CPU
  - Slaves: imaging detector, SHWS, mask, BIC, etc.

SHWS Detector



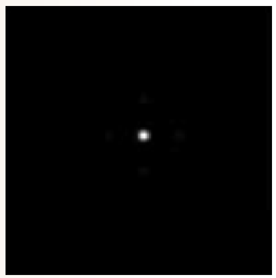
- Microlens array
  - 500µm-pitch gives 88 samples over each primary mirror segment
- TruSense KAI-16070 interline CCD
  - 36.0mm × 23.9mm, 4864 × 3232 pixels (15.7MP)
  - 7.4µm square pixels
  - 48% QE at λ = 500nm
  - 12 electrons rms read noise

Imaging Detector

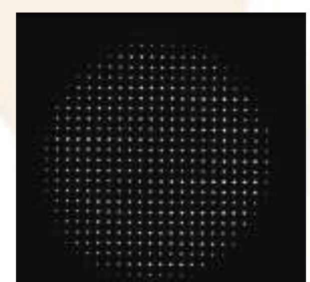
- Aptina MT9P031 CMOS
  - 2592 × 1944 pixels (5MP)
  - 2.2µm square pixels oversample the Ø14.2µm spot from a single primary mirror segment
  - 5.70mm × 4.28mm, 7.13mm diagonal
  - 0.3 degree (18 arcmin) field-of-view (diagonal)
  - 64% QE at λ = 500nm

Camera Data Transmission

- Imaging detector: 3 types of images

	Focused point source	Unfocused point source	Extended source
			
Number of useful pixels	< 800	~800K	~5M
Compression method	Location and intensity of each useful pixel	JPEG	JPEG

- SHWS: {x,y} centroid location for each subaperture spot



Telescope Command List

- beginTelescopeCheckout()
  - takeDarkFieldMeasurements()
  - checkoutMask()
  - checkoutMirrorSegment(segment_name)
- beginSegmentBlindSearch()
  - adjustMirrorSegmentPointing(segment_name, tip, tilt)
  - captureImage(exposure_time)
- beginCoarseCalibration()
  - coarseCalibrateSegment(segment_name)
  - adjustMirrorSegmentPiston(segment_name, piston)
- beginFineCalibration()
  - fineCalibrateSegment(segment_name)
  - takeWavefrontData(exposure_time)
  - deformableMirrorVoltages(segment_name, v[0:42])
- capturePointSourceImage(exposure_time)
- captureExtendedSourceImage(exposure_time)
- takeTemperatureData()
- captureBoomInspectionCamImage()
- switchMaskState(mask_state)
- …. Low-level commands not included!

Camera checkout commands

Mirror segment blind search and tip, tilt adjustment

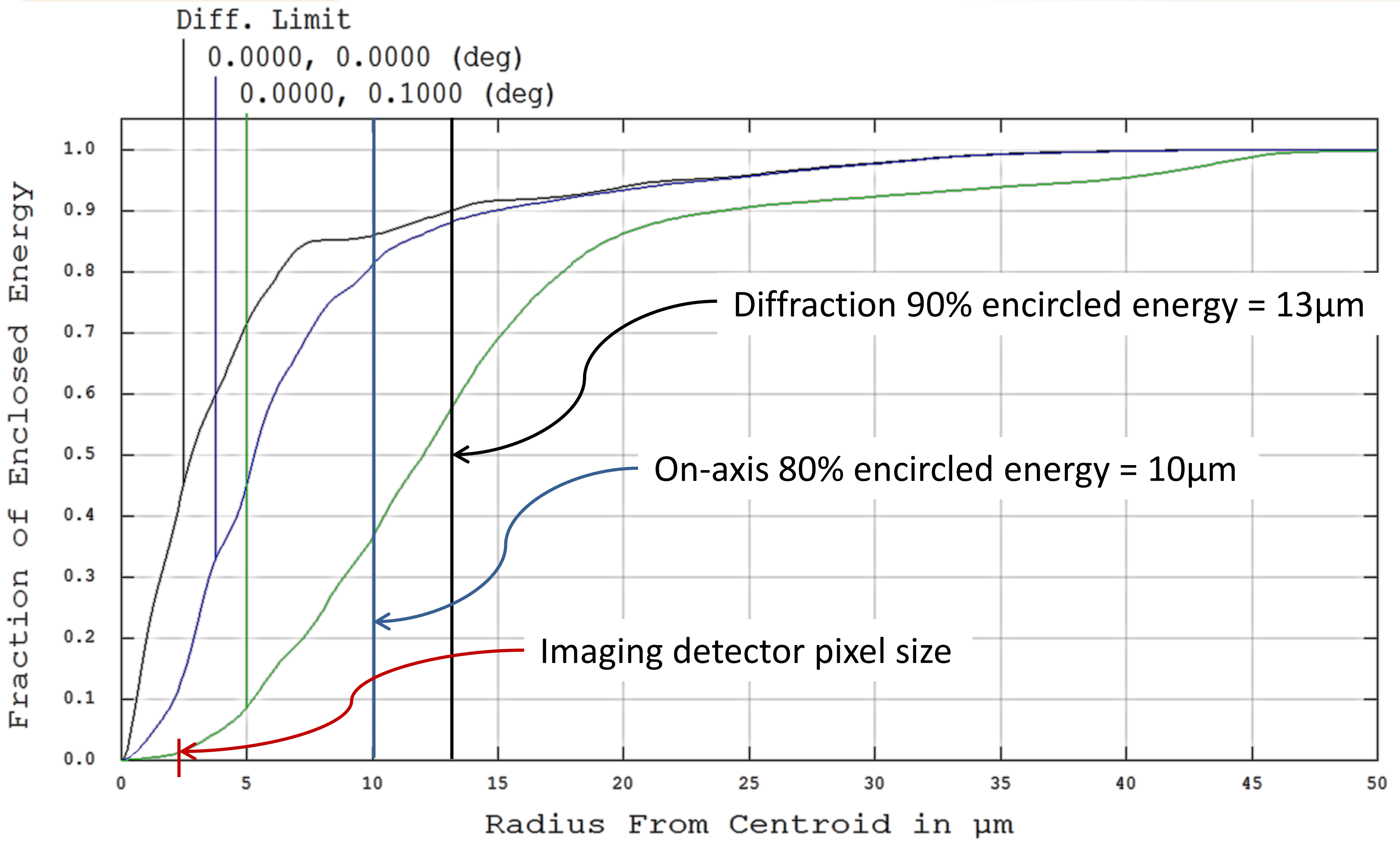
Mirror segment voltage adjustment

Diagnostic and telemetry commands

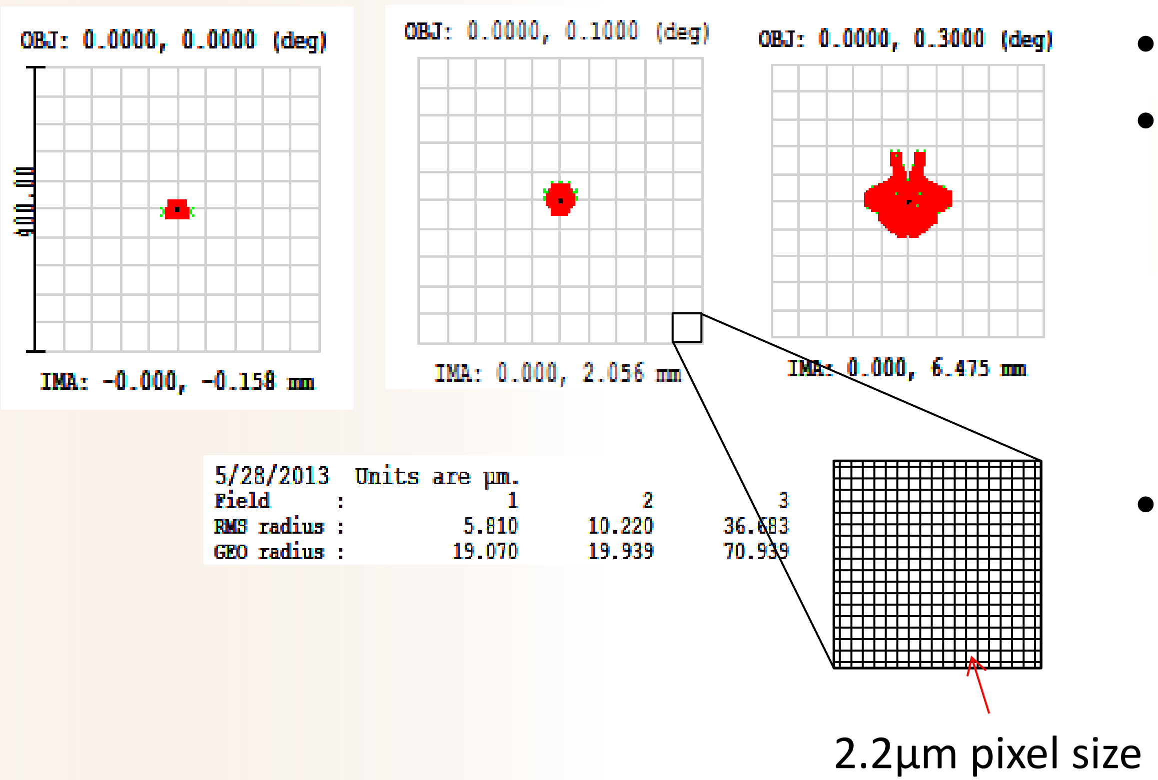
Optical Analysis

- Spot diagrams and encircled energy analysis performed using Zemax
  - For a diffraction-limited, single Ø10cm mirror, 90% encircled energy radius = 13μm
  - Require 80% encircled energy radius < 13μm
- Require SNR > 100 for both SHWS and imaging detector

Encircled Energy Analysis



Geometric Spot Diagrams



5/28/2013 Units are µm.

Field :	1	2	3
RMS radius :	5.810	10.220	36.683
GEO radius :	19.070	19.939	70.939

- Grid is 400µm across
- Spot diagrams are presented using a superposition of the wide and compact pupil modes
- Imaging-band wavelengths: 522-545nm shown

SHWS SNR Calculations

- SHWS design informs the limiting photon count
- For a 50ms exposure with 100nm bandwidth around λ=500nm, we need a flux of 10^6 photons/cm^2/s to achieve SNR = 100
- Corresponds to apparent magnitude ~1.5-1.8

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

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

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

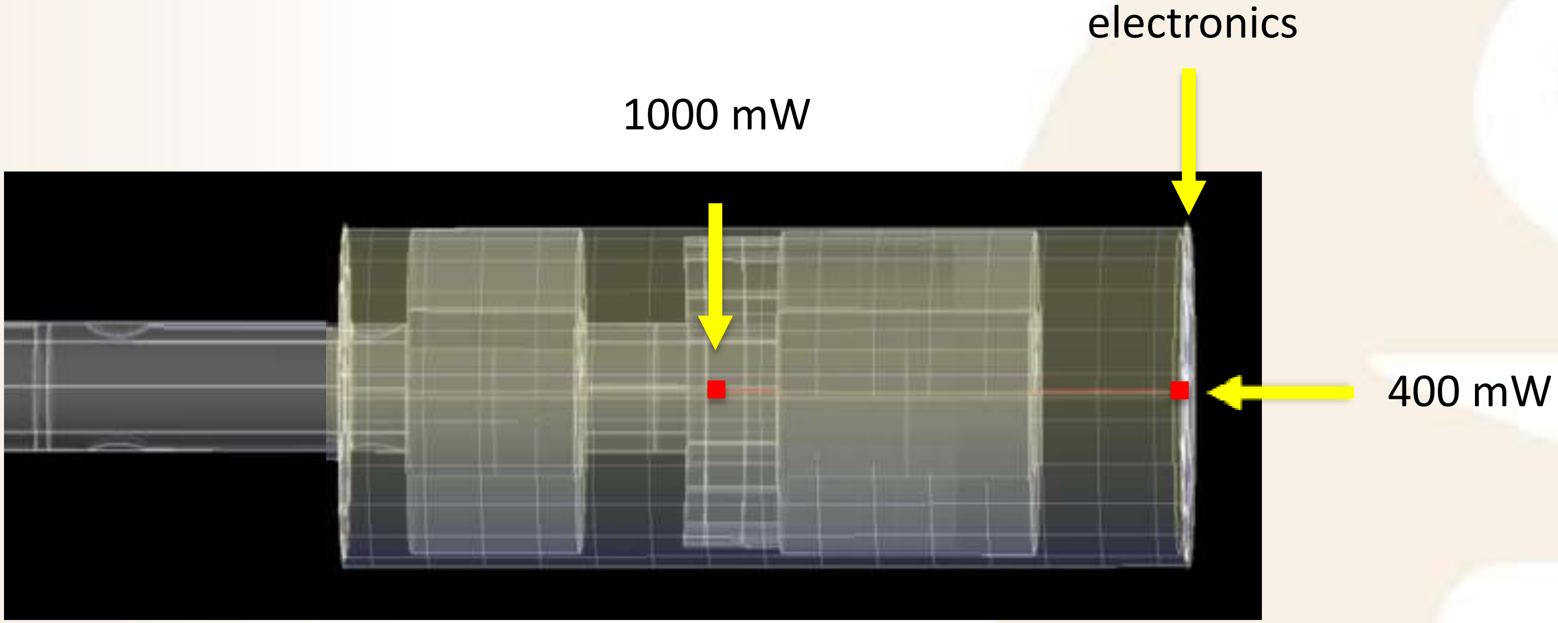
$$\eta = \eta_{mirror} \times (\eta_{lens})^4 \times (QE) = 0.42e^-/photon$$

$$T_{int} = 50ms, A_{mirror} = \pi(4.5cm)^2, n_{lenslets} = 88$$

$$N_{ron} = n_{pixels} \times 12e^-/pixel = 195.1e^-$$

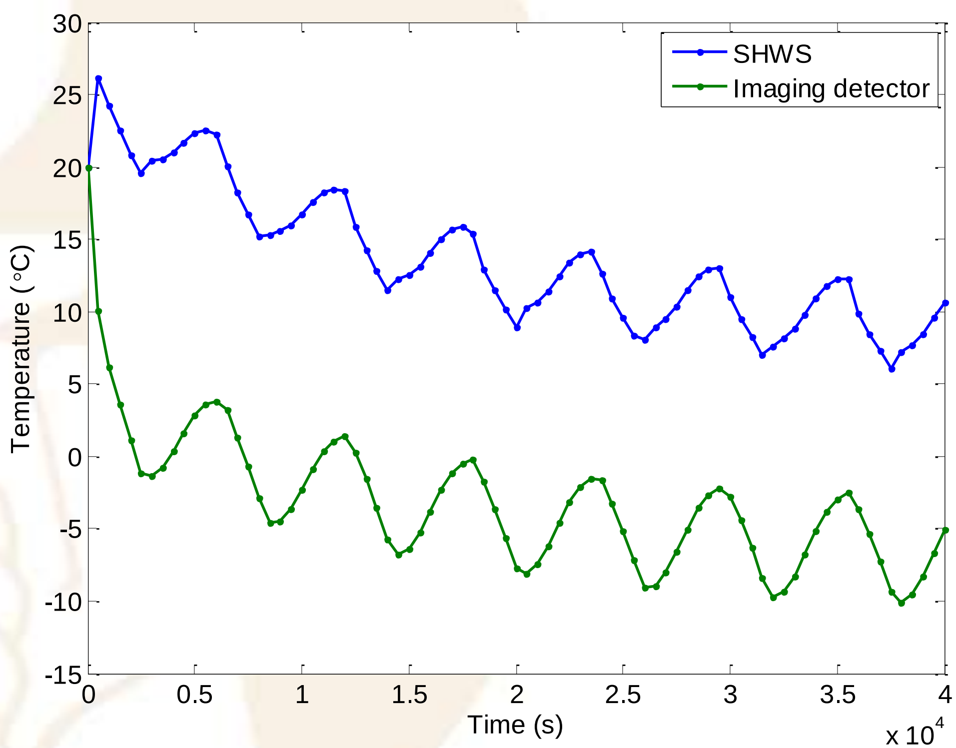
$$F = 2.6 \times 10^6 photons/cm^2/s$$

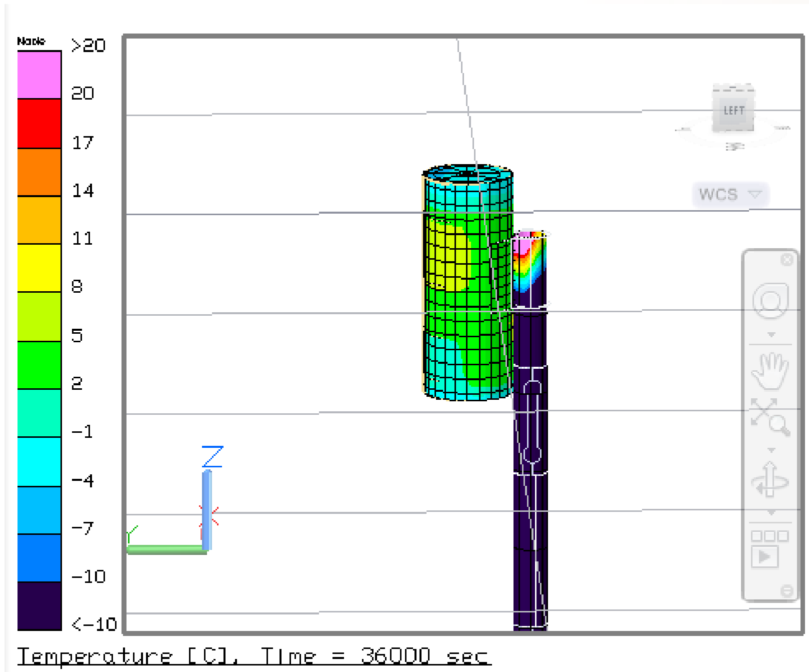
Camera Thermal Model



- 1000mW and 400mW thermal loads model sensors
- Operating range for sensors and electronics: -50°C to 70°C
- Lower noise at colder temperatures
- Interior of camera: black paint; exterior: MLI; top: white
- Titanium case, glass lenses

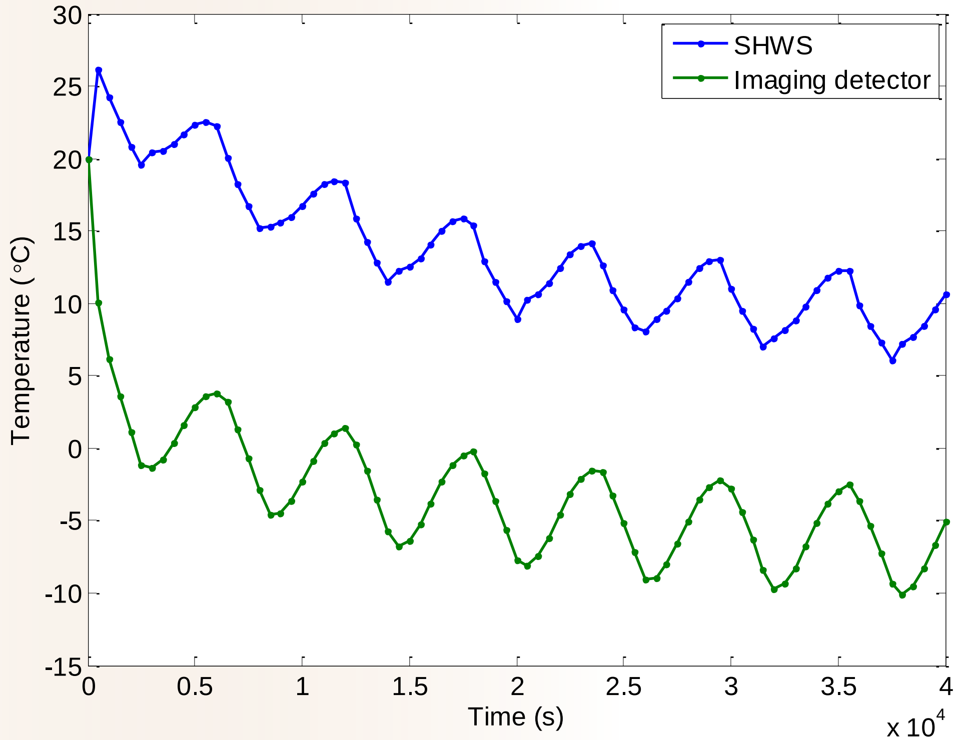
Thermal Modeling Results

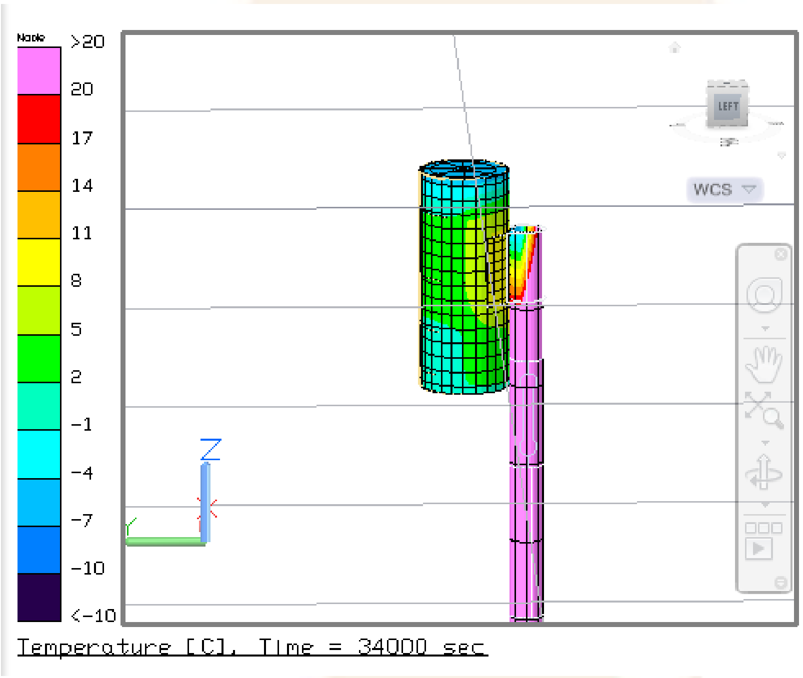




Profile during eclipse

Thermal Modeling Results





Profile in sunlight

Camera Mass Budget

Part	Mass (g)
Lenses, filters, DBS	300
Lens mounts	300
Mask mechanism	150
Sensors	400
Structure	1000
Fasteners & Wiring	300
Insulation	50
Total	2500
Margin (37.5%)	1500

Camera Power Budget

Part	Peak (W)	Nominal (W)
Telescope CPU	0.600	0.450
Imaging detector	0.381	0.262
SHWS	1.600	1.000
Boom inspection camera	0.218	0.150
Wireless module	0.128	0.100
Mask	0.600	0.600
Total	3.527	2.562

Interfaces

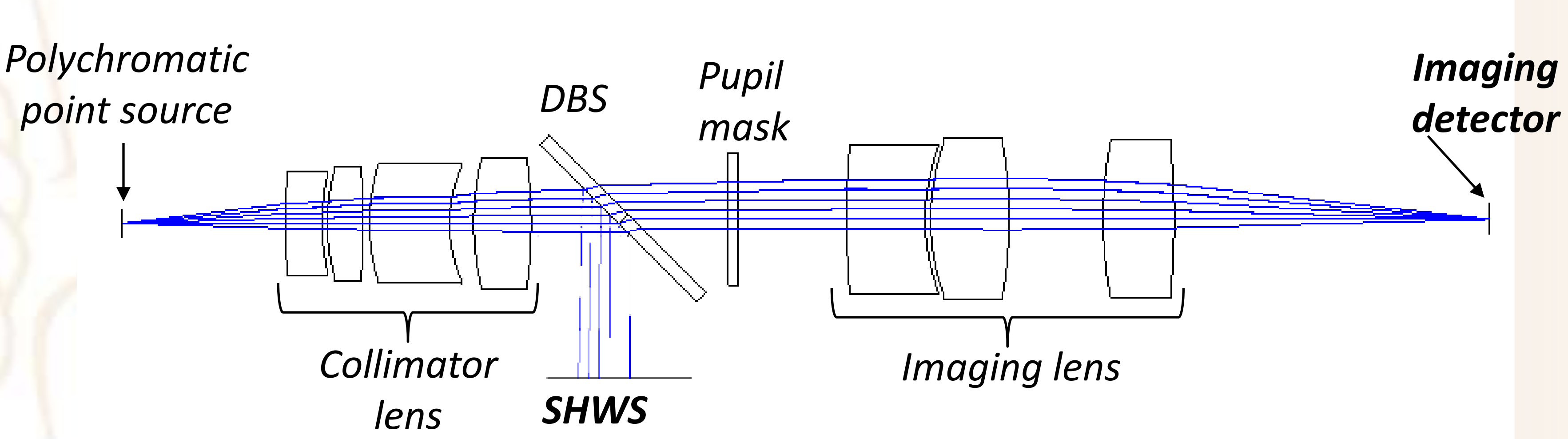
- Mechanical
  - 3-point kinematic interface to boom mount
- Electrical
  - Data and 5V power over I^2C connection to S/C
- Wireless
  - 2.4GHz ZigBee communication to DM1, DM2, RM1, RM2
- Thermal
  - MLI exterior, white-painted top
  - Conduction to/from boom mount
- Optical
  - f/11.4 converging light beams from 4 primary mirror segments
  - 0.3 degree full field-of-view

Fabrication, Assembly & Integration

- To be contracted out:
  - Lens manufacturing
  - Lens group assembly
- To be done at Caltech:
  - Fabrication and assembly of camera
  - Initial alignment with primary mirror and boom
- To be done at Surrey:
  - Final alignment and integration with the boom and S/C

Optical Testing

- Test with polychromatic point source at the M1 prime focus
- Science detector requirements
  - 80% encircled energy radius < 90% diffraction-limited EE radius
  - Full field-of-view = 0.3°
- Tests to be performed in thermal chamber to characterize temperature effects



Future Work

- Mechanical and optical prototyping
- Optical element manufacturing and testing
- Command hardware development and testing
  - Telescope CPU
  - Various hardware drivers
- Software development

Review Outline

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4. System Summary, Launch Vehicle, Project Plan (15 mins)
5. Discussion (15 mins)

Deployable Boom

John Steeves

Carlos Laguna, Falk Runkel, Lee Wilson

September 9th, 2013

Problem Definition

- Design and fabricate a deployable boom suitable for the AAReST S/C
  - Key Characteristics
    - Lightweight and compact
    - Self-Deploying (utilizes strain energy for self-deployment)
  - Key Challenges
    - Maintaining optical-quality tolerances during telescope operation
      - Stiffness, deployment error & thermal issues
    - Controlling deployment process (forces on instruments)

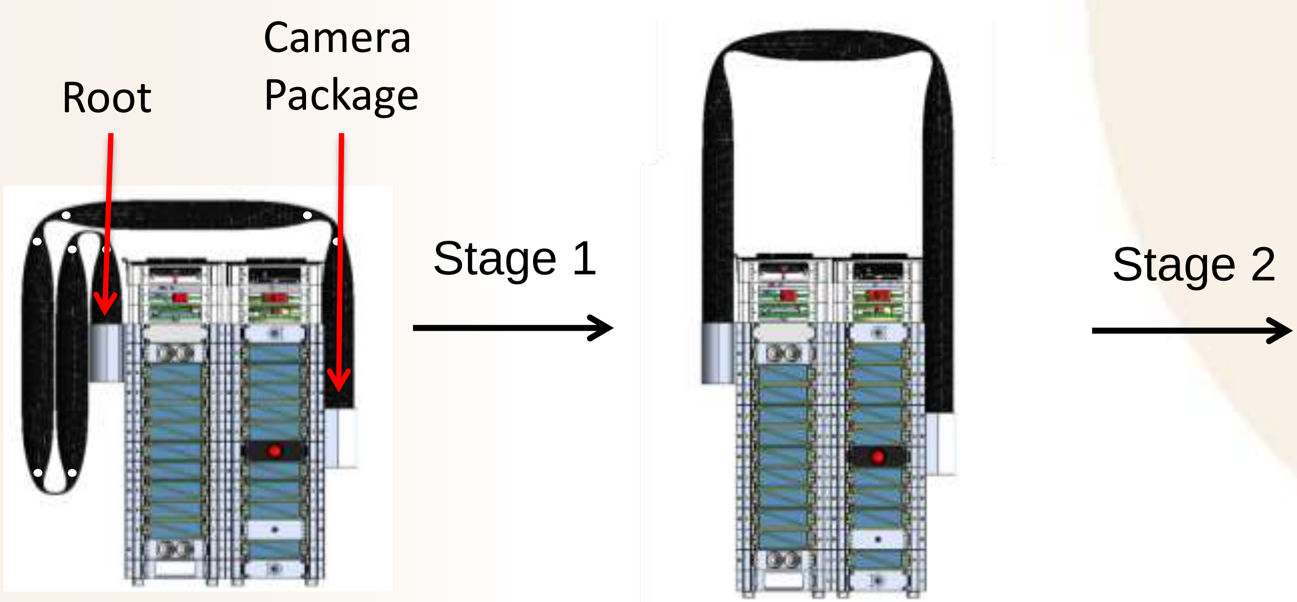
Boom Requirements

- Functional
  - Package into a tight launch configuration for volume conservation
  - Deploy to final imaging state once in orbit
  - Accommodate a 1.16m focal length for the AAReST Telescope
- Performance
  - Boom deployment shall not impart rates greater than the control authority of the S/C ACS.
  - Static elongation of boom shall be no more than 500 µm in order to maintain telescope focus (can be accommodated by rigid body actuators on mirrors)
    - 50 µm axial displacement during calibration and imaging (depth of focus of imaging system)
  - Static lateral boom deflections shall be less than 2mm
    - 200 µm/s during imaging (avoid image smearing during calibration & imaging)
  - Avoid coupling between S/C ACS system in imaging mode

Boom Architecture

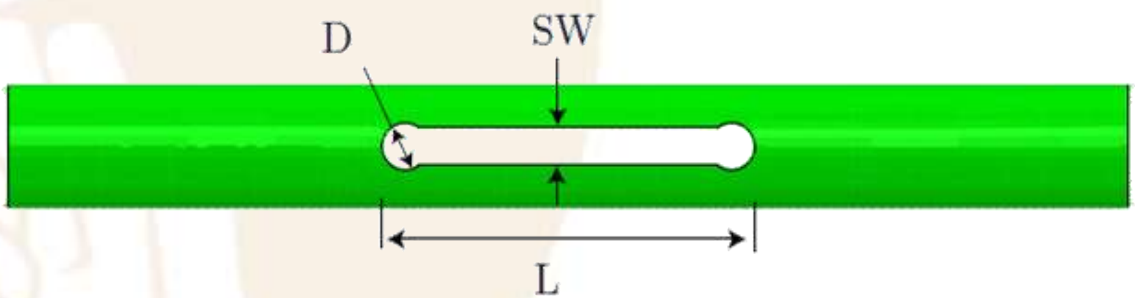
Boom Architecture

- Boom wrapped around S/C via folding tape-spring hinges
  - 4 hinges in total
  - L_{tot} = 1.35m, D = 38mm, m = 80g
  - Rigidly attached to S/C and instrumentation package
- Two-stage deployment process

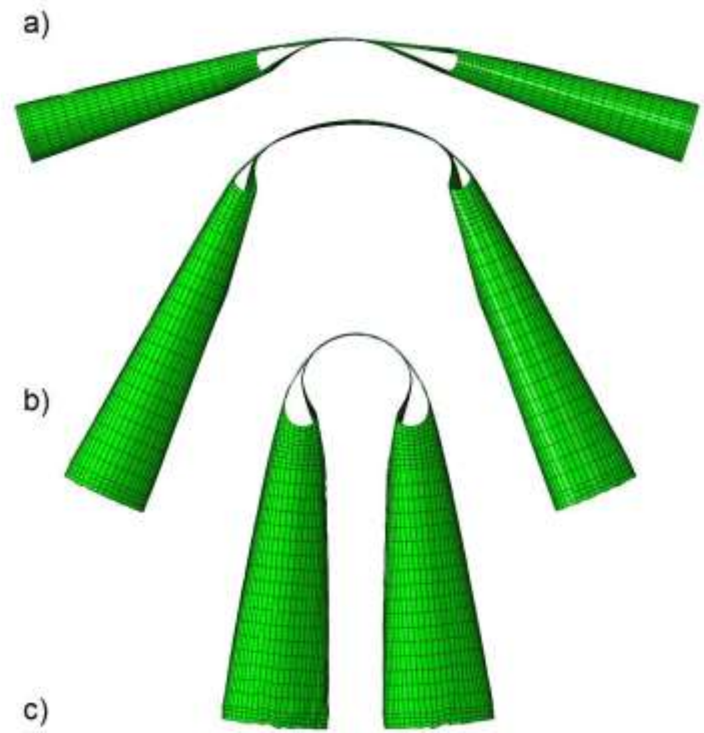


Hinge Design

- Materials
  - Combination of plain-weave fiberglass (60 µm thick) and unidirectional carbon fiber (90 µm thick)
  - $[_{+/-}45_f / 0_c / _{+/-}45_f]$ lay-up
  - 210µm total thickness
  - 38mm diameter

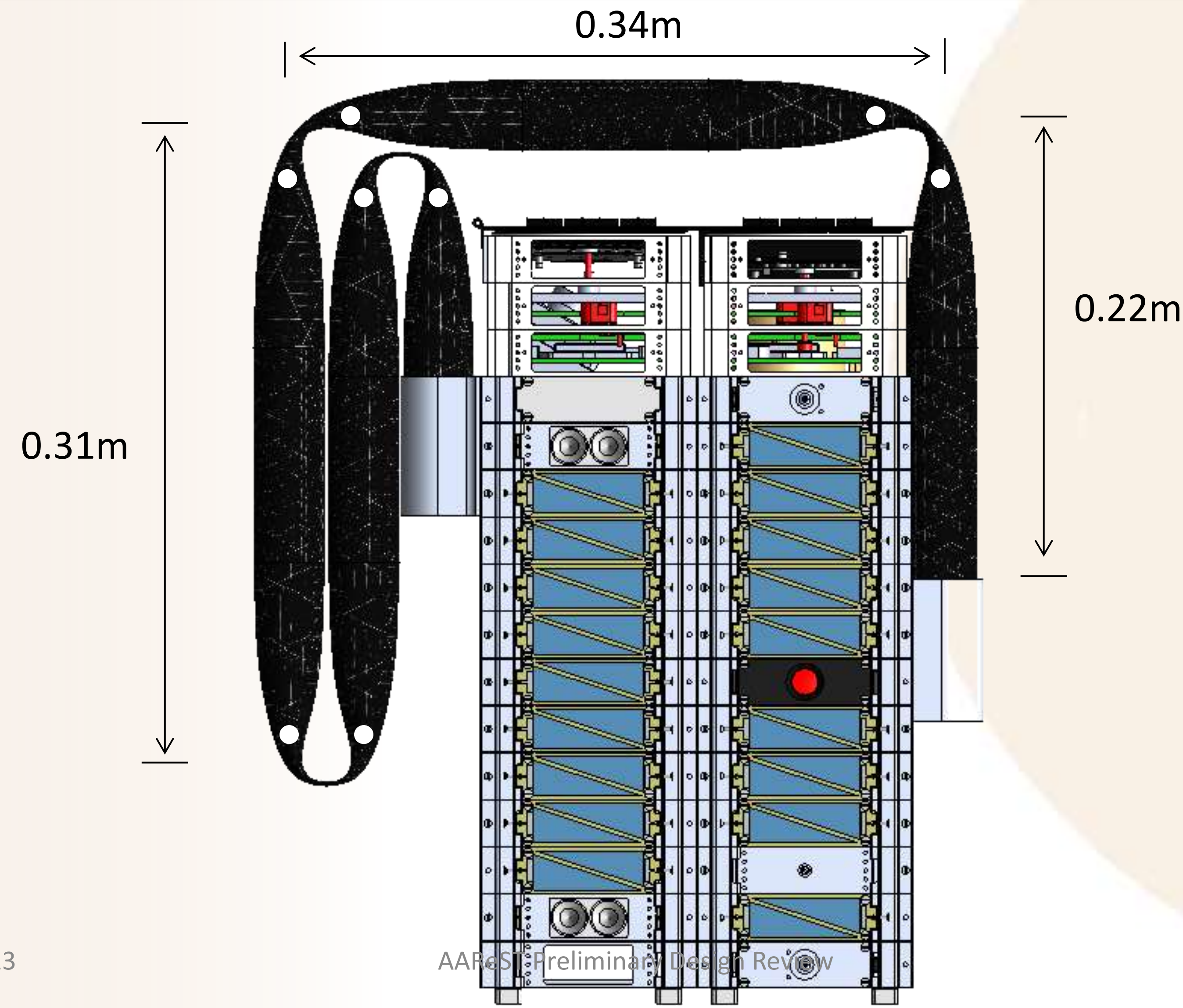


- Cutting pattern
  - "Dog-bone" hinge cutting pattern
  - D = 15 mm, L = 90 mm, SW = 8 mm
- Structural optimization techniques used to develop design

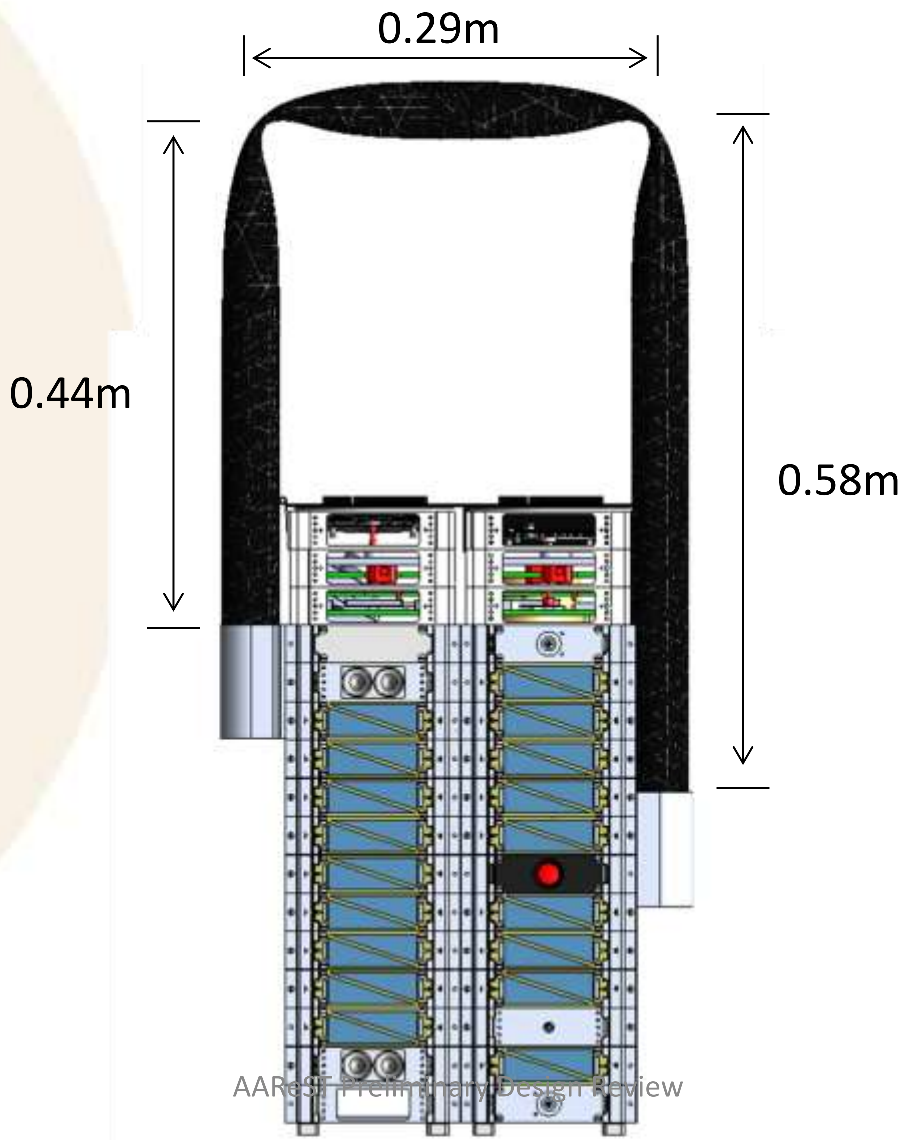


Based off of Mallikarachchi, H.M.Y.C. and Pellegrino, S. (2008-2012)

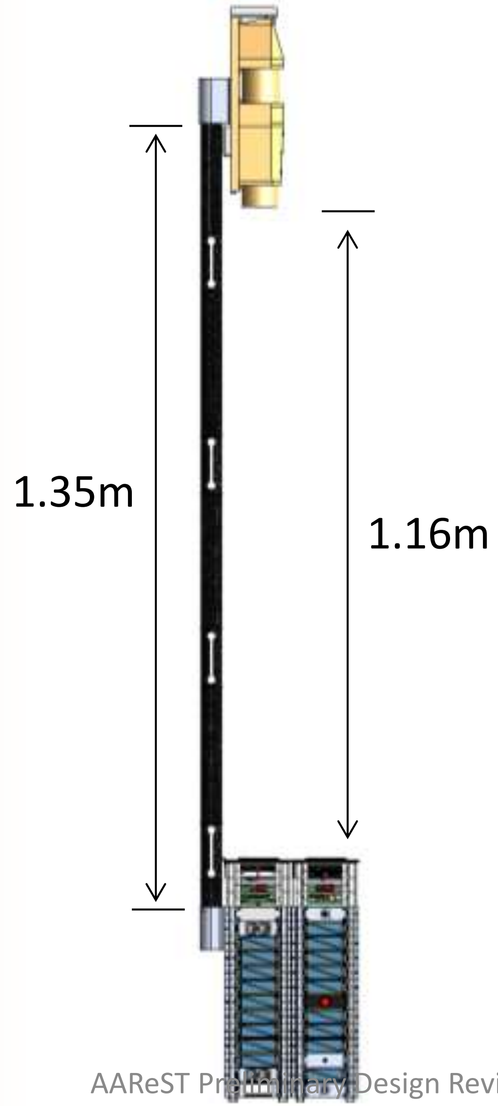
Boom Design



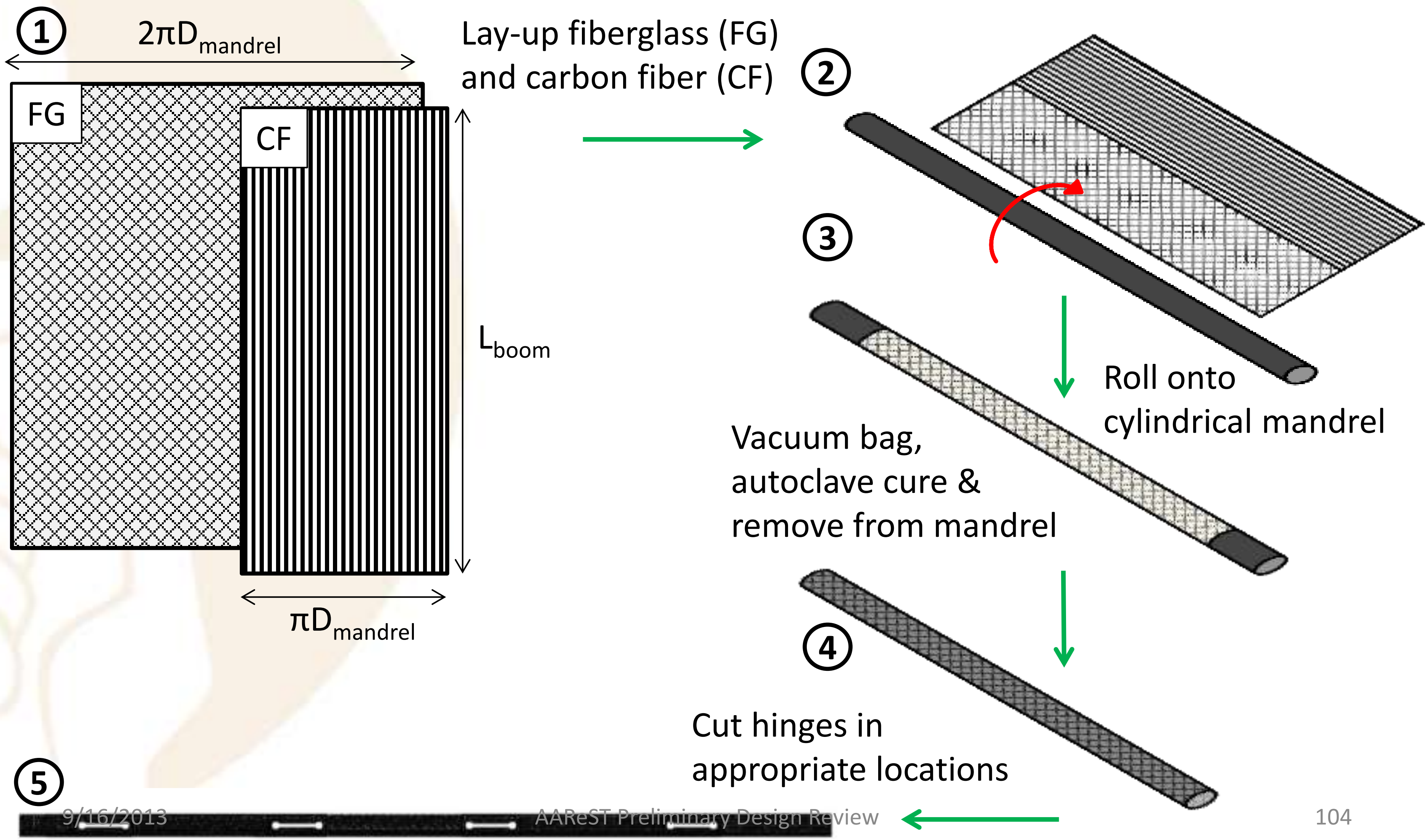
Boom Design



Boom Design

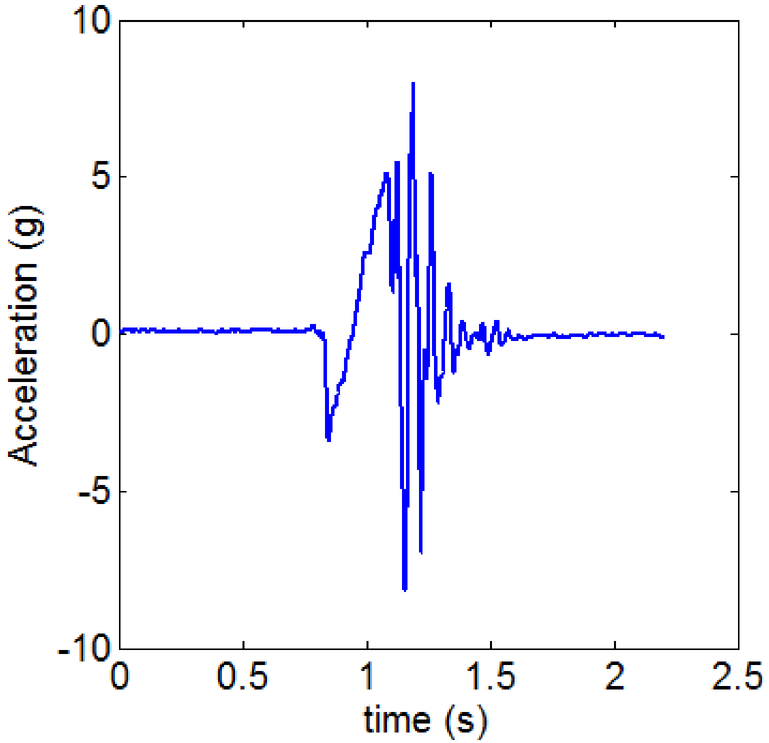


Fabrication Process



Deployment

First Stage Deployment



- First stage deployment initiated by burn wire (wrapped around folded boom)
- 2 hinges deploy, 2 remain folded at 90°
  - Compliant nature of boom accommodates small errors in deployment
- High velocity but low energy due to low mass of boom
  - Maximum torque applied to S/C = 0.4Nm

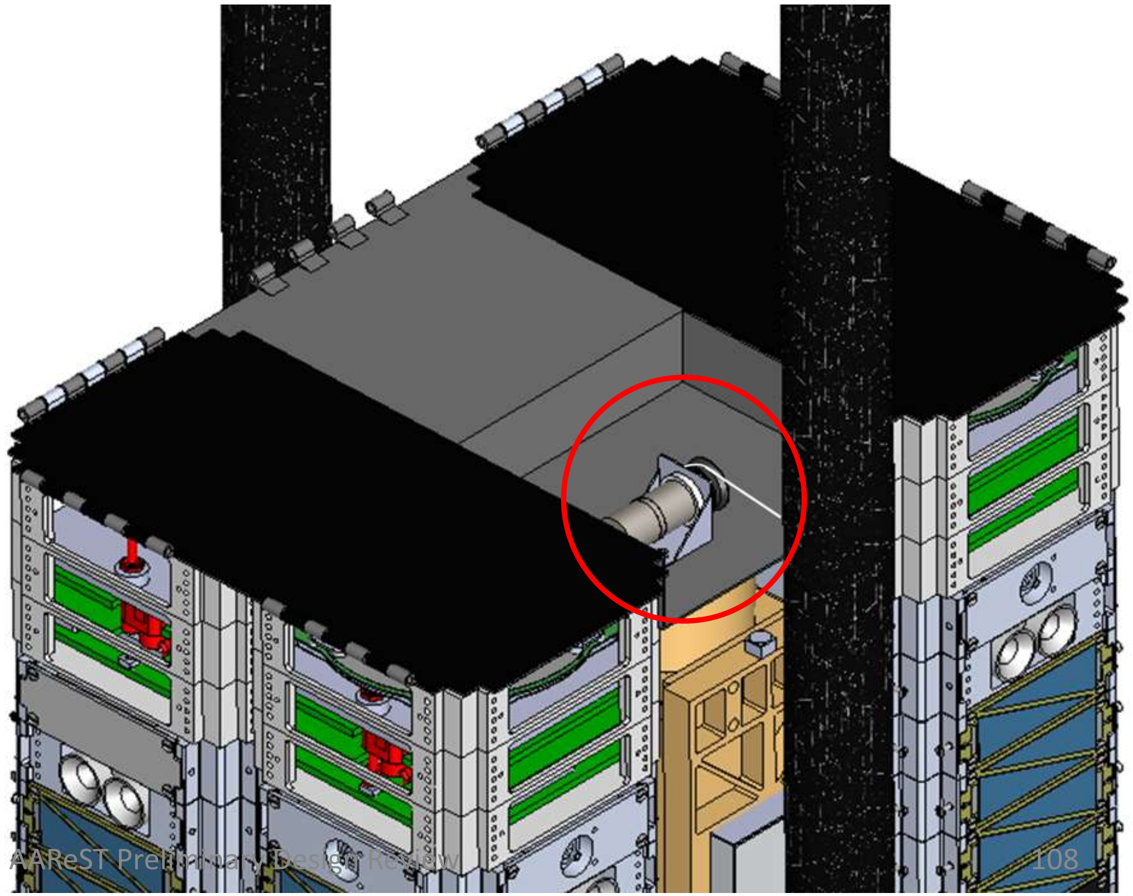
Second Stage Deployment

- Rate controlled deployment in order to minimize shock loading on instruments
  - Spool/cable system with stepper motor
- Deployment initiated by release of instrumentation package from S/C (frangible nut)
- Stiffness ratio of hinges designed to ensure collision avoidance between Camera and S/C
  - “Outward then up” motion

Deployment Control

- Required to ensure 2nd stage deployment remains quasi-static
- Cable spool driven by brushless DC motor (CDA-InterCorp)
  - 52Nmm max torque
  - < 2W input
  - 80g total mass

CDA InterCorp



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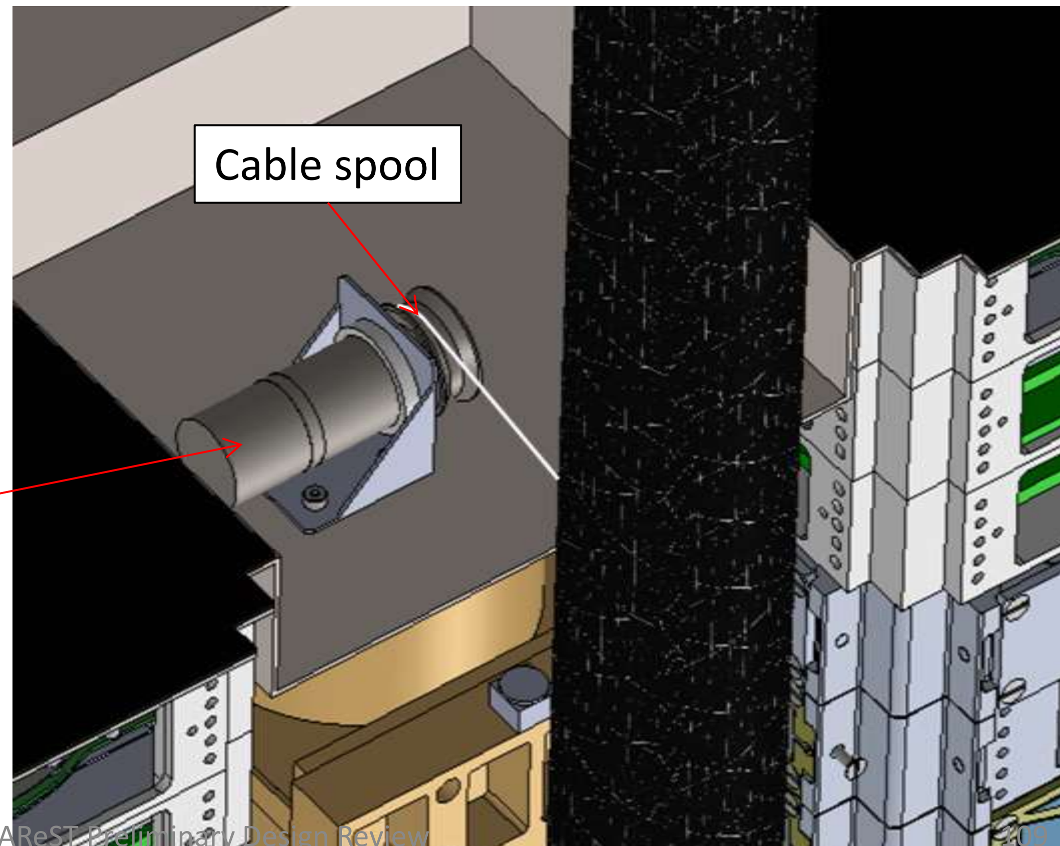
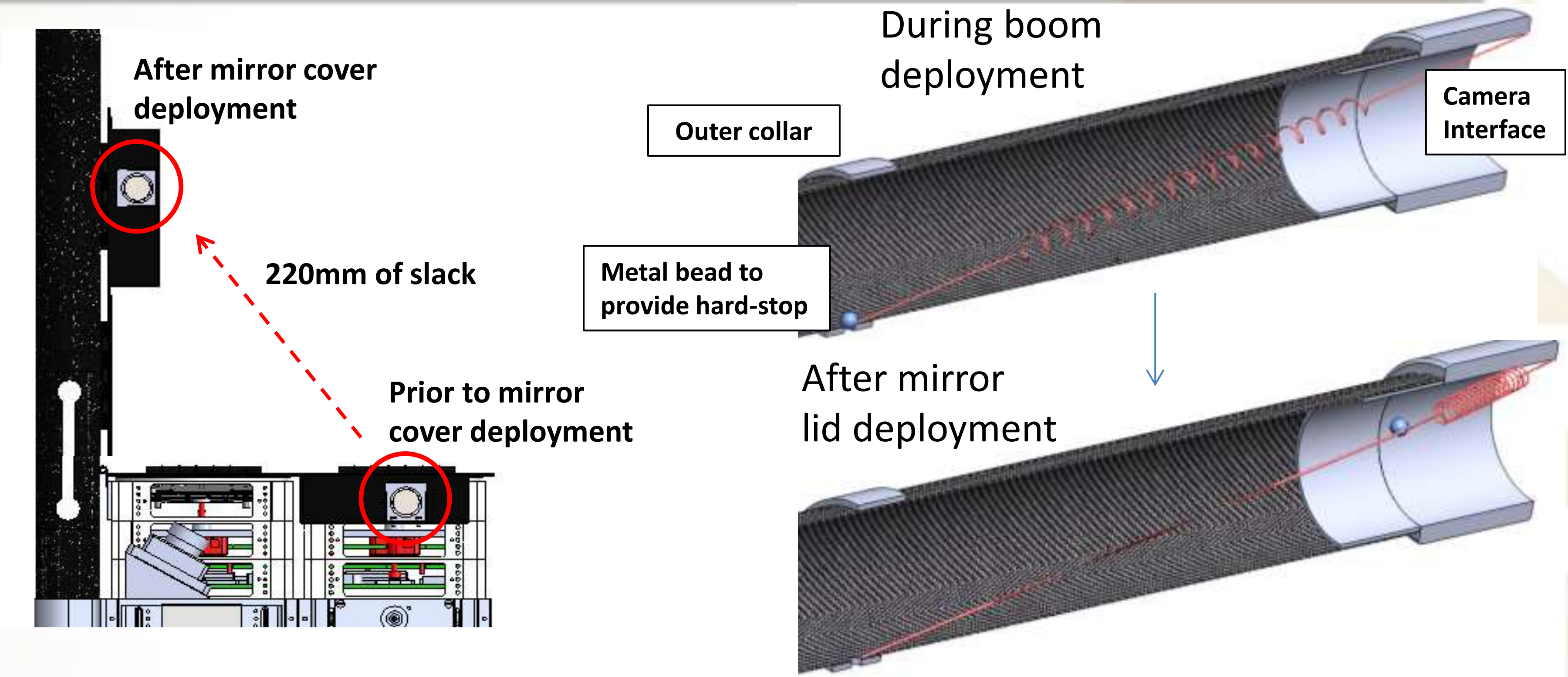
CDA InterCorp



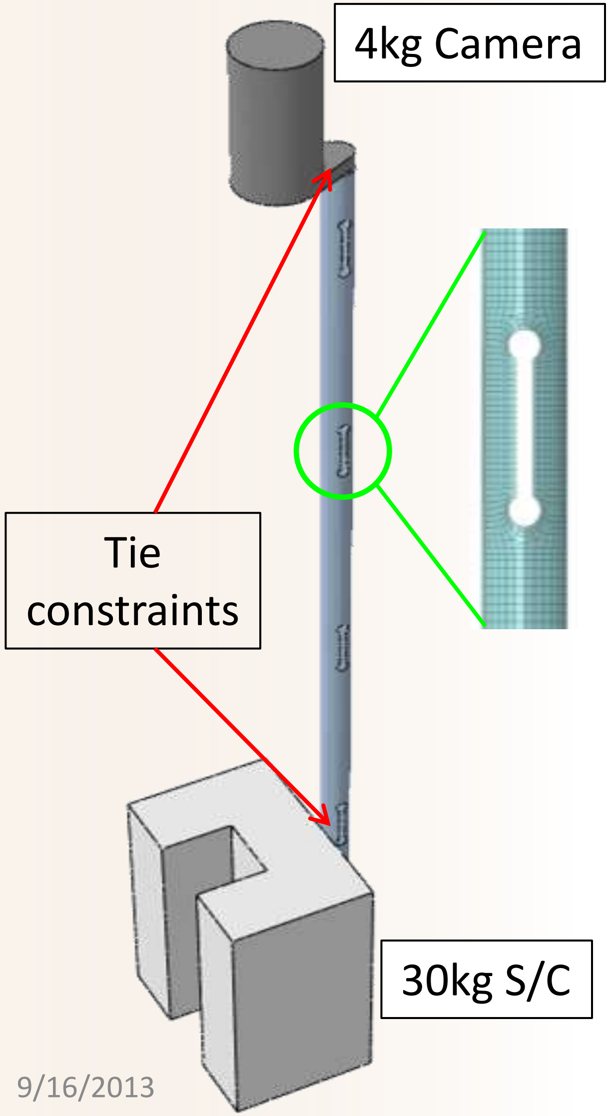
Cable Retraction



- Cable will become slack once mirror cover is deployed (after 2nd stage deployment)
  - Slack cable could potentially obstruct optical path
- Long, low stiffness spring located inside boom
  - Fixed at camera package
  - Metal bead provides hard-stop during deployment
  - Cable retracted once mirror lid deploys

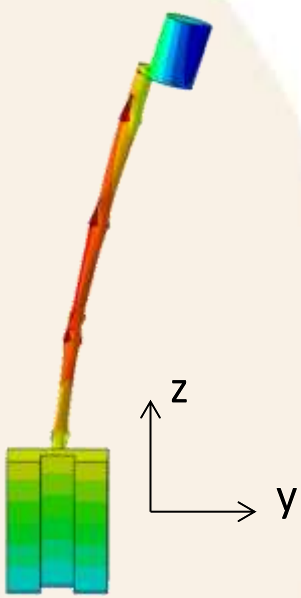
Structural Modeling

Structural Model

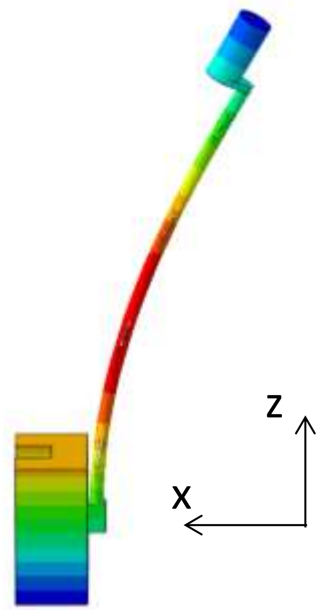


- Structural dynamics modeled using Abaqus Standard/CAE 6.12
- Boom: shell elastic elements
- S/C & Camera: 3D continuum elements
- 4kg Camera, 30kg S/C
- Boom properties defined using general shell section (ABD matrix – determined experimentally)
- Free boundary conditions

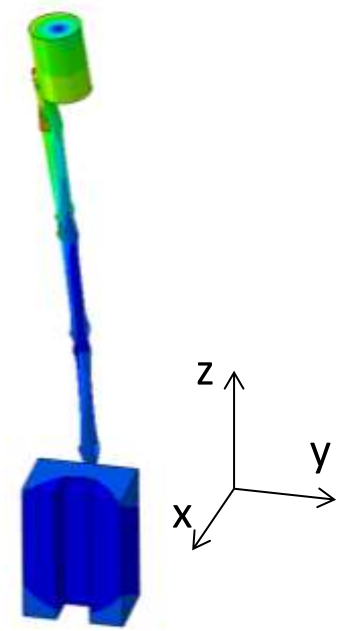
Structural Model



Mode 1
Bending (yz-plane)



Mode 2
Bending (xz-plane)

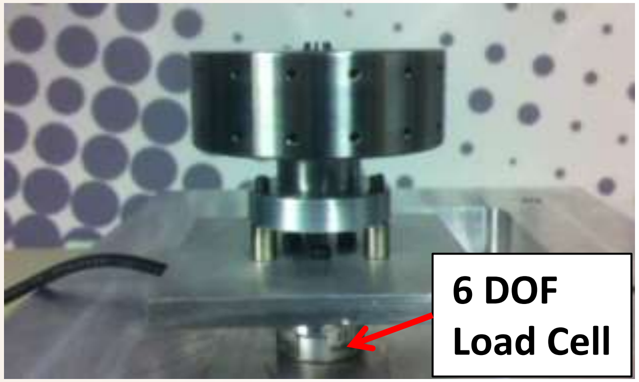


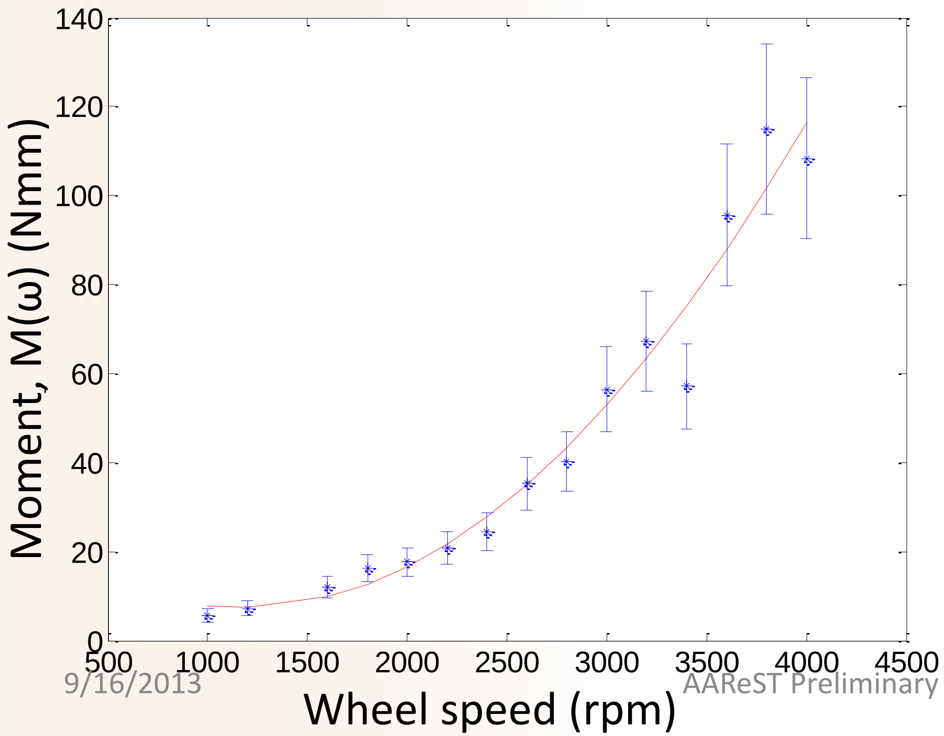
Mode 3
Torsion

	Mode	Frequency (Hz)
1	Bending (yz-plane)	4.2
2	Bending (xz-plane)	5.6
3	Torsion	7.1

Note: Bending modes measured experimentally in order to validate model (fixed/free BCs)

Disturbance Analysis





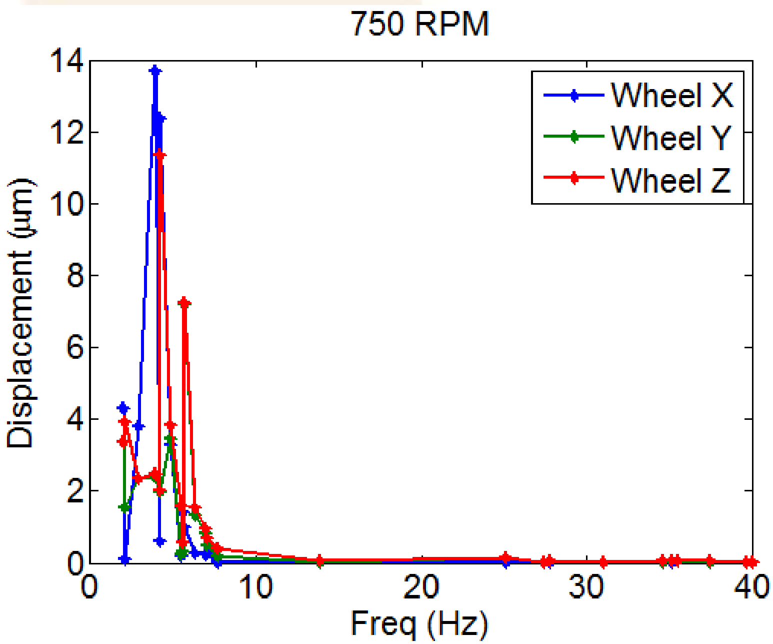
- Reaction wheel provided by Surrey for characterization
- Jitter due to imbalances measured using 6DOF load cell
  - Used as boundary conditions for structural model
- Camera displacements/rotations calculated as a function of wheel speed

$$M(\omega) = \sum_i A_i \omega^2 \sin(2\pi h_i \omega)$$

- *Note: Data collected for a non-isolated, unbalanced wheel (worst-case scenario)*

Based on Masterson et. al (2001)

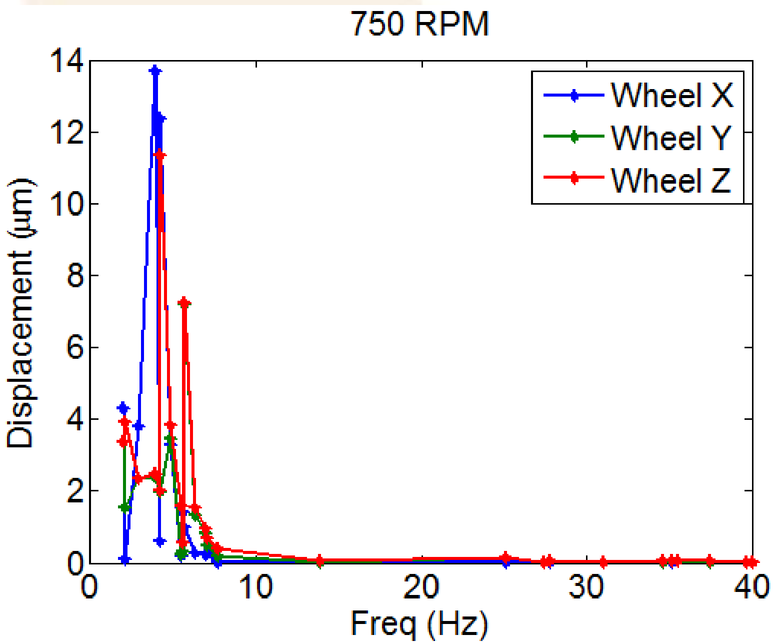
Disturbance Analysis



- Torque imbalances applied to Coresat structure
- Loading due to three orthogonal wheels modeled
- Maximum deviations from optical axis determined (displacements and rotations)
  - Information fed into optical model

Wheel Speed (rpm)	Displacements		Rotations	
	Amplitude (μm)	Rate (μm/s)	Amplitude (deg)	Rate (deg/s)
500	8	130	$5e^{-4}$ (1.8arcsec)	0.008
750	14	225	$9e^{-4}$ (3.2arcsec)	0.014
1000	30	480	$1.9e^{-3}$ (6.8arcsec)	0.030

Disturbance Analysis



- Torque imbalances applied to Coresat structure
- Loading due to three orthogonal wheels modeled
- Maximum deviations from optical axis determined (displacements and rotations)
    - Information fed into optical model

Recommendation: Keep wheel speeds less than 750rpm while imaging

Wheel Speed (rpm)	Displacements		Rotations	
	Amplitude (µm)	Rate (µm/s)	Amplitude (deg)	Rate (deg/s)
500	8	130	$5e^{-4}$ (1.8arcsec)	0.008
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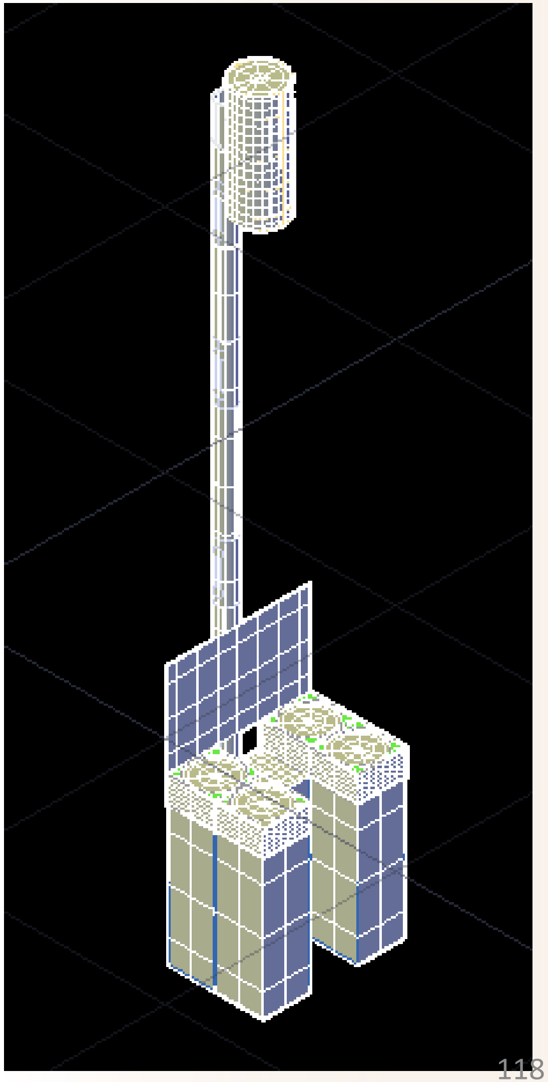
1000	30	480	$1.9e^{-3}$ (6.8arcsec)	0.030

Thermal Model

Thermal Model

AAReST	External Surface	Material	Internal Heat Load	Heat Max and Min
Mirror Crafts (x2)	Solar Panels (sides), Black Paint (bottom)	Aluminum	6W/Craft	-
Core Craft	Solar Panels (sides), Black Paint (bottom)	Aluminum	18W	-
Mirror Boxes (x4)	White Paint (outside), Black Paint (inside)	Aluminum	2W/Mirror	Range: dT<30K (+/- 15°C)
Mirrors	Aluminum Out, Black Under Side	Glass/Pyrex	No Heat	Range: dT<30K (+/- 15°C)
Camera	MLI/ White Paint/ Black Paint	Titanium (6AL-4V)	Hot: 400 & 1000 mW Sensors	Range: -50 to 70 °C
Boom	Black Paint	Carbon Fiber (orthotropic)	No Heat	-
Sun shield	Black Chrome/ White Paint	Aluminum	No Heat	-



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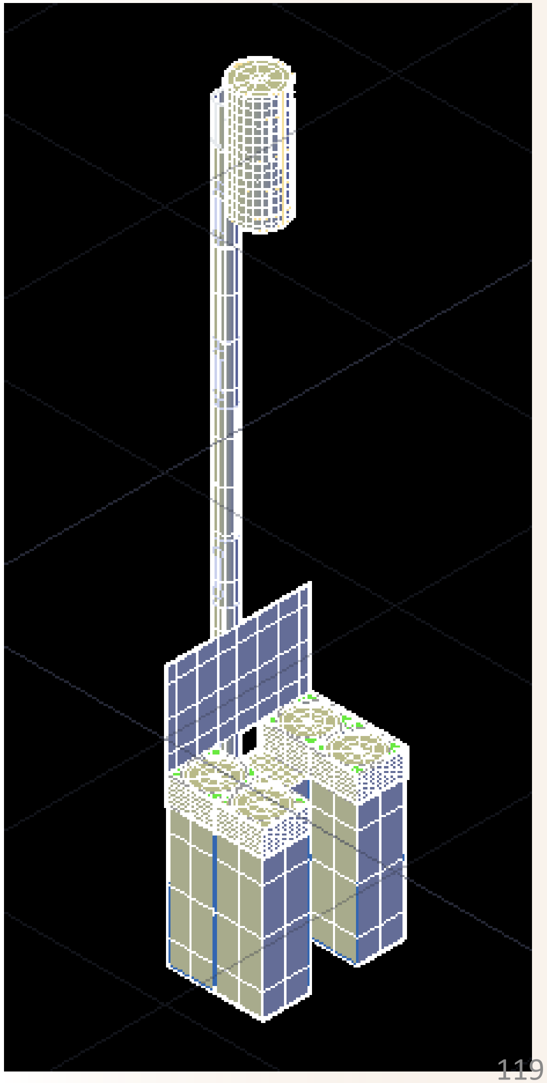
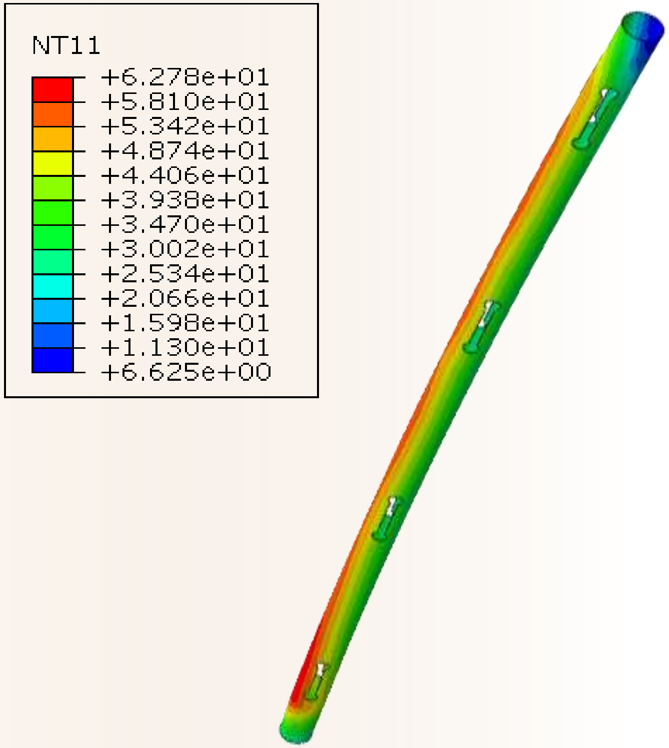
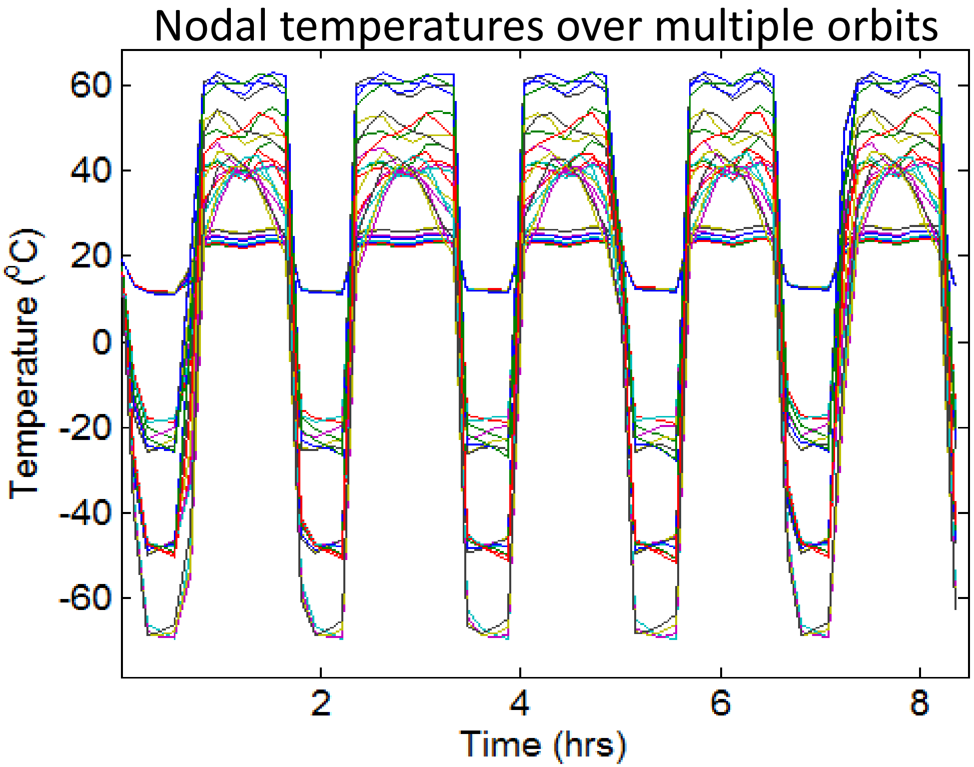


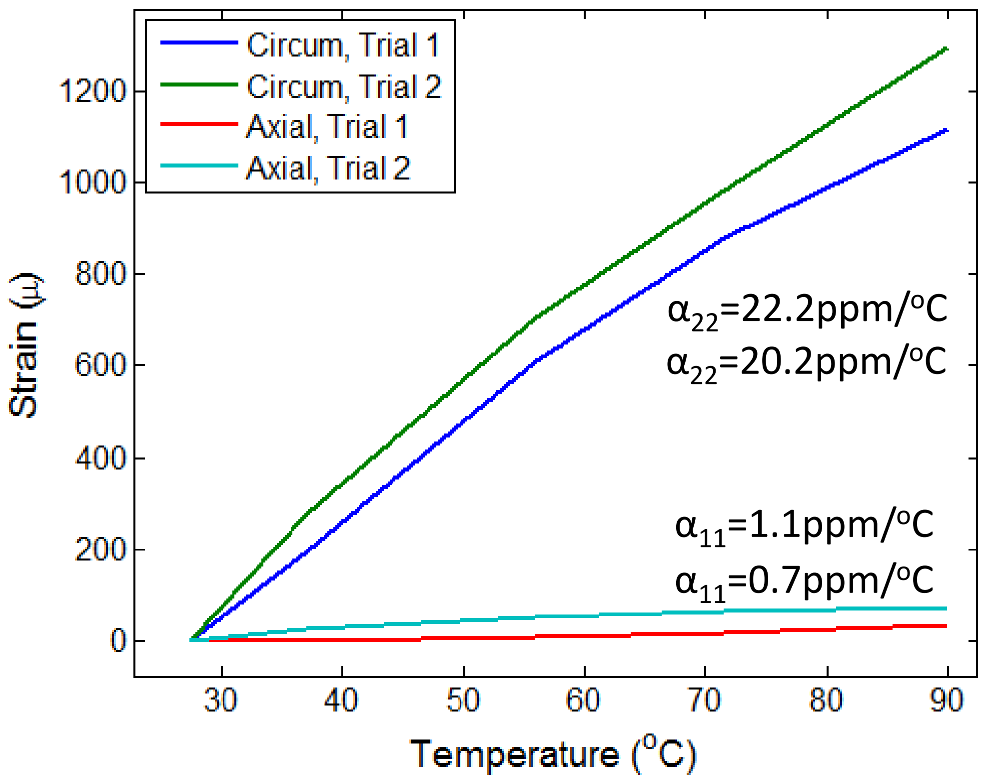
Thermal Profiles





- Boom thermal profiles determined for Sun-Synch orbit (11am-11pm)
  - Determined assuming black paint across boom surface (worst-case scenario)
  - Significant circumferential gradient due to solar loading
- Deflections due to thermal profiles obtained via FEA
  - Hot (full sun) and cold (eclipse) profiles studied

CTE Measurements

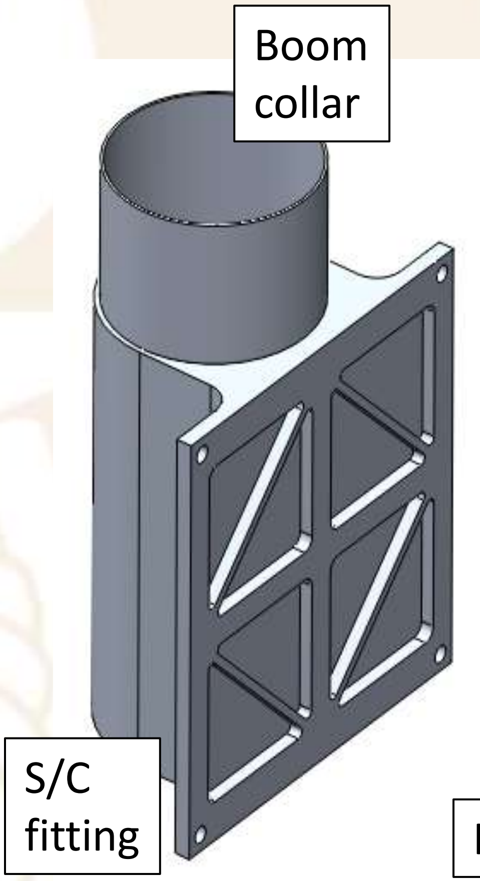


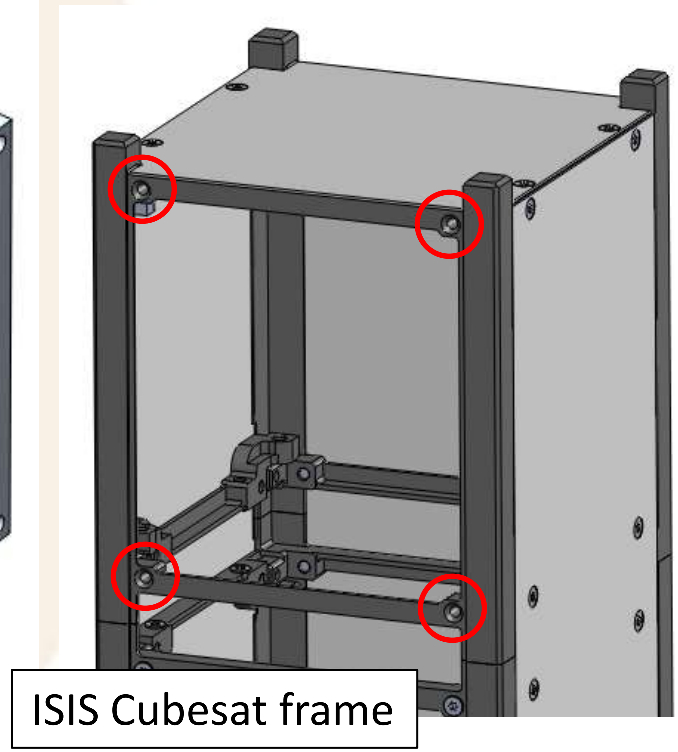
- Preliminary values of axial and circumferential CTE measured using 3D-DIC
- Tests performed in Thermal Chamber over a 65°C operating range
- **Axial:** α_{11}= ~ 1.0ppm/°C (dominated by carbon fibers)
- **Circum:** α_{22}= 21ppm/°C (dominated by fiberglass & epoxy resin)
- *Note: Deflections are stable for approximately half the orbit*
  - *Below 2mm requirement*
  - *Produces a shift of the image on the focal plane*

Case	Axial Deflection (μm)	Lateral Deflection (μm)	Rotation (deg)
Hot	25	625	0.04
Cold	-127	97	0.006

Interfaces

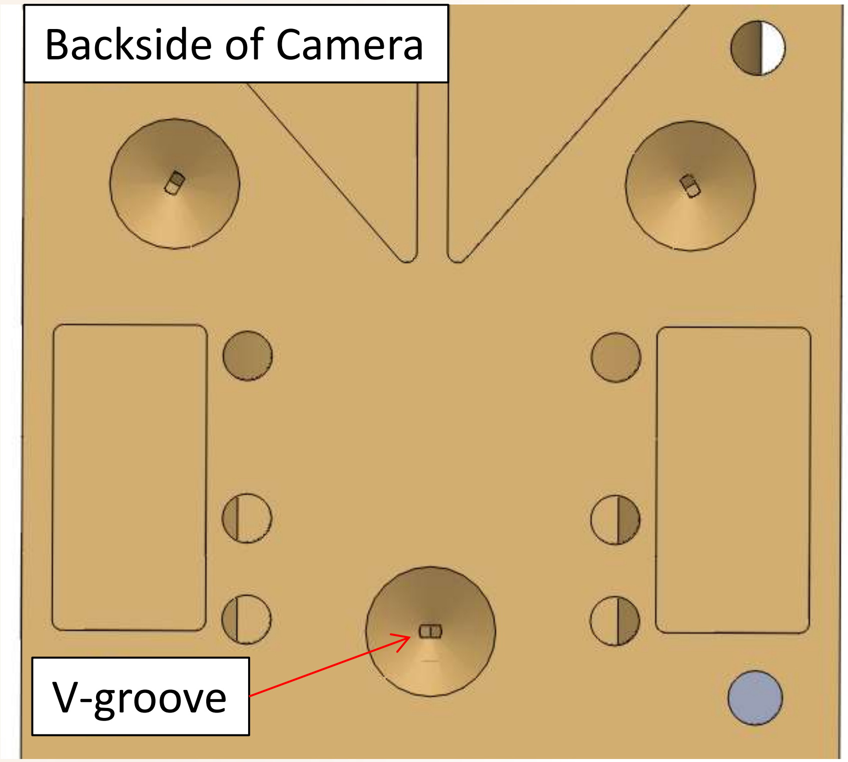
Interface to S/C

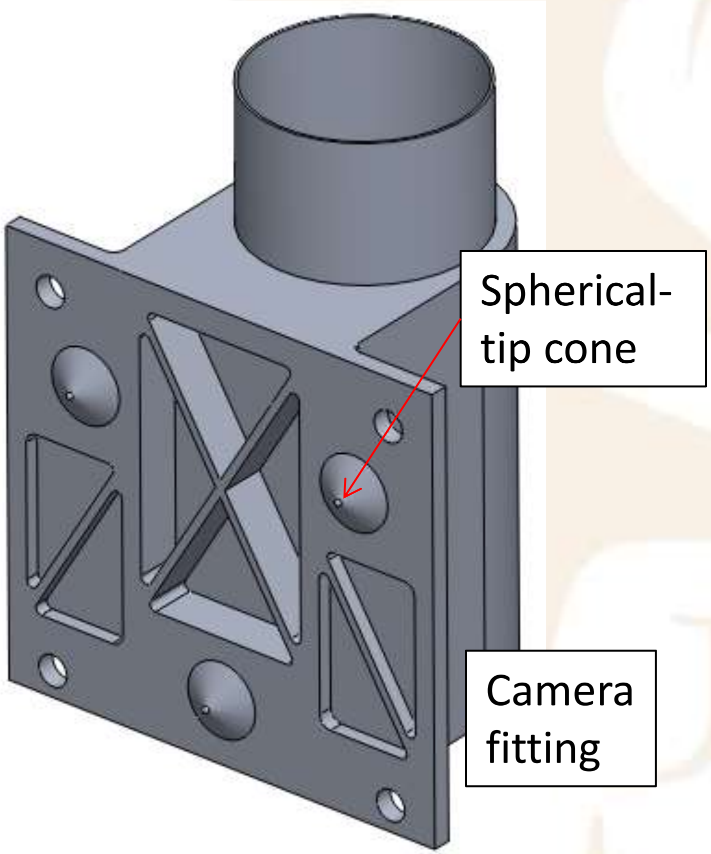




- Boom epoxied onto attachment collar
  - Collar pressure fit into S/C fitting then bolted in place
- S/C Fitting bolted into ISIS Cubesat frame
- May need to incorporate a secondary adapter plate in order to correct for errors introduced during assembly

Interface to Camera





- Kinematic mount used to provide alignment between Camera and Boom
  - Camera: V-grooves mounted at 120°
  - Boom Fitting: Matching spherical-tip cones
- Preloaded using surrounding bolt holes

Boom Mass Budget

Component	Mass (kg)
Boom	0.08
S/C Fitting	0.10
Camera Fitting	0.18
Cabling (electronic)	0.10
Burn wire	0.02
Motor/Spindle	0.10
Cabling (deployment)	0.02
Retraction Mechanism	0.05
Total	**0.65**

Future Work

- Utilize cyanate ester resin
  - Improved thermal properties
  - Low outgassing
- Quantify viscoelasticity of boom material
- Monitor damage of hinges due to multiple folding/deployment processes
- Further refinement of manufacturing techniques
- Study flexible structure interaction with ACS

Review Outline

1. Mission Overview (20 mins)
2. Spacecraft Design (60 mins)
3. Telescope Design (160 mins)
   a) Mirrors
   b) Camera
   c) Boom
   d) Telescope System Performance
   e) Test and Calibration
4. System Summary, Launch Vehicle, Project Plan (15 mins)
5. Discussion (15 mins)

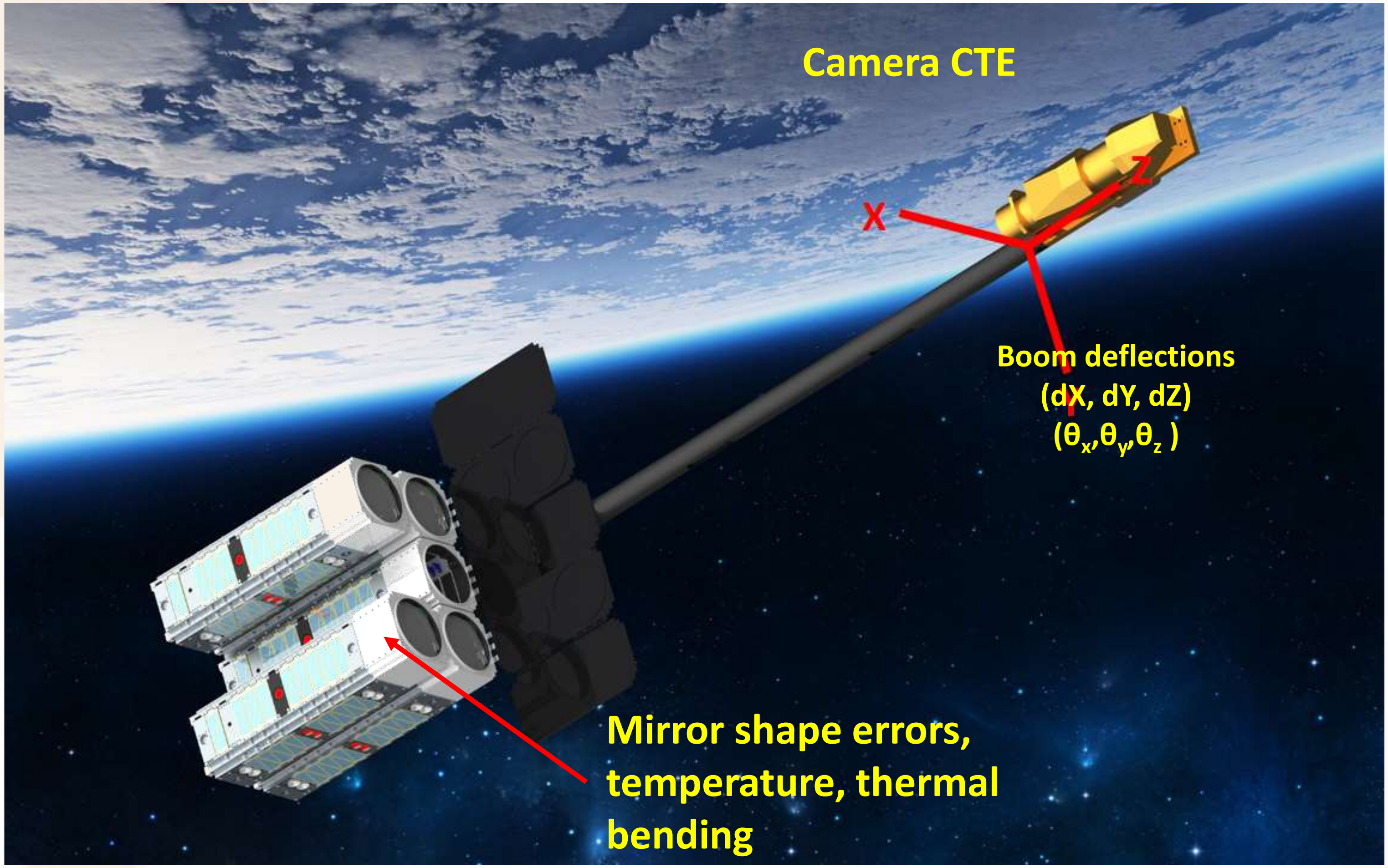
Performance Analysis

Keith Patterson

September 9th, 2013

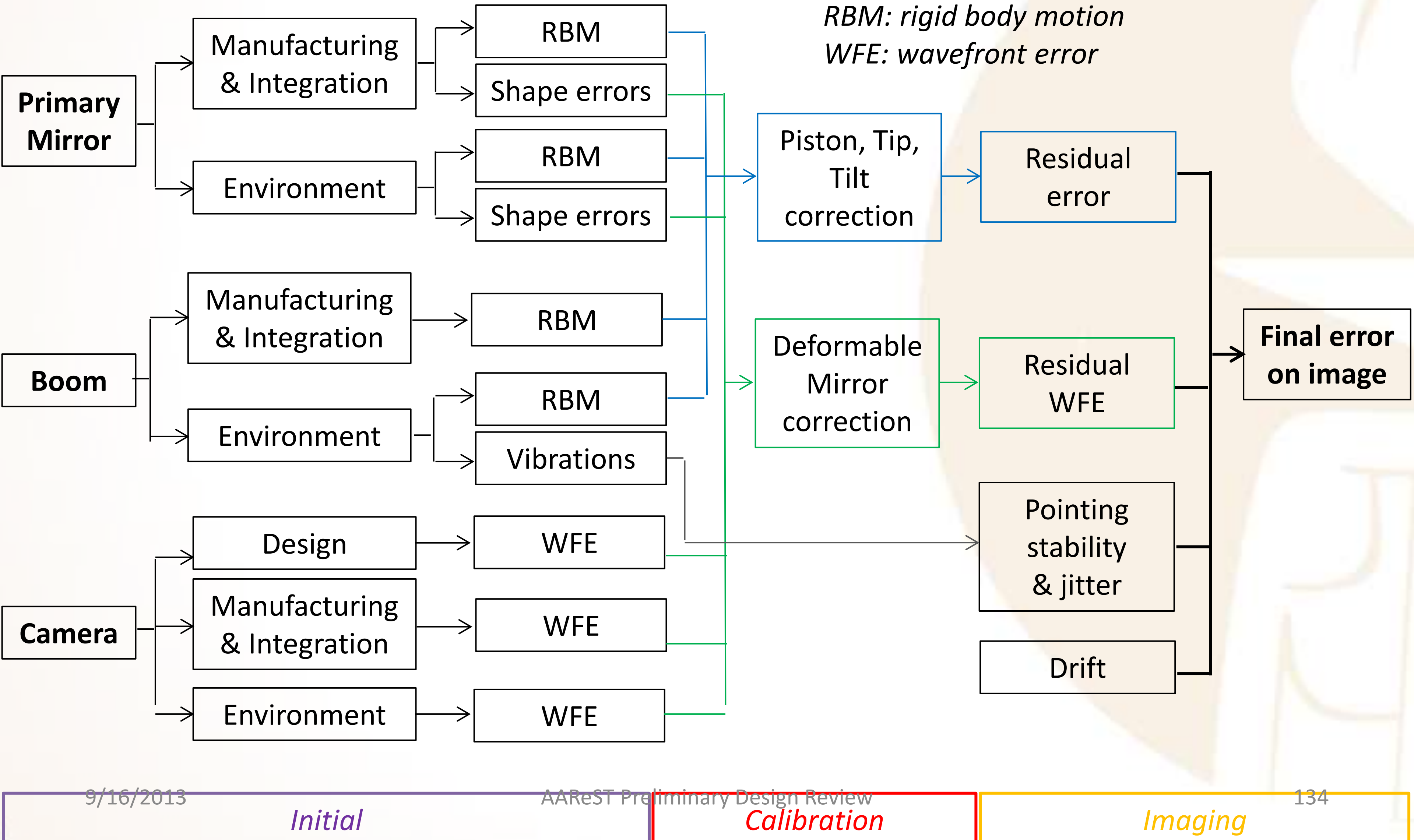
AAReST Performance Simulation

Error sources:

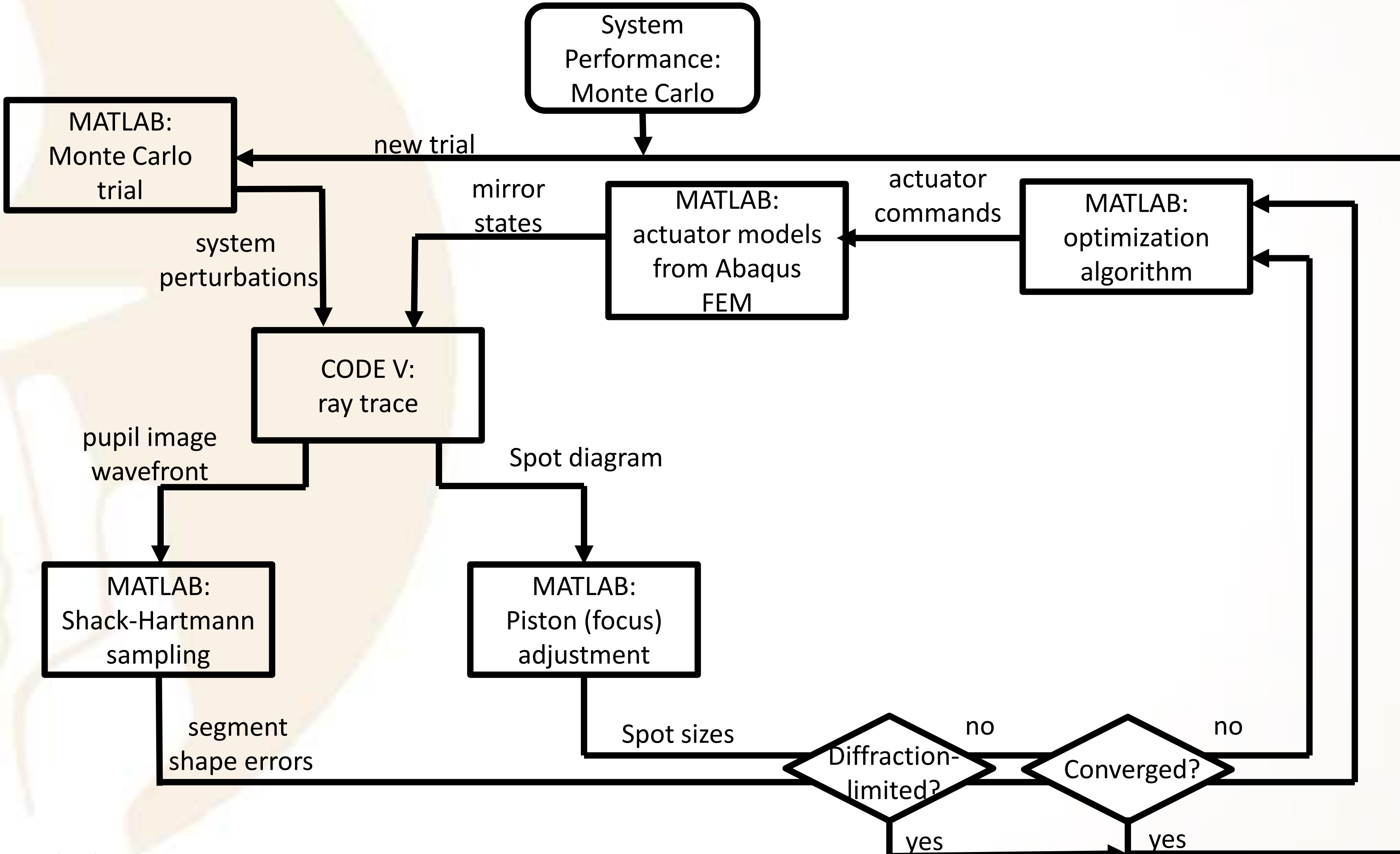


Error Sources

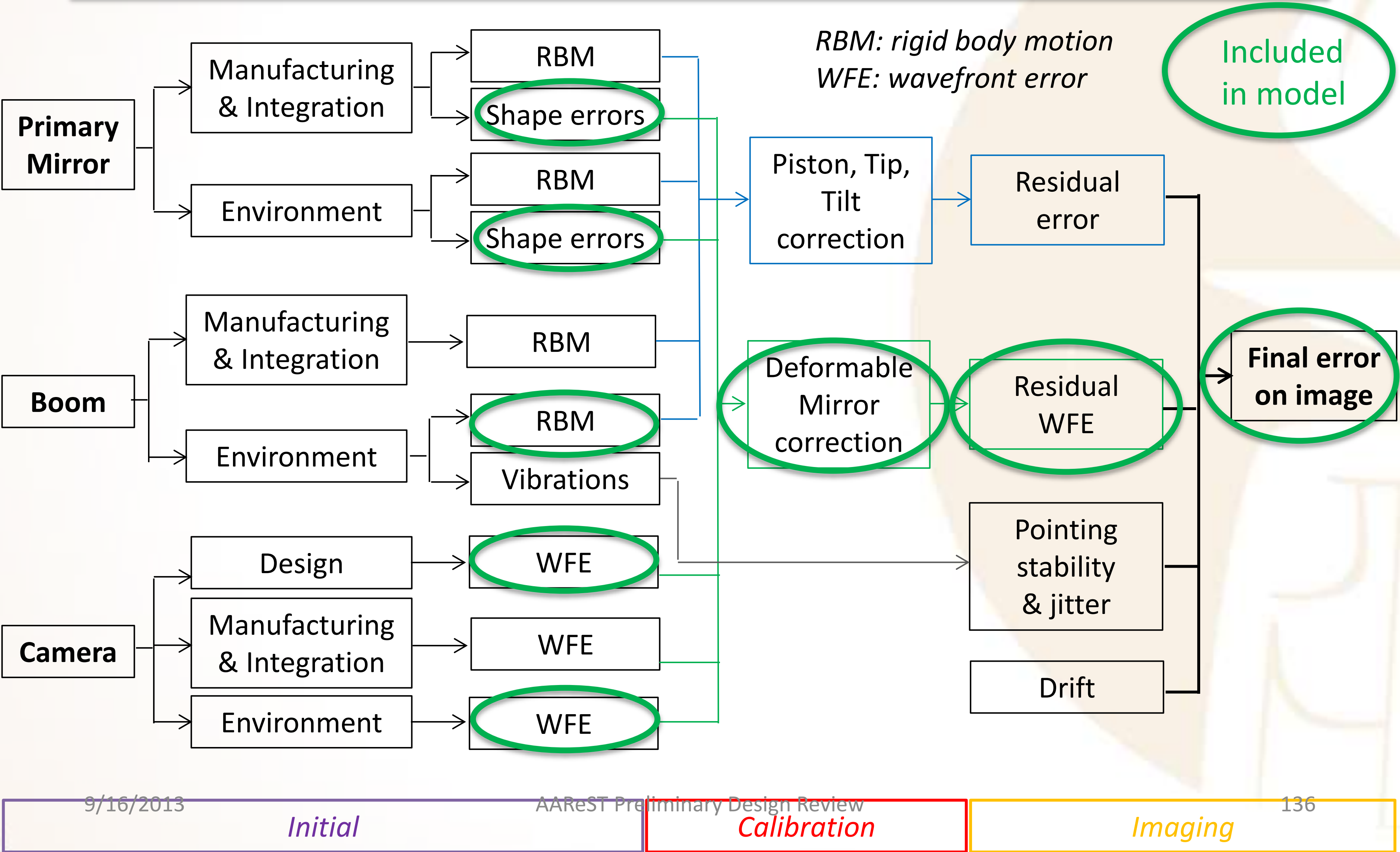
RBM: rigid body motion
WFE: wavefront error



Performance Analysis Model



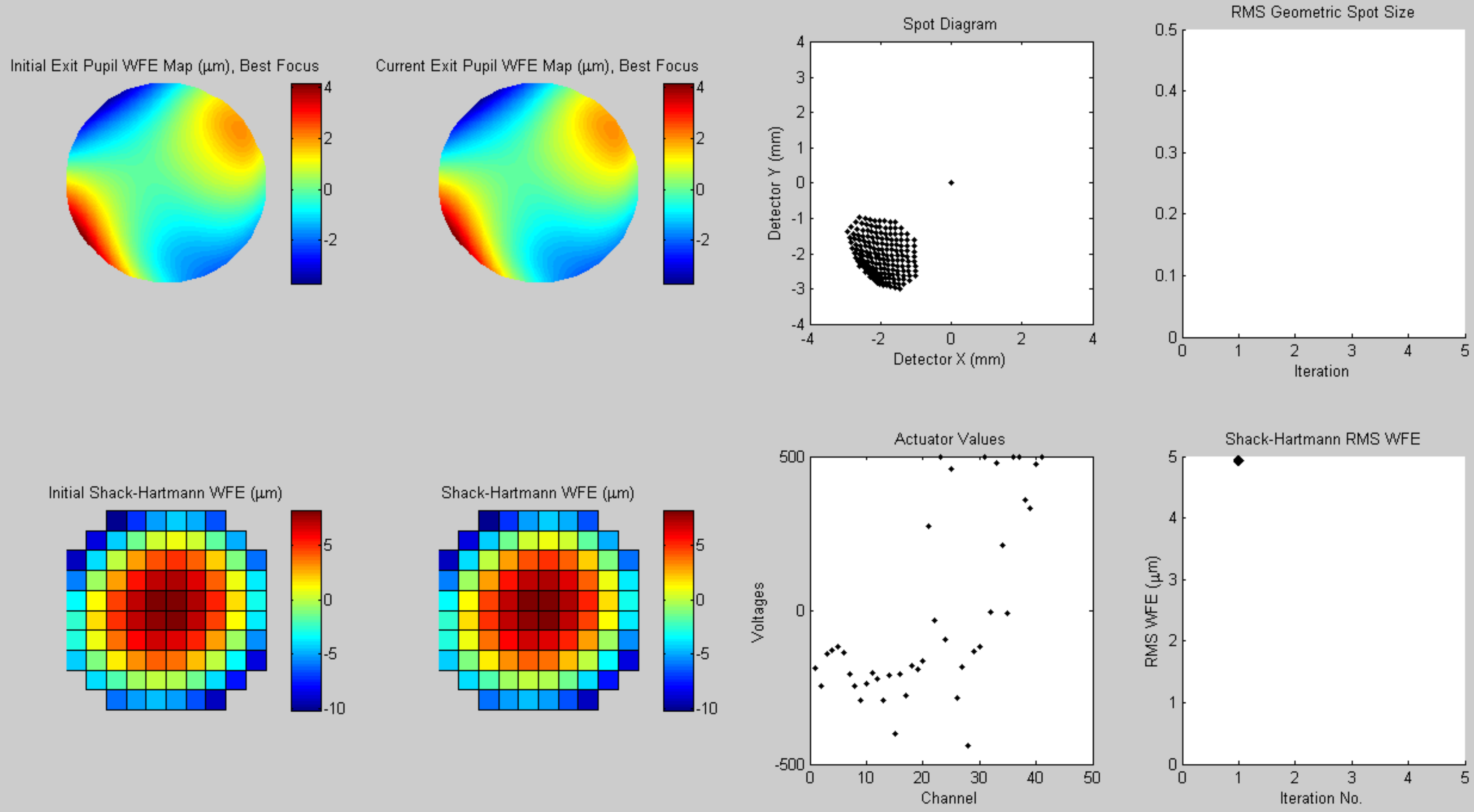
Error Sources



Error Budget Values

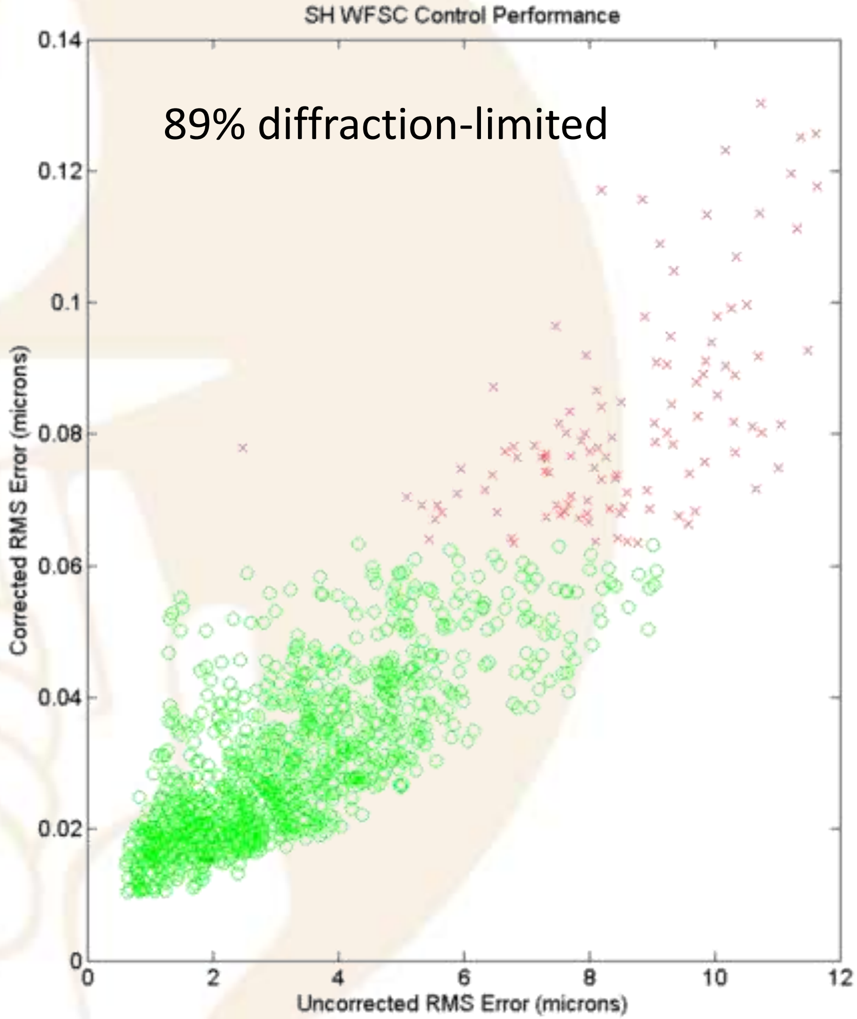
- Mirror temperature: -20C to +20C
- Camera temperature: -20C to +20C
- Mirror initial shape bounds (surface amplitudes, non-normalized, microns, +/-):
  - Z4 = .002; astigmatism_0
  - Z5 = .005; defocus
  - Z6 = .002; astigmatism_45
  - Z7 = .001; trefoil_x
  - Z8= .001; coma_x
  - Z9 = .001; coma_y
  - Z10 = .001; trefoil_y
  - Z11 = .0005; tetrafoil_y
  - Z12 = .0005; 2_astigmatism_0
  - Z13 = .001; spherical
  - Z14 = .0005; 2_astigmatism_45
  - Z15 = .0005; tetrafoil_y
  - Z16:66 = .0001; higher order modes
- Boom deflection bounds (+/-):
  - X: 0.625 mm
  - Y: 0.625 mm
  - Z: 0.127mm
  - Tip: 0.04 deg
  - Tilt: 0.04 deg

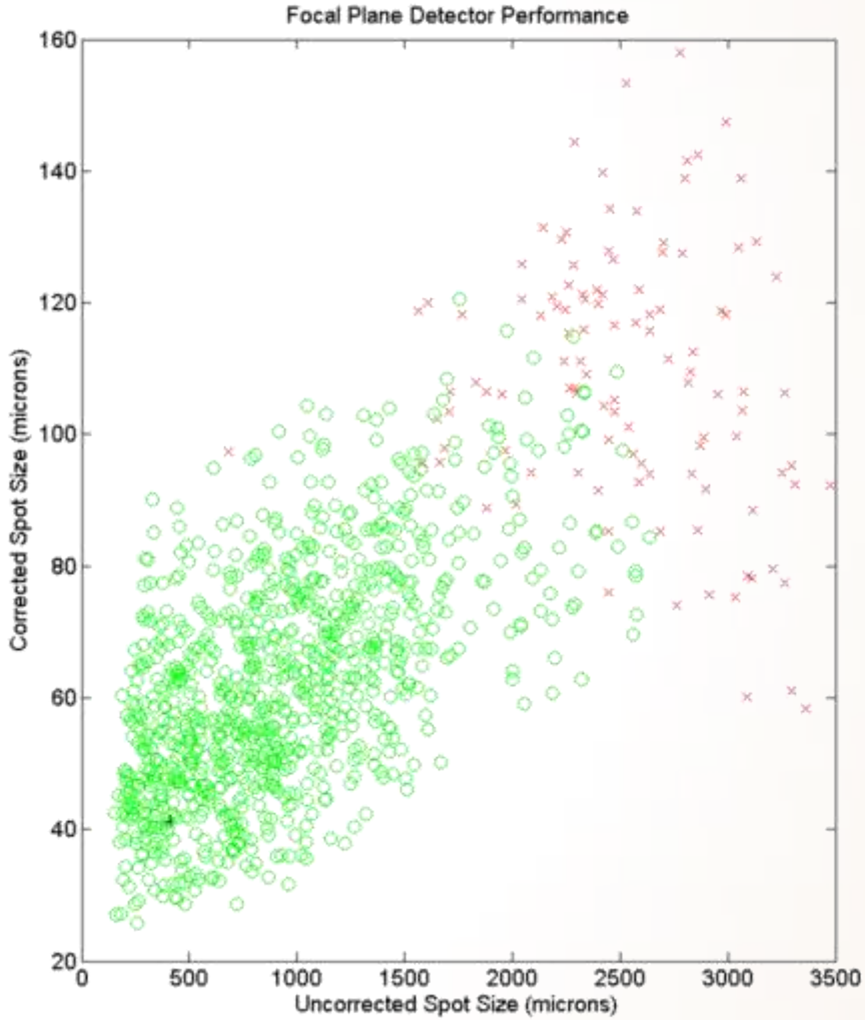
Example Performance Trial



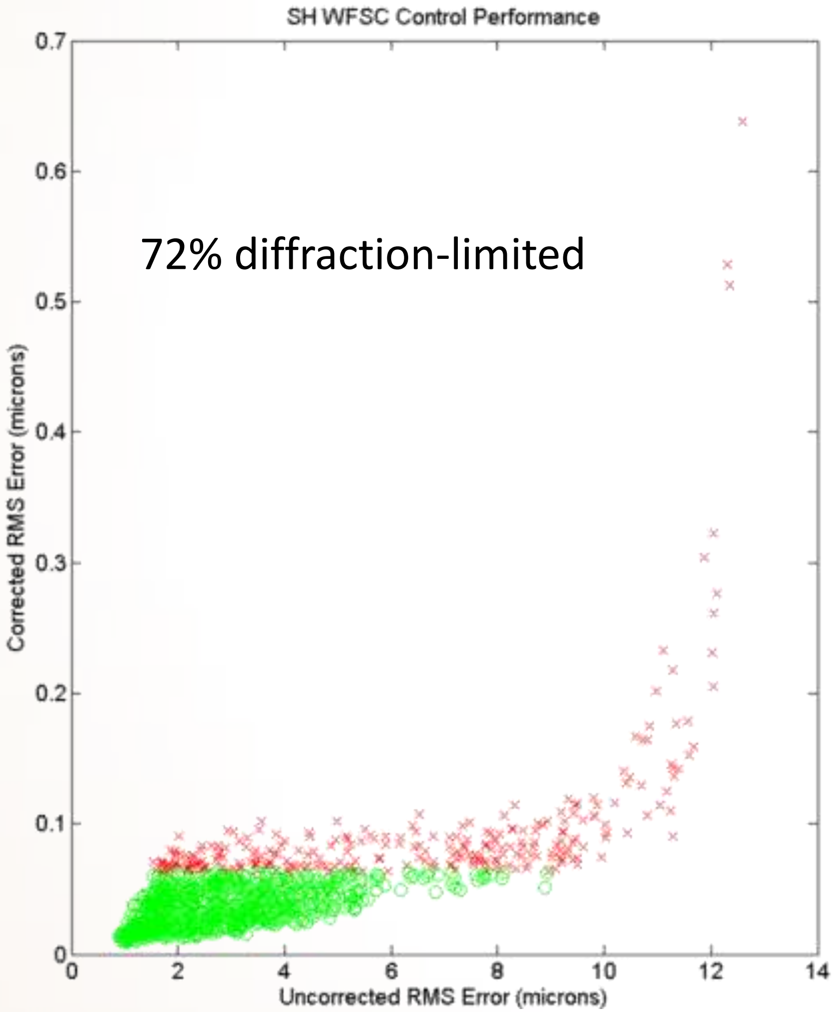
Performance Results (Compact)

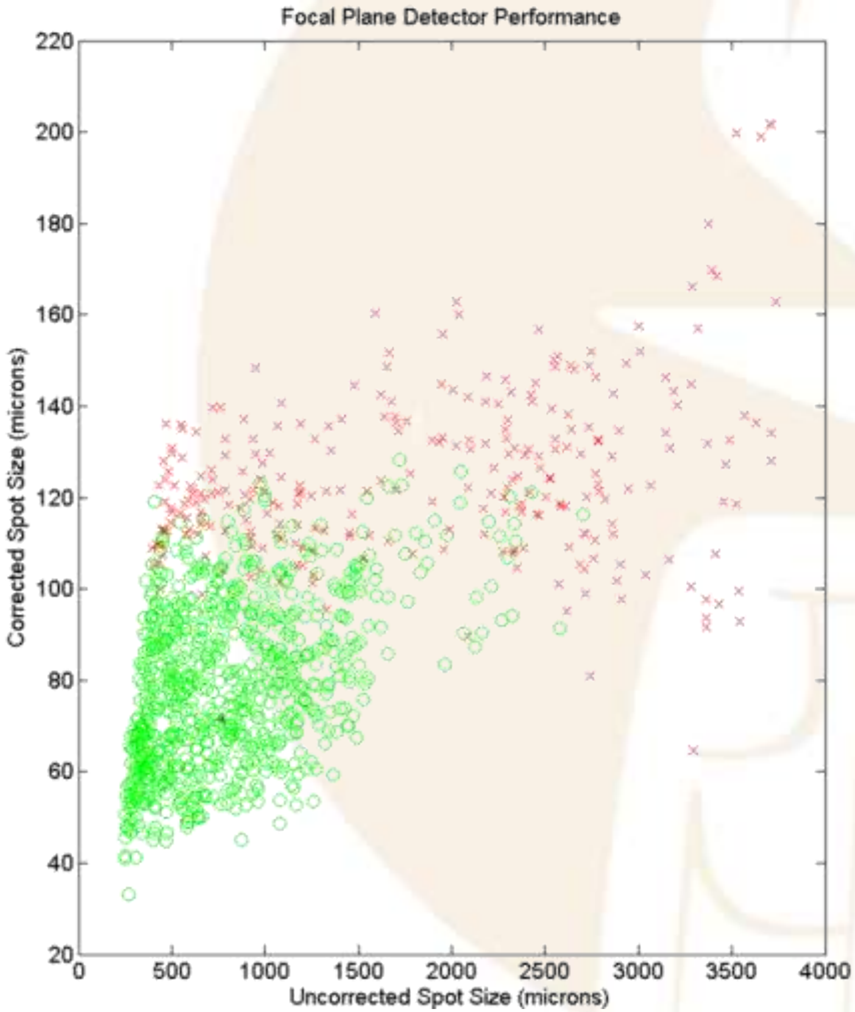
89% diffraction-limited





Performance Results (Wide)





System Performance Take-aways

- Mirror initial shape quality, astigmatism stroke, and operating temperatures are critical
- Low Shack-Hartmann sampling degrades camera spot size performance but increases SH SNR
- Non-common path errors and bandpass differences between detector and SH can degrade camera spot performance
- Boom deflection and alignment is of secondary importance compared to mirror quality
- Needed additions to model (future work)
  - Spacecraft pointing model (Newton-Euler)
  - Pointing controller
  - Mirror tip tilt controller
  - Camera optics manufacturing and integration errors

Review Outline

1. Mission Overview (20 mins)
2. Spacecraft Design (60 mins)
3. Telescope Design (160 mins)
   a) Mirrors
   b) Camera
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   e) Test and Calibration
4. System Summary, Launch Vehicle, Project Plan (15 mins)
5. Discussion (15 mins)

AAReST Integration and Test

Marie Laslandes

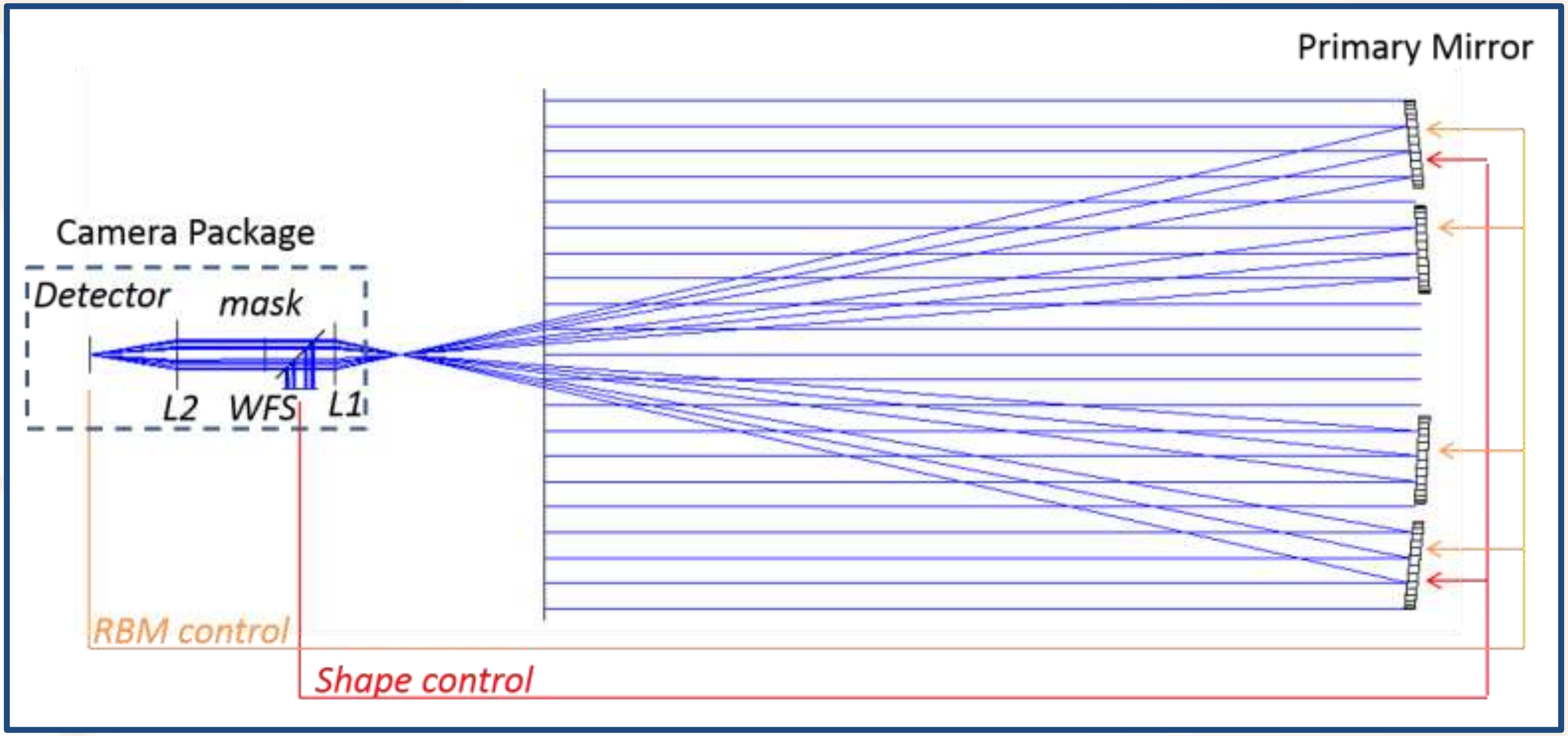
September 9th, 2013

Objectives

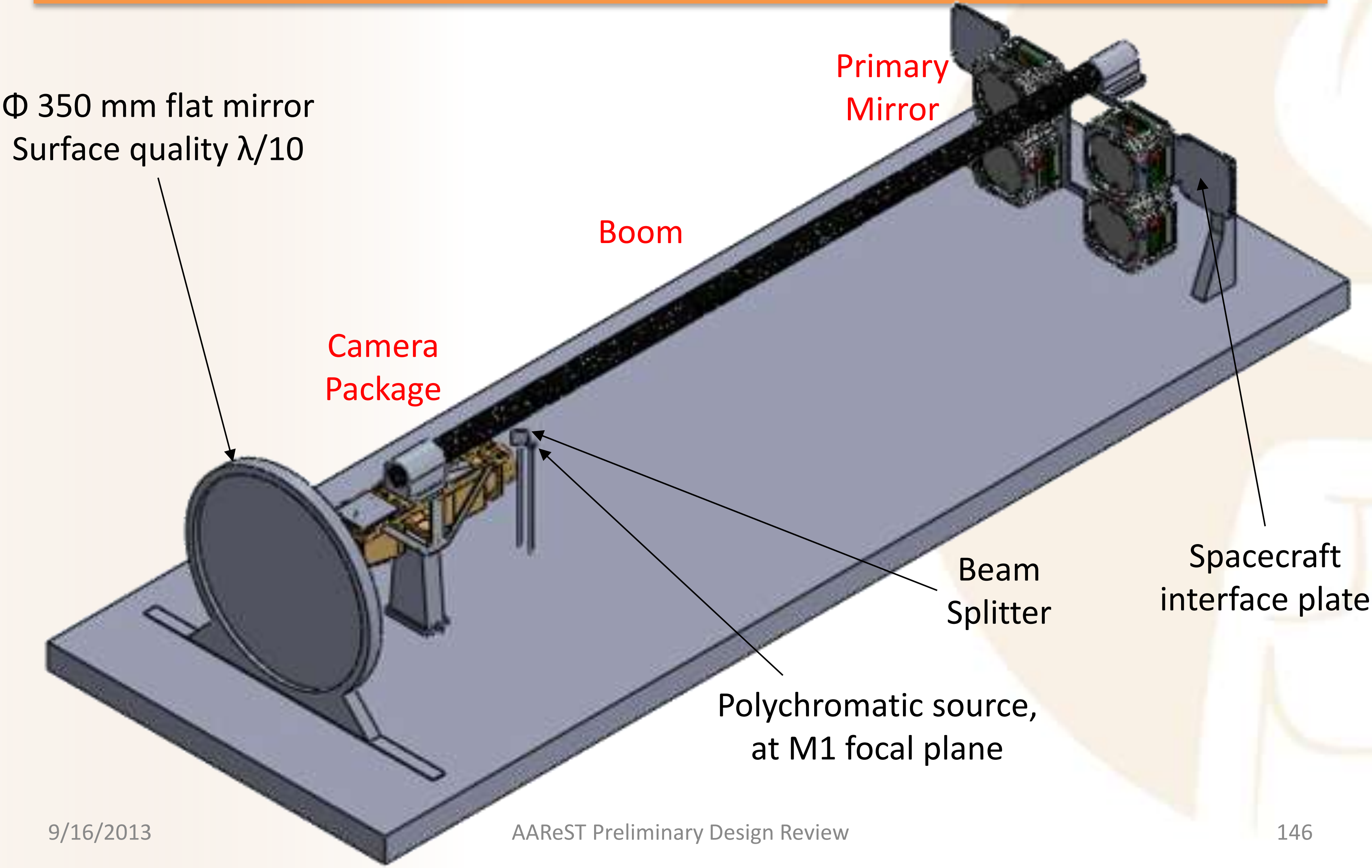
- Assembly segments/boom/camera
  - Verify mechanical interfaces
  - Optical alignment
- Optical performance validation
  - Validate calibration process
- Functioning
  - Mechanism
  - Electronic
  - Control & Algorithm
  - Communications

Test bed - requirements

- Generation of a large collimated beam
  - Auto-collimation technique
  - Only test 2 segments at a time
- Space-craft simulator
  - Mechanical interfaces
  - Communications
  - Power supply



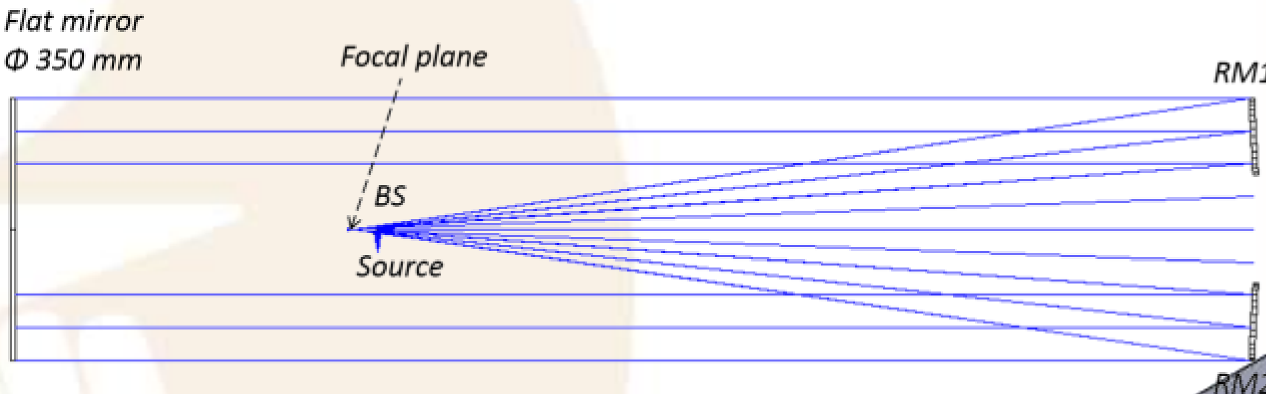
Test-bed - Design

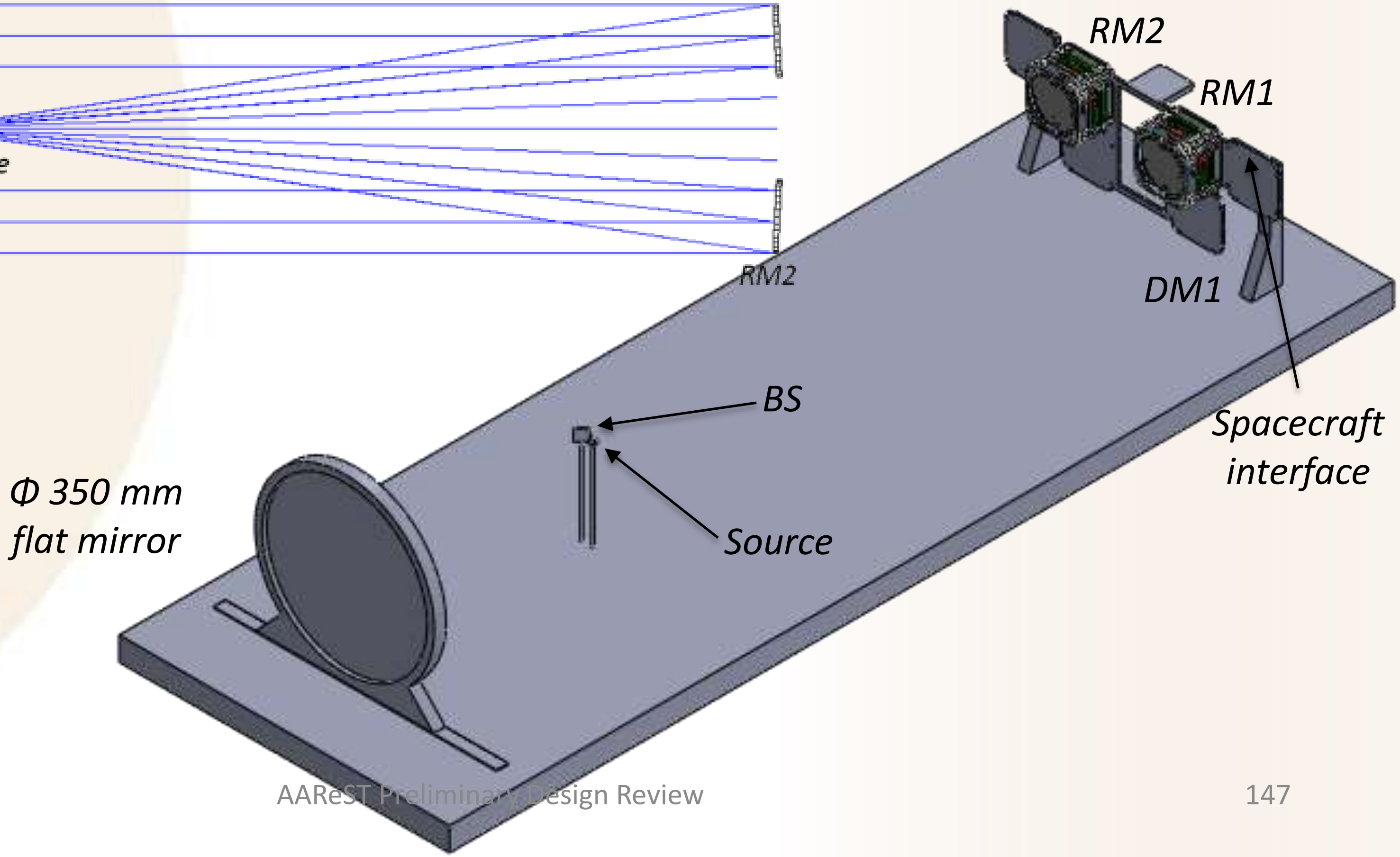


Reference Mirrors alignment

- Mount segment on spacecraft interface plate
- Piston, Tip, Tilt each mirror

- Criteria:
  PSF size, shape and location

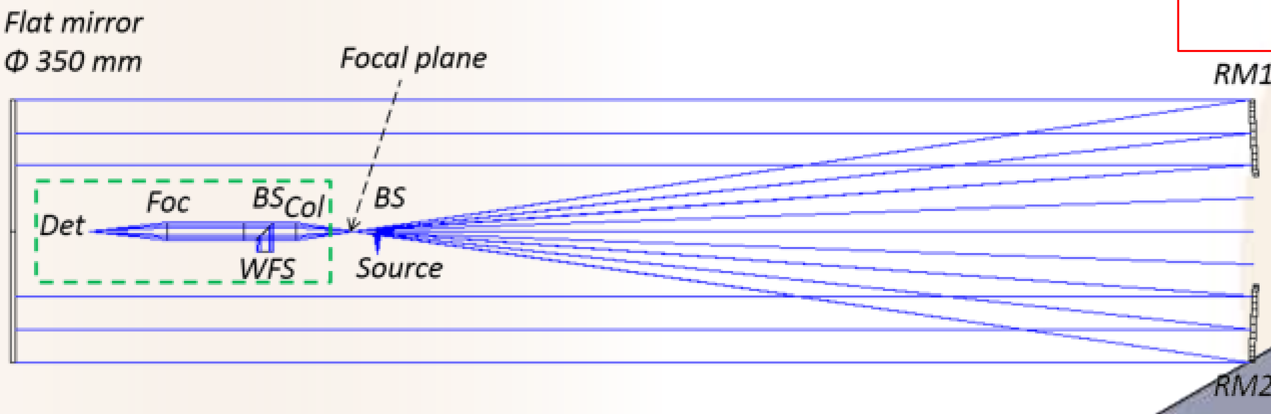


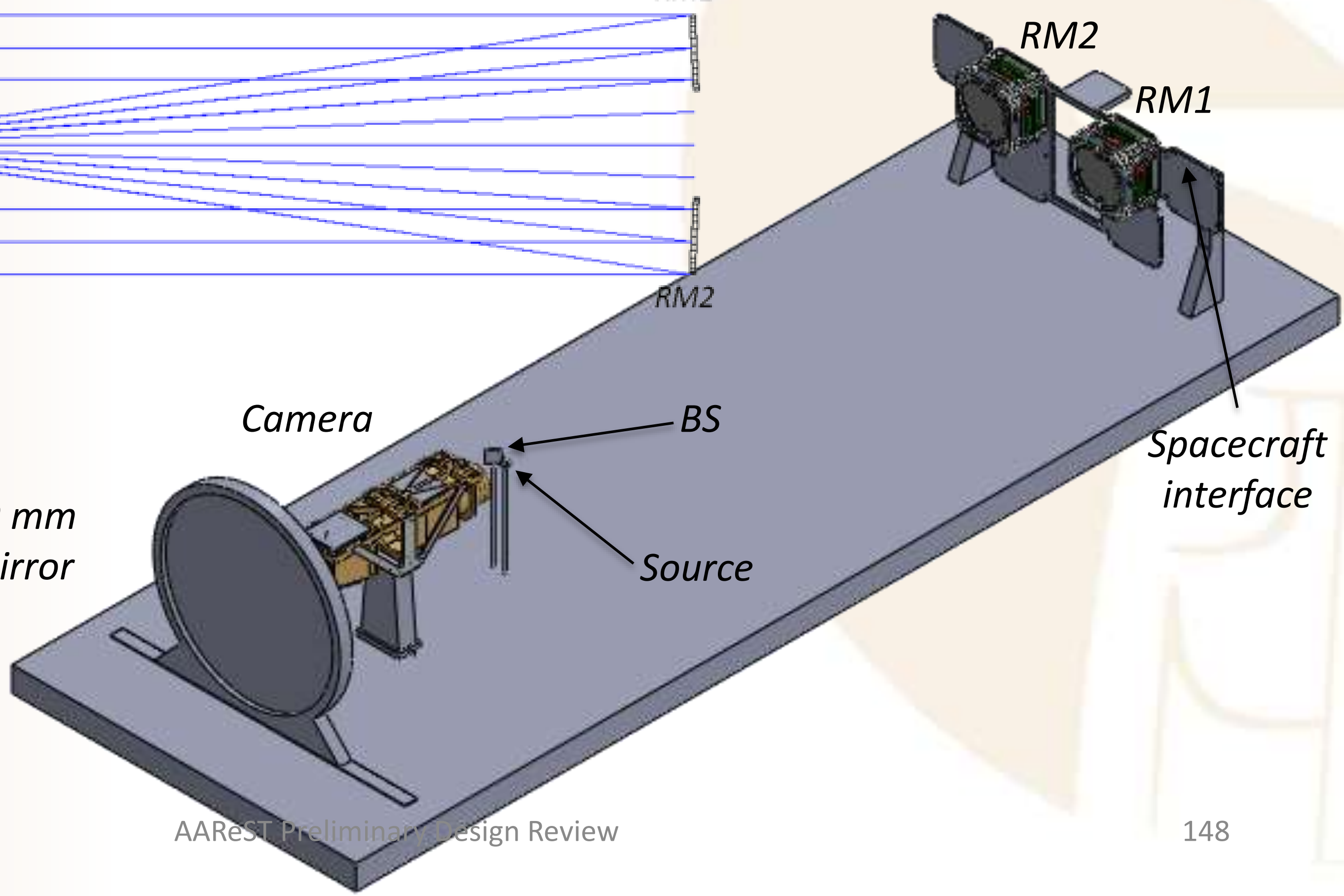


Camera

- Position camera: adjust translation and rotation according to prime focus

- Criteria:
  PSF : 80% of EE on 13um
  WFE < λ/20 rms

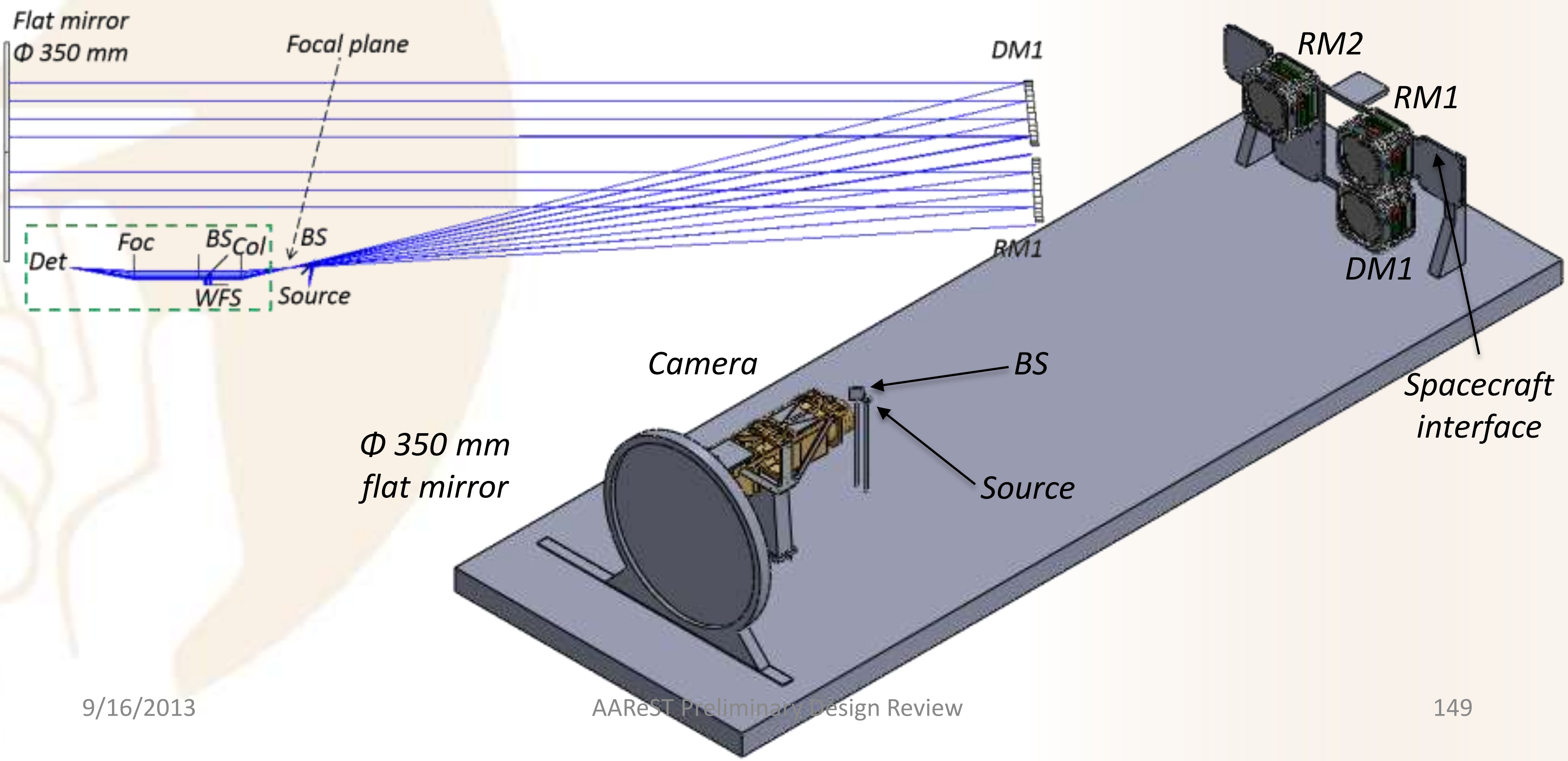




Deformable Mirror 1 alignment

- Mount DM1 in narrow configuration
- Illuminate RM1&DM1: tilt source, translate flat mirror
- Piston, Tip, Tilt DM

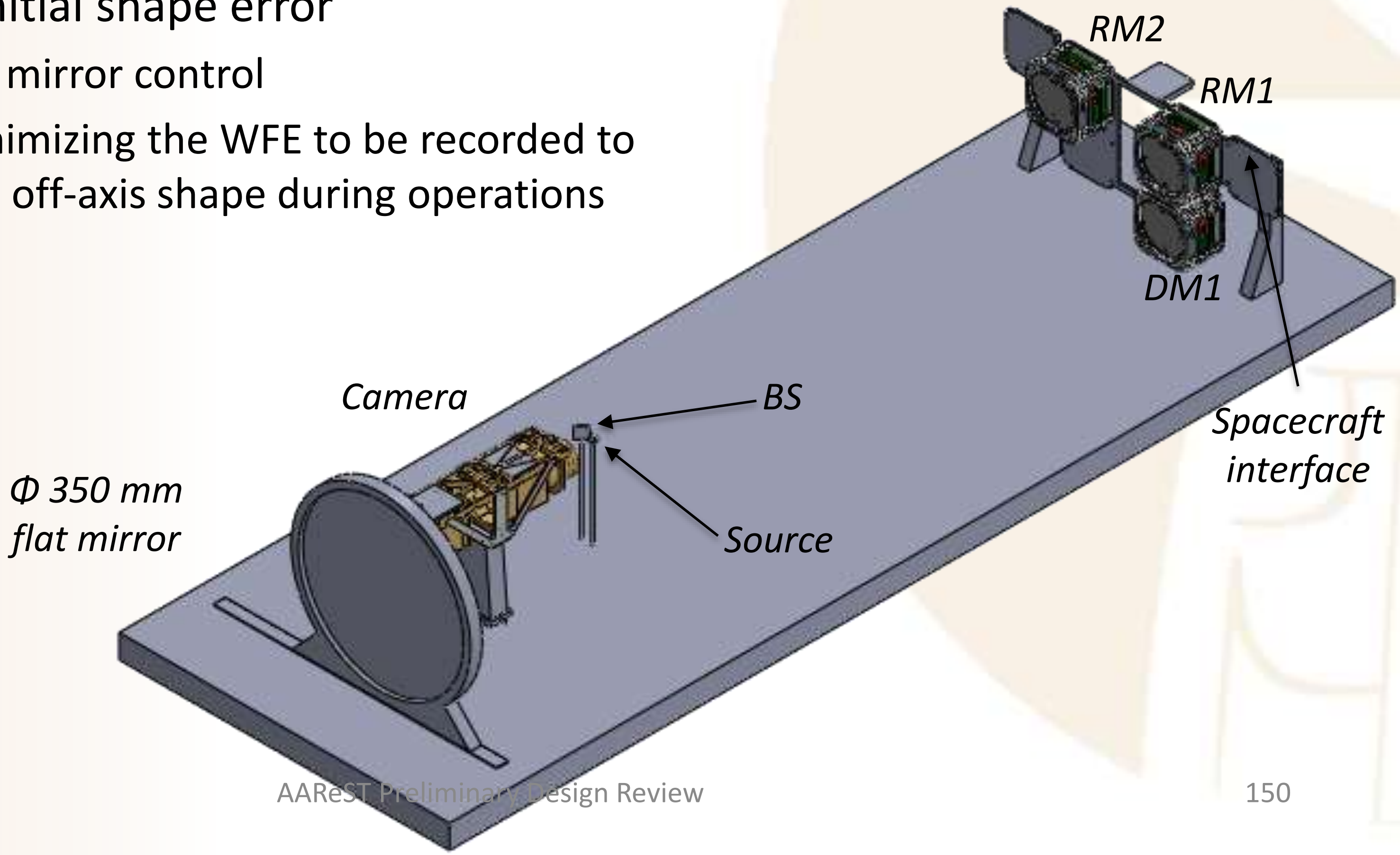
- Criteria:
  - PSF size and location
  - Measurable WFE



Deformable Mirror 1 correction

- Control law from Influence Function measurement
- Reference wave-front: flat
- Correction of initial shape error
  - Will validate mirror control
  - Voltages minimizing the WFE to be recorded to approximate off-axis shape during operations

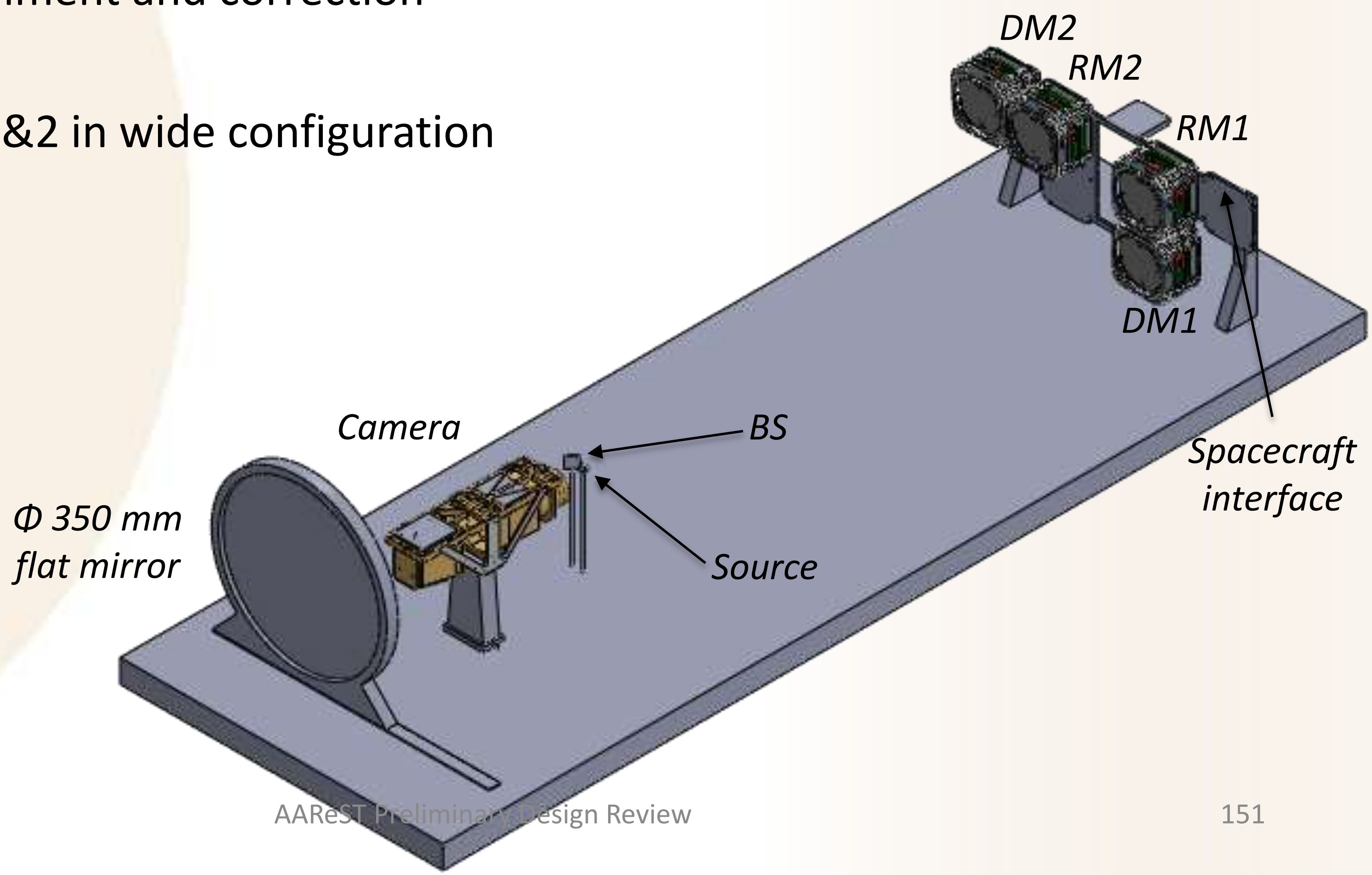
- Criteria:
  PSF : 80% of EE on 13um
  WFE < $\lambda/20$ rms



Deformable Mirror 2

- Mount DM2 in narrow configuration
- Illuminate RM2&DM2: tilt source, translate flat mirror
- Repeat DM alignment and correction

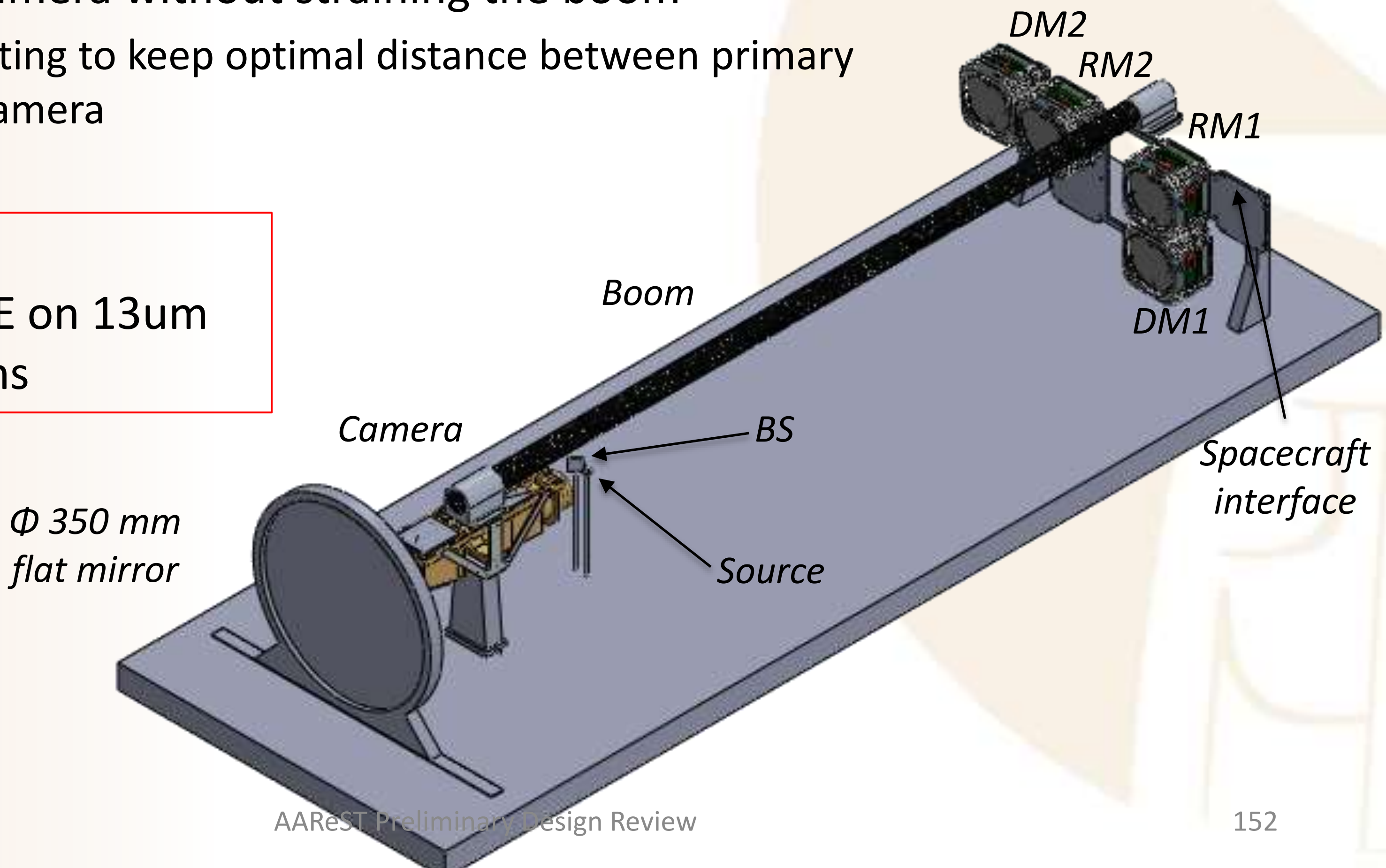
- Repeat for DM1&2 in wide configuration



Boom integration

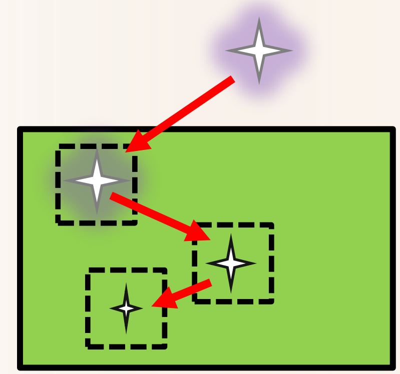
- With RM1&2 illuminated
- Attach unconstrained boom to spacecraft interface plate
- Link boom to camera without straining the boom
  - Adjust mounting to keep optimal distance between primary mirror and camera

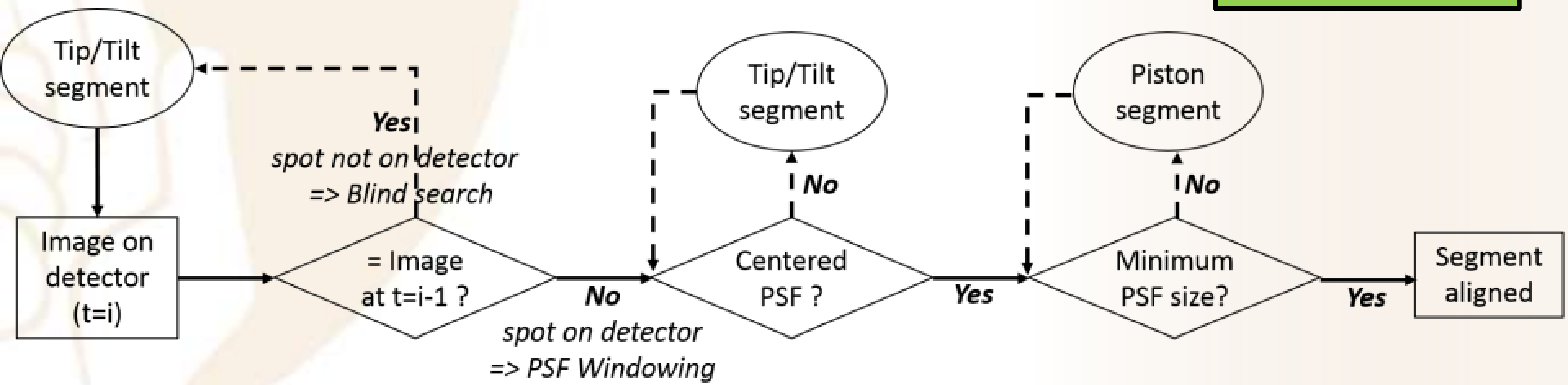
- Criteria:
  PSF : 80% of EE on 13um
  WFE < λ/20 rms



Telescope calibration process

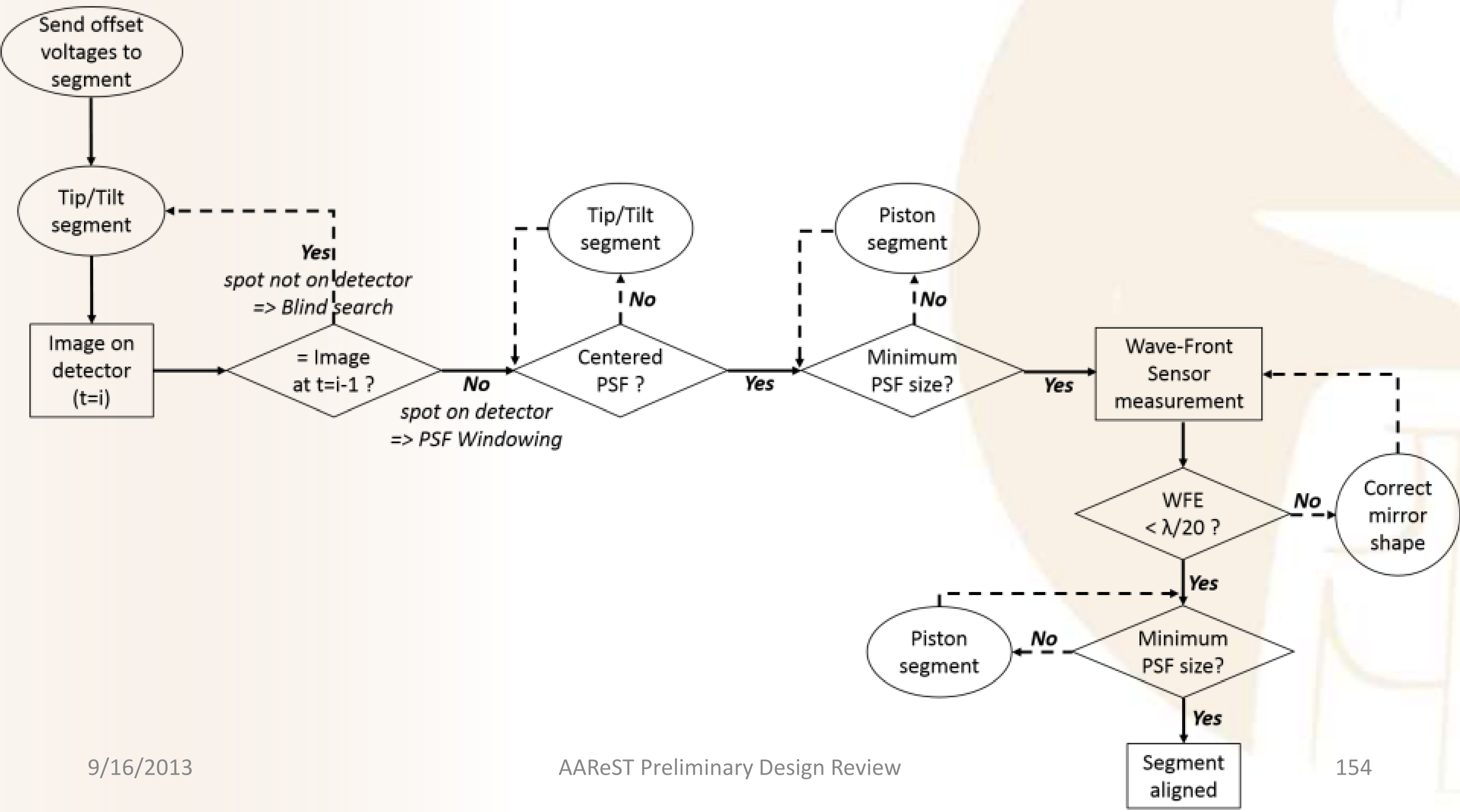
- Reference Mirror process:





Telescope calibration process

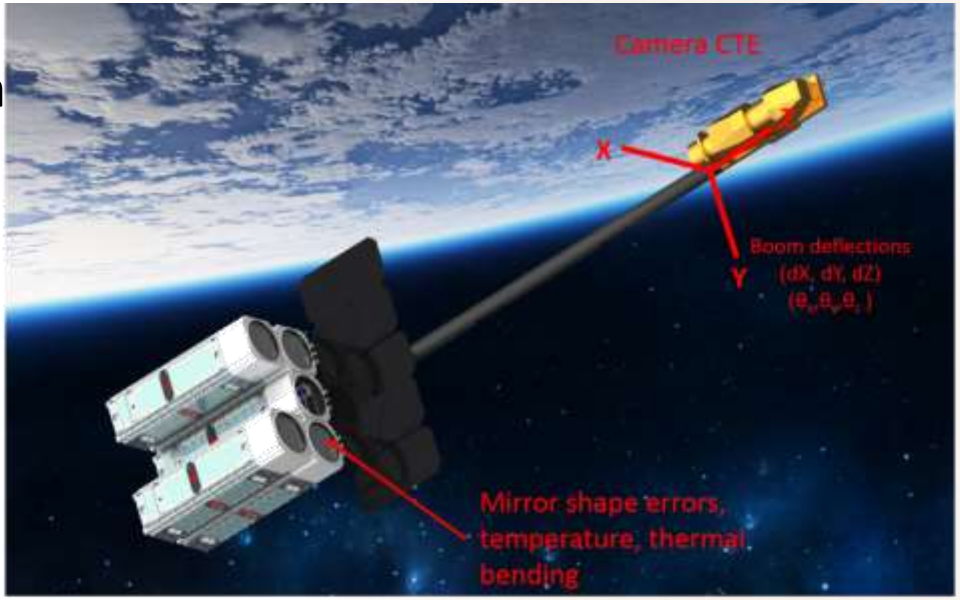
- Deformable Mirror process:



Test telescope calibration

- With any aligned configuration (2 segments)

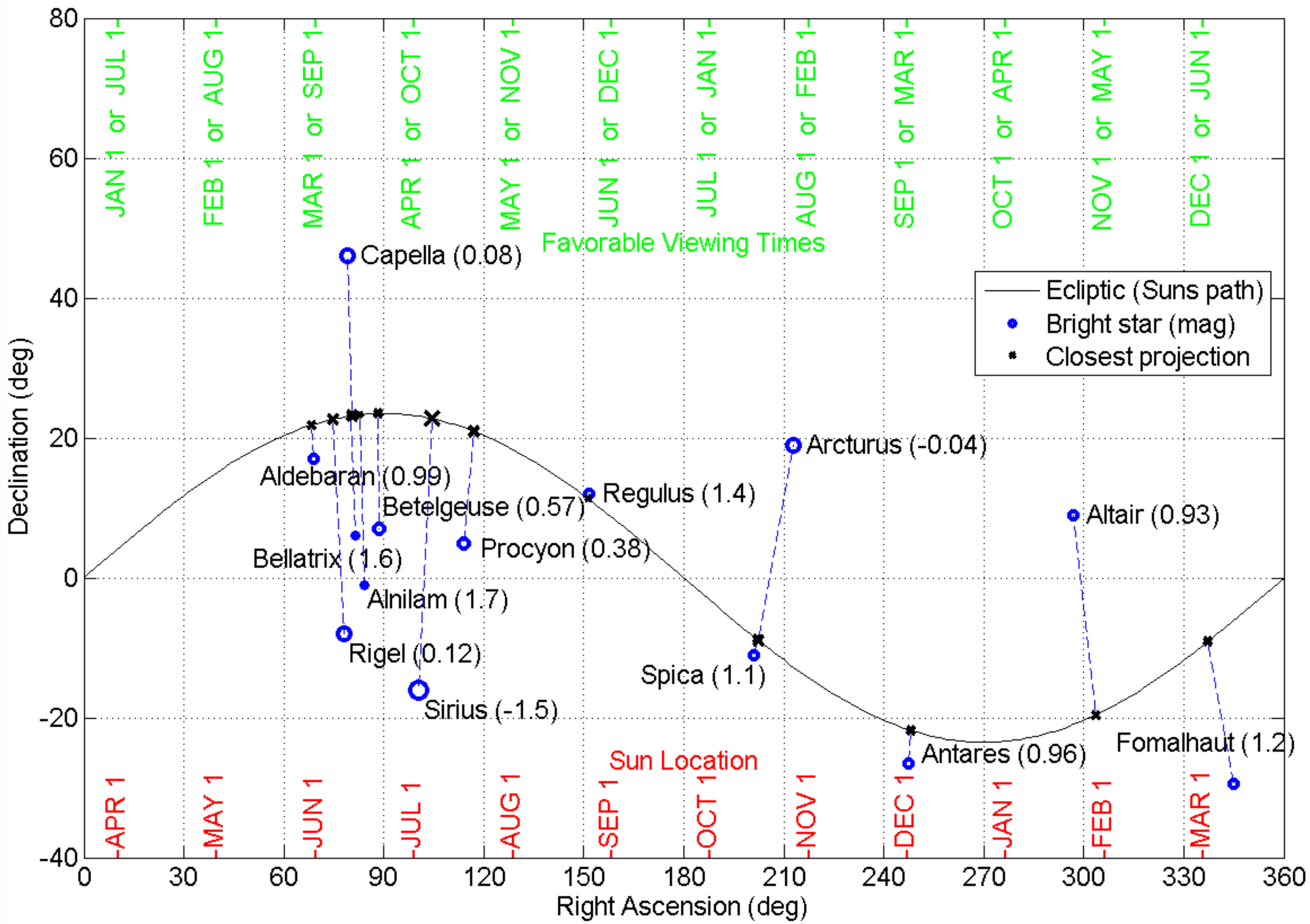
- Validate overall calibration process: introduce an expected perturbation (values from model and testing)
  - Camera temperature: translate camera
  - Boom deflection: translate/rotate camera
  - Segment misalignment: piston, tip, tilt segments



- Criteria: performance after calibration
  PSF : 80% of EE on 13um
  WFE < λ/20 rms

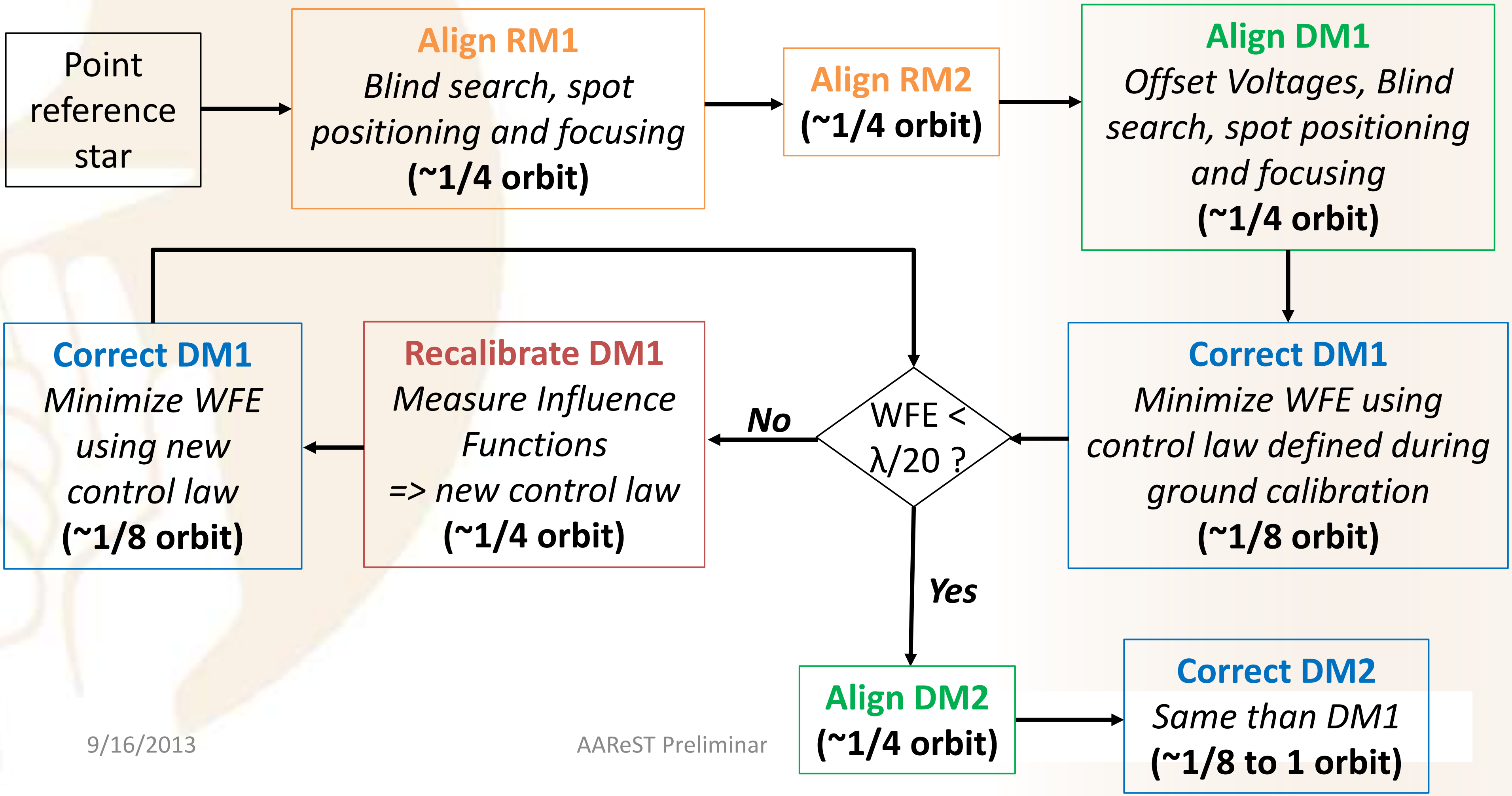
In-flight calibration: reference star

- Point telescope to reference star
  - bright star
  - near Zodiac
  - ±3 months from sun

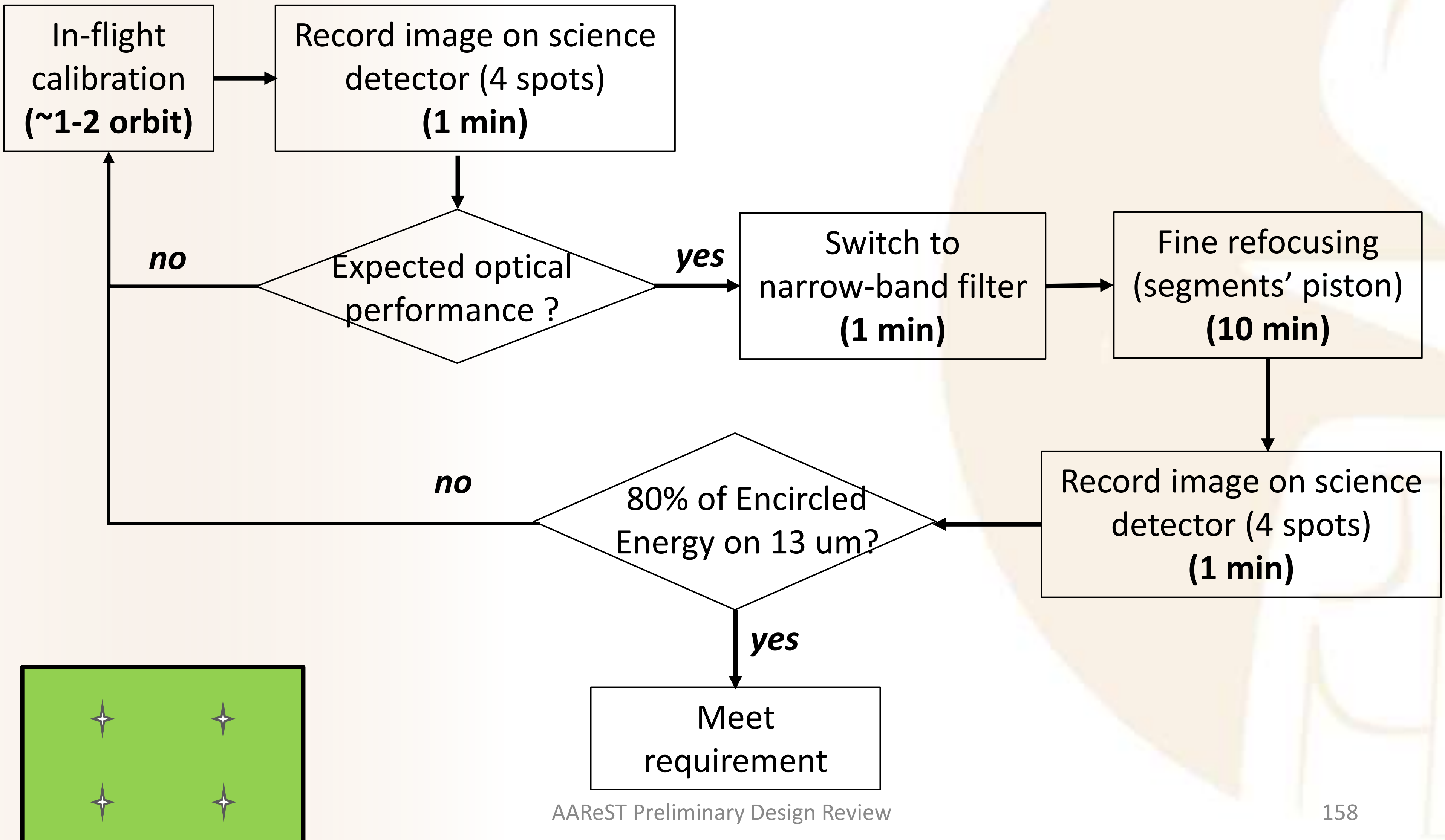


In-flight calibration

- Star camera: pointing knowledge
  - If star disappear from FoV during process, stop and wait (or repoint)

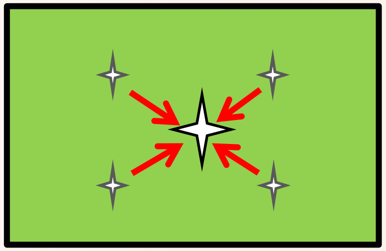


Imaging


In-flight calibration
(~1-2 orbit)
Record image on science detector (4 spots)
(1 min)
Expected optical performance ?
no
yes
Switch to narrow-band filter
(1 min)
Fine refocusing (segments' piston)
(10 min)
Record image on science detector (4 spots)
(1 min)
80% of Encircled Energy on 13 um?
no
yes
Meet requirement

Imaging (extended)

- Co-align segments
  - Adjust each segment tip/tilt to superimpose spots
  - Fine refocusing: adjust segments' piston
  - Possibly: adjust DM1&2 shapes
  - Record image of the combined spot on science camera



- Extended source imaging
  - Calibrate on a star near the moon and then point at the moon
- Co-phase segments
  - If technique demonstrated on Earth

Conclusion and future work

- Integration and test plans defined
  - Optical elements
  - Mechanical interfaces
  - Control algorithm
- Integration on S/C
  - Ship segments in individual boxes and camera attached to deployed boom
  - Assemble on spacecraft
  - Optical test with same set-up to validate performance
  - Overall environmental testing
- Operation scheme defined, to be validated and refined with testing
- Start breadboard this year
  - Test-bed optical elements: white source, large flat mirror
  - Space-craft simulator: define interfaces

Review Outline

1. Mission Overview (20 mins)
2. Spacecraft Design (60 mins)
3. Telescope Design (160 mins)
    a) Mirrors
    b) Camera
    c) Boom
    d) Telescope System Performance
    e) Test and Calibration
4. System Summary, Launch Vehicle, Project Plan (15 mins)
5. Discussion (15 mins)

Launch Vehicle Options

- Multiple opportunities now exist for small secondary payloads (<40kg)
  - Secondary launches on EELVs
  - ISS Cargo and jettison through the JEM airlock
- Orbit needs to be constrained to LEO (<650km) for communication performance and to de-orbit post mission.
  - No preferred inclination
- Looking for a low-cost/free ride share
  - NASA Earth science mission
  - NASA Space Technology Program mission
  - KSC LSP offers the CLI Program where NASA covers the launch cost.
- Used Delta-IV H for launch environments

Telescope Mass & Power Summary

Component	#	Unit Mass (kg)	Total Mass (kg)	Unit Peak Power (W)	Unit Avg Power (W)
Camera Package	1	2.5	2.5	4.2	2.75
Mast + Cabling	1	0.44	0.44	0	0
Deformable Mirror	2	0.68	1.36	2.0	0.2
Reference Mirror	2	0.75	1.5	2	0
Cover	1	0.25	0.25	2	0
Subtotal			**6.05**	**12.2**	**2.95**
Contingency		30%	1.815	20%	20%
Total			**7.82**	**14.64**	**4.49**

Data Rates/Volume

- Daily Data Volume
  - Best case: 3600s*9.6kb/s= 34.56Mb
  - Worst case: 17Mb

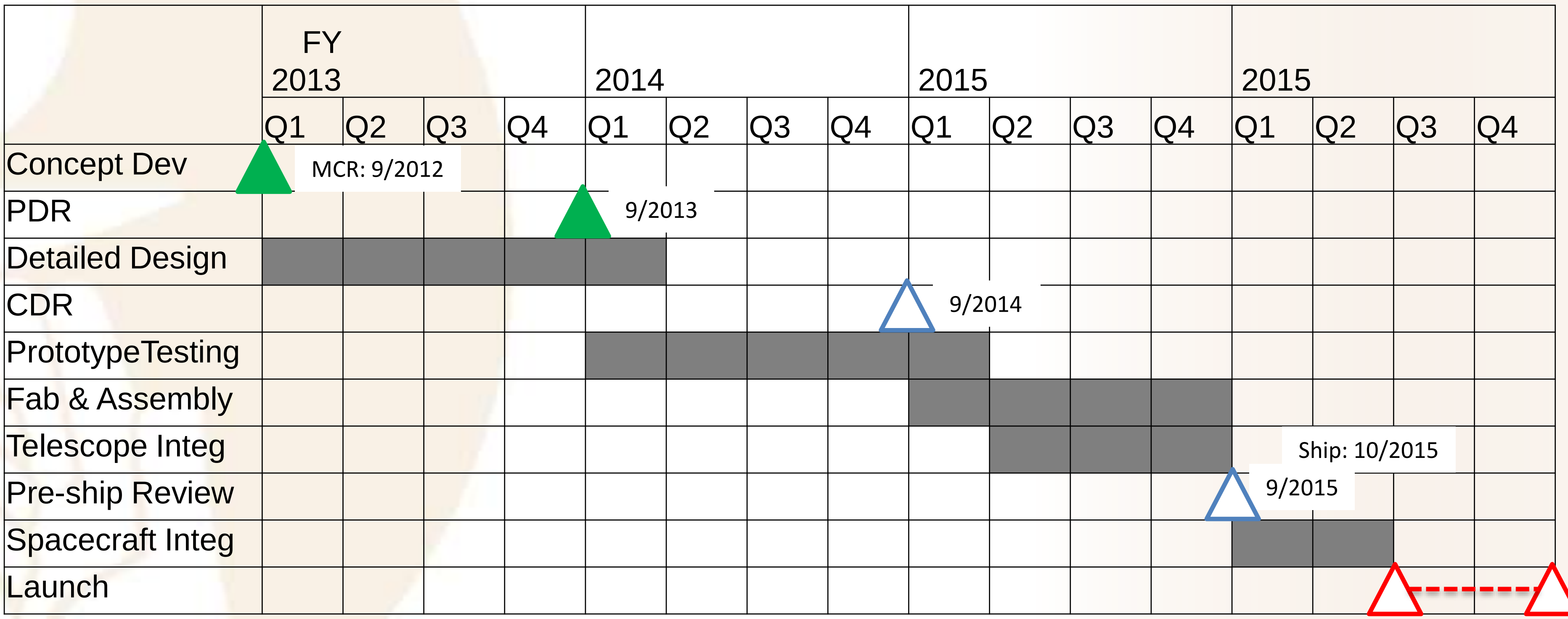
- Telescope data volume (per day-16 orbits)
  - Camera image: 15.7Mp (10 bits/pixel)
  - Windowing data reduction (50x50): 4 * 2500*10 = 100 kb
  - SHWFS: 5Mp (12 bits/pixel)
  - SHWFS data reduction: 4 * 88 Bytes * 12 bits/byte = 2816 bits
  - Telemetry (temps, state): 9600 bits
  - TOTAL: 10 images*100kb + 10*2816 + 9600 = 1.038Mb

  - Well within the available data downlink volume contraints

Plan

- Develop element prototypes and test Projects
  - Will include flight-like controllers, optics and mechanisms.
- Potential list of student Projects
  - Optical breadboard with two mirrors
    - Includes thermal testing of structure
  - Mirror Thermal and acoustics testing
  - Camera breadboard
  - Continue boom development
- Will be refined with the AE105 class instructors (Davis, Freeman, Scharf)

Schedule


FY 2013
2014
2015
2015
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Concept Dev
MCR: 9/2012
PDR
9/2013
Detailed Design
CDR
9/2014
PrototypeTesting
Fab & Assembly
Telescope Integ
Ship: 10/2015
Pre-ship Review
9/2015
Spacecraft Integ
Launch

Discussion

- Did we demonstrate readiness to proceed to a Project CDR?
  - Does the preliminary design appear feasible?
  - What concerns do you have that we need to address as we go to CDR?

- Please provide written input to:

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