Presentation Agenda

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

Kathryn Jackson
Outline

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

Primary Mirror segments (both rigid and deformable)

Camera and wavefront sensing Optics
Optical System Overview

Camera Optics
Collimating lens group
Focusing lens group

Primary Mirror segments (both rigid and deformable)

Camera Optics
Optical System Overview

- Primary Mirror segments (both rigid and deformable)
- Collimating lens group
- Wavefront sensors
- Focusing lens group
- Camera Optics
Mirror Boxes
Baseline Requirements

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

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

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

- Reference (R)
- Compact (C)
- Wide (W)
Requirement: PSF

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

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

Compact/Narrow Mirror location:

- W
- C
- R
- W

FFT Diffraction Encircled Energy
Requirement: PSF

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

Wide Mirror location:

W
C
R
C
R
W

caltech.edu
Requirement: Throughput
Requirement: Throughput

Wavelength design band
Bandpass Filter

![Graph showing Bandpass Filter characteristics]

- Blue line: With coloured glass bandpass filtering
- Orange line: Unfiltered
- Pink line: With coating bandpass filter

Wavelength [nm]

Throughput [%]
WFS Geometry

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

- Spot size:

\[ A_D = 2.44 \frac{\lambda f_i}{D_i} \]

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

22.4µm/5.5µm = 4 x 4 pixels
WFS SNR with a 2nd Magnitude star for a 50ms exposure for a single mirror segment

Signal to noise for given flux
\( F = \text{flux} = 3.4 \times 10^6 \text{ photons/cm}^2 \):
\( N = \text{signal} \)
\( N_\rho = \text{photon noise} \)
\( N_{\text{RON}} = \text{Read out noise} \)
\( T_s = \text{integration time} = 50\text{ms} \)
\( A = \text{segment area} = \pi (4.5\text{cm})^2 \)
\( \eta = \text{throughput} = e^{-/\text{photon}} \)
\( n_{\text{pix}} = \text{number of pixels/spot} = 12 \)
\( n_l = \text{number of lenslets/segment} = 177 \)

\[
\text{SNR} = \frac{S}{N_{\text{RON}} + N_\rho}
\]
\( N_{\text{RON}} = 13e^- \)
\( N_\rho = \sqrt{S} \)
\[
S = F \cdot T_s \cdot \eta \cdot \frac{A}{n_{\text{pix}} n_l}
\]
\[
S = 3.4 \times 10^6 \frac{\nu}{\text{cm}^2 \text{s}} \cdot 50 \times 10^{-3} \text{s} \cdot \eta \cdot \frac{63.6 \text{cm}^2}{12 \times 177}
\]
WFS SNR with a 2nd Magnitude star for a 50ms exposure for a single mirror segment

Signal to noise for given flux
\[ S = \text{flux} = 3.4 \times 10^6 \text{ photons/cm}^2: \]

\[ N = \text{signal} \]
\[ N_\rho = \text{photon noise} \]
\[ N_{\text{RON}} = \text{Read out noise} \]
\[ T_s = \text{integration time} = 50\text{ms} \]
\[ A = \text{segment area} = \pi (4.5\text{cm})^2 \]
\[ \eta = \text{throughput} = e^-/\text{photon} \]
\[ n_{\text{pix}} = \text{number of pixels/spot} = 12 \]
\[ n_l = \text{number of lenslets/segment} = 177 \]

\[ \text{SNR} = \frac{S}{N_{\text{RON}} + N_\rho} \]
\[ N_{\text{RON}} = 13e^- \]
\[ N_\rho = \sqrt{S} \]
\[ S = F \cdot T_s \cdot \eta \cdot \frac{A}{n_{\text{pix}} n_l} \]
\[ S = 3.4 \times 10^6 \frac{\nu}{\text{cm}^2 \text{ s}} \cdot 50 \times 10^{-3} \text{ s} \cdot \eta \cdot \frac{63.6 \text{ cm}^2}{n_{\text{Pix}}} \]

SHWFS
\[ \eta \sim 0.35 \frac{e^-}{\nu} \]
\[ \text{SNR} = 110 / \text{lenslet} \]

Science Cam
\[ \eta \sim 0.035 \frac{e^-}{\nu} \]
\[ \text{SNR} = 116 \]
Optical Systems Status

• Camera Lens assembly
  – Verify lenses are manufactured and aligned correctly

• Rigid Mirrors
  – Integration into testbed with science imager for coarse alignment and SHWFS for fine WFE measurement

• Deformable Mirrors
  – Characterization using high order wavefront sensing
  – Integration into testbed with SHWFS readout
  – Active control in testbed using some flight like electronics.
Camera Lens Assembly Verification

Full Scale Testbed

Primary Mirror Simulator using off the shelf lenses

- L1: D = 50.8mm, f = 113mm
- L2: D = 50.8mm, f = 250mm
- L3: D = 12.7mm, f = 100mm
Simulation and Measurement

Telescope simulator raytrace.
Telescope simulator camera measurement.
Measurement overlaid on raytrace.
Rigid Mirrors

- Matched off-axis hyperboloidal mirrors cored from single parent.
- Material: Zerodur
- Mass: 321g
- Surface quality: $\lambda/10$ PV at 630nm.
Rigid Mirrors: Validation in Testbed

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

Science detector readout with single rigid mirror in place.
Rigid Mirror image with expected Airy Disc
Rigid Mirror in SHWFS

RMS = 353nm
(T/T/F removed)
White Light (Wide Band)

50μm Encircled energy boundary
Deformable Mirrors

Resting Shape: 2.6 μm RMS, 17.5 μm PV

Influence Function: Actuator 1 0.25 μm/V

Caltech
DM In testbed measured by SHWFS
Active Element Control

Segmented primary mirror

Segment Rigid Body Motion control through imaging detector measurement

Deformable Mirror shape control through Shack-Hartmann measurement
Active Element Control

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

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

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

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

Stephen Bongiorno and Kathryn Jackson
Outline

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

- 200 μm slumped D263 Schott glass
- 10 μm glass bead filled Epotek 301 epoxy
- 300 μm curved piezoceramic meniscus (PZT5A from Noliac)

Ground plane
- 41 patterned electrodes
- HV Multiplexer
Requirements

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

• Initial shape
  – Measured 2.6 μm RMS shape error. (<30 μm RMS defocus is correctable)
  – Radius of curvature ( +/-6 inch RoC is correctable)
  – High order error (dimples etc.)
    • Must be measurable with SHWS
    • Minimal impact on encircled energy

• Actuation
  – For perfectly spherical optic we need ~3 μm stroke to achieve hyperboloid optical prescription
  – To test real mirror with shape error, we will test with AAReST camera in telescope testbed
Optical shape measurement

Reverse-Hartmann

Shack-Hartmann
pzt3gs16 - Shape and influence

PZT3GS16 RMS=4.7 μm PV=25.6 μm

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

• Unactuated mirror shape is well within range of actuation
• 59.4 μm P-V at 240V max actuation
• Note: mirror was not centered in RH testbed
pzt3gs16 – Closed-loop

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

RMS=409 nm PV = 3.18 μm
pzt5r1m1 – Shape and Influence

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

Differential Modal Control Error: 4\mu m RMS input

- Coma
- Astigmatism
- Focus

104 nm
DM integration

- pzt3gs16 integrated in mirrorbox
- Awaiting encircled energy test results
Flight mirror fabrication timeline

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

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

Maria Sakovsky
Subsystem Requirements

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

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

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

**Environmental:**
- Survive launch on PSLV with acceptable optical and mechanical performance
- Survive temperatures of -50°C to +50°C
- Function in vacuum environment
Mechanical Overview

- **Materials:**
  - Titanium for optical mounts; Al6061 for all other parts;
  - Mask gears of dissimilar material to prevent cold welding
  - RTV silicone (low outgassing) padding for B/S and SHWS

- **Key accomplishments:**
  - Assembly procedures created and executed
  - Fit check, integration with optics, motor functionality, dummy electronic boards

- **Mass:** 3.1 kg < 4 kg
- **Volume:** 29.8 X 9.6 X 8.0 cm$^3$ < 35.0 X 10.0 X 10.0 cm$^3$
Mechanical Overview

- **Materials:**
  - Titanium for optical mounts; Al6061 for all other parts;
  - Mask gears of dissimilar material to prevent cold welding
  - RTV silicone (low outgassing) padding for B/S and SHWS

- **Key accomplishments:**
  - Assembly procedures created and executed
  - Fit check, integration with optics, motor functionality, dummy electronic boards

- **Mass:** 3.1 kg < 4 kg

- **Volume:** 29.8 X 9.6 X 8.0 cm³ < 35.0 X 10.0 X 10.0 cm³
Mechanical Overview
Optical Performance

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

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

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

![Thermal Testing Diagram](image_url)
Thermal Testing Setup

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

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

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

NASA-STD-7002A

- Qualification 14.1 Grms
- Acceptance 10.0 Grms
- Min. Workman. 6.8 Grms

PLSV (ISRO)

- Acceptance 4.47 Grms
- Qualification 6.7 Grms

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

1. Control, y
2. Control, x
3. Control, z (input)
4. B/S, z
5. Collimator assembly, z
6. Collimator assembly, y
7. Collimator assembly, x
8. SHWS, y
Vibration Testing Results

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

<table>
<thead>
<tr>
<th>Test Criteria</th>
<th>Pass/Fail</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survivability</td>
<td>Pass</td>
<td>No damage in optics or mechanical assembly</td>
</tr>
<tr>
<td>Motor Alignment</td>
<td>Pass</td>
<td>Gears mesh after test cycles</td>
</tr>
<tr>
<td>Science Camera Performance</td>
<td>Pass</td>
<td>Slight shift in spot location; no change in shape/size</td>
</tr>
<tr>
<td>SHWS Performance</td>
<td>Pass</td>
<td>Slight shift in spot location; No spots obscured; negligible change in Zernike coefficients (17 nm max defocus)</td>
</tr>
</tbody>
</table>
Conclusion and Remaining Tests

- Camera meets all requirements
  - Mechanical, functional requirements met
  - Optical performance as expected
  - Environmental testing done to show survivability and functionality

- Remaining work:
  - Swap out B/S and lenses for flight optics
  - Vibration testing to check electronics survivability
  - Fabrication of external interfaces
  - Verification of power requirement (currently met by operating in various modes)
Backup
Ch 1 RV Transfer Function

Channel 1 RV Transfer Function Overlays

Transfer Function [V/g²/Hz²] vs Frequency [Hz]

Pre-6dB: Blue
Pre-3dB: Red
Pre-3dB: Purple
Pre-0dB: Orange
Pre-0dB: Green
Post-0dB: Blue

caltech.edu
Ch 2 RV Transfer Function

Channel 2 RV Transfer Function Overlays

- pre-6dB
- pre-3dB
- pre-3dB
- pre-0dB
- pre-0dB
- post-0dB

Transfer Function [s^2/Hz]

Frequency [Hz]

caltech.edu
Ch 3 RV Transfer Function

Channel 3 RV Transfer Function Overlays

- pre-6dB
- pre-3dB
- post-3dB
- pre-0dB
- post-0dB
- post-3dB

Transfer Function [sqrt((g²)/(Hz²))]

Frequency [Hz]
Ch 4 RV Transfer Function

Channel 4 RV Transfer Function Overlays

Frequency [Hz]

Transfer Function [sqrt(g^2/Hz)]
Channel 6 RV Transfer Function Overlays

Transfer Function [sqrt(g^2/(Hz))]

Frequency [Hz]
Ch 7 RV Transfer Function

Channel 7 RV Transfer Function Overlays

Transfer Function [sqrt(g^2/Hz)(g^2/Hz)]

Frequency [Hz]

pre-6dB
pre-3dB
pre-3dB_P
pre-0dB
pre-0dB_P
post-0dB_P

caltech.edu
Ch 8 RV Transfer Function
Ch 1 RV Test Results (0dB Run)

Channel 1 Acceleration Time History (0dB Run), Max Accel Amplitude = 24.25g

Channel 1 Power Spectral Density for Windowed Portion Only (0dB Run)
GRMS = 4.36

Control (GRMS = 6.85)
Specification (GRMS=6.71)
Tolerance (+/- 3.0 dB)
Ch 2 RV Test Results (0dB Run)

Channel 2 Acceleration Time History (0dB Run), Max Accel Amplitude = 27.36g

Channel 2 Power Spectral Density for Windowed Portion Only (0dB Run)
GRMS = 4.18

Specifications:
- Control (GRMS = 6.85)
- Specification (GRMS = 6.71)
- Tolerance (+/- 3.0 dB)
Ch 3 RV Test Results (0dB Run)

Channel 3 Acceleration Time History (0dB Run), Max Accel Amplitude = 35.43g

Channel 3 (CONTROL) Power Spectral Density for Windowed Portion Only (0dB Run)
GRMS = 6.85
Ch 4 RV Test Results (0dB Run)

Channel 4 Acceleration Time History (0dB Run), Max Accel Amplitude = 58.99g

Channel 4 Power Spectral Density for Windowed Portion Only (0dB Run)
GRMS = 11.59

- Ch 4 Response
- Control (GRMS = 6.85)
- Specification (GRMS=6.71)
- Tolerance (+/- 3.0 dB)
Ch 5 RV Test Results (0dB Run)

Channel 5 Acceleration Time History (0dB Run), Max Accel Amplitude = 92.50g

Channel 5 Power Spectral Density for Windowed Portion Only (0dB Run)
GRMS = 17.00

Control (GRMS = 6.85)
Specification (GRMS=6.71)
Tolerance (+/- 3.0 dB)
Ch 6 RV Test Results (0dB Run)

Channel 6 Acceleration Time History (0dB Run), Max Accel Amplitude = 67.40g

Channel 6 Power Spectral Density for Windowed Portion Only (0dB Run)
GRMS = 13.31

GRMS = 6.85
Specification (GRMS=6.71)
Tolerance (+/- 3.0 dB)
Ch 7 RV Test Results (0dB Run)

Channel 7 Acceleration Time History (0dB Run), Max Accel Amplitude = 88.64g

Channel 7 Power Spectral Density for Windowed Portion Only (0dB Run)
GRMS = 14.98
Ch 8 RV Test Results (0dB Run)

Channel 8 Acceleration Time History (0dB Run), Max Accel Amplitude = 121.57g

Channel 8 Power Spectral Density for Windowed Portion Only (0dB Run)
GRMS = 30.10

Control (GRMS = 6.85)
Specification (GRMS=6.71)
Tolerance (+/- 3.0 dB)
Presentation Agenda

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

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

Requirements Overview

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

Mirrors & Mounts
Picomotors
Launch Restraint System
Electronics
Frame
Outline

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

Assembly
• Fully assembled mirror boxes from CAD models
• Assembly procedures

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

Integration
• Integration of rigid mirror box on optical testbed
• Optical alignment
Rigid Mirror Box Vibration Tests

**Test Setup**

- Accelerometers
- Dummy Mirror Mass
- Shaking Directions

**Test Pass/Fail Evaluation Criteria**

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Pass</th>
<th>Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequencies peaks shift</td>
<td>&lt;5%</td>
<td>&gt;5%</td>
</tr>
<tr>
<td>Springs location</td>
<td>not-shifted</td>
<td>Shifted</td>
</tr>
<tr>
<td>Picomotors</td>
<td>operational</td>
<td>not-operational</td>
</tr>
<tr>
<td>Screws</td>
<td>tight</td>
<td>Loose</td>
</tr>
<tr>
<td>Vectran cable</td>
<td>not-shifted</td>
<td>shifted</td>
</tr>
</tbody>
</table>
Rigid Mirror Box Vibration Tests

Results

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

Channel 7 RV Transfer Function Overlays

Channel 7 Acceleration Time History (0dB Run), Max Accel Amplitude = 123.99g, 131.8 N
Bond Strength Tests

Highest Peak Measured from Vibe Tests: 131.8 N per pad

<table>
<thead>
<tr>
<th>Documented Technical Data Sheet</th>
<th>Tensile Lap Shear Strength</th>
<th>Tensile Bond Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test Setup</td>
<td>Tensile Failure Load</td>
</tr>
<tr>
<td>Test #1</td>
<td>no primer - no surface grinding - no wait after surface cleaning - application through hole (0.254mm thickness) - room temperature cure</td>
<td>88.8 N</td>
</tr>
<tr>
<td>Test #2</td>
<td>no primer - 180 grit surface grinding - 20 min wait after surface cleaning - application by hand (thicker) - 1 hour at 66 °C cure</td>
<td>486.6 N</td>
</tr>
<tr>
<td>Test #3</td>
<td>primer EA 9203 - 240 grit surface grinding - 20 min wait after surface cleaning - application by hand (thicker) - 1 hour at 66 °C cure</td>
<td>721.1 N</td>
</tr>
<tr>
<td>Test #4</td>
<td>primer EA 9203 - 240 grit surface grinding - 20 min wait after surface cleaning - application by hand (thicker) - 1 hour at 66 °C cure</td>
<td>329.2 N</td>
</tr>
<tr>
<td>Test #5</td>
<td>primer EA 9203 - 240 grit surface grinding - 20 min wait after surface cleaning - application by hand (thicker) - 1 hour at 66 °C cure</td>
<td>511.3 N</td>
</tr>
<tr>
<td>Test #6</td>
<td>primer EA 9203 - 240 grit surface grinding - 20 min wait after surface cleaning - application through hole (0.5mm thickness) - 1 hour at 66 °C cure</td>
<td>589.6 N</td>
</tr>
<tr>
<td>Test #7</td>
<td>primer EA 9203 - 240 grit surface grinding - 20 min wait after surface cleaning - application through hole (0.5mm thickness) - 1 hour at 66 °C cure</td>
<td>518.1 N</td>
</tr>
<tr>
<td>Test #8</td>
<td>primer EA 9203 - 240 grit surface grinding - 20 min wait after surface cleaning - application through hole (0.5mm thickness) - 1 hour at 66 °C cure</td>
<td>649.3 N</td>
</tr>
</tbody>
</table>
Deformable Mirror Box Vibe Tests

Test Setup

Accelerometers

Flat Deformable Mirror (PZT + Glass)

Test Pass/Fail Evaluation Criteria

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Pass</th>
<th>Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequencies peaks shift</td>
<td>&lt;5%</td>
<td>&gt;5%</td>
</tr>
<tr>
<td>Springs location</td>
<td>not-shifted</td>
<td>shifted</td>
</tr>
<tr>
<td>Picomotors</td>
<td>operational</td>
<td>not-operational</td>
</tr>
<tr>
<td>Screws</td>
<td>tight</td>
<td>loose</td>
</tr>
<tr>
<td>Vectran cable</td>
<td>not-shifted</td>
<td>shifted</td>
</tr>
<tr>
<td>Deformable Mirror</td>
<td>not-broken</td>
<td>broken</td>
</tr>
</tbody>
</table>

9 January 2017

AAReST Payload CDR
Deformable Mirror Box Vibe Tests

Channel 7 RV Transfer Function Overlays

- pre-12dB
- pre-6dB
- pre-3dB
- pre0dB

Visible Cracks on Mirror surface at -3dB

9 January 2017 AAReST Payload CDR 91
Deformable Mirror Mounts

- Ball bearing held with epoxy
- Mirror plate
- Silicone rubber
- 10 x Mirror Posts
- Spherical Magnets
- Magnet support pillar

Cross-section of mirror mounts in launch restraint configuration
Mirror Failure Analysis

Two sides of the mirror to consider

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

Equilibrium

$$F_p = \frac{-10 f_{post} + m x_{max} + 3(f_{magnet} + f_{post})}{3} = 12.401 N$$
PZT Failure Analysis

Hertzian contact stress theory

- Contact between a sphere and a half-space

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

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

\[ E^* = 49.72 \text{ GPa} \]
\[ p_0 = 1.0152 \text{ GPa} \]

PZT Compressive Strength
\[ \sigma_{\text{upZT}} = 0.81458 \text{ GPa} \]
# New Mirror Mounts Design

<table>
<thead>
<tr>
<th>Old Design</th>
<th>New Design</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Old Design Diagram" /></td>
<td><img src="image2.png" alt="New Design Diagram" /></td>
</tr>
<tr>
<td><strong>ball bearing</strong></td>
<td>Custom ball bearings</td>
</tr>
<tr>
<td><strong>deformable mirror</strong></td>
<td>deformable mirror</td>
</tr>
<tr>
<td><strong>spherical magnet</strong></td>
<td>cylindrical magnet</td>
</tr>
</tbody>
</table>

## Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Old Design</th>
<th>New Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spheres radius: $R_{\text{sphere}}$</td>
<td>$2.38,\text{mm}$</td>
<td>$R_{\text{new}} = 7.65,\text{mm}$</td>
</tr>
<tr>
<td>Bearings thickness: $t_{\text{total}}$</td>
<td>$2,\text{mm}$</td>
<td></td>
</tr>
<tr>
<td>Magnet pull force (including mirror thickness): $f_{\text{magnet}}$</td>
<td>$3.11,\text{N}$</td>
<td>$f_{\text{new}} = 4.67,\text{N}$</td>
</tr>
<tr>
<td>Contact pressure (based on NASA-qualification loads [-6dB]): $p_0$</td>
<td>$1.02,\text{GPa}$</td>
<td>$p_{0\text{new}} = 0.407,\text{GPa}$</td>
</tr>
<tr>
<td>Contact area (from Hertzian theory): $a$</td>
<td>$76.2,\mu\text{m}$</td>
<td>$98.4,\mu\text{m}$</td>
</tr>
</tbody>
</table>

-caltech.edu 9 January 2017  AAReST Payload CDR  95
Separation Device Tests

Tests

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

<table>
<thead>
<tr>
<th>Current [A]</th>
<th>Cutting Time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 2.16</td>
<td>No Cut</td>
</tr>
<tr>
<td>2.20</td>
<td>27.9</td>
</tr>
<tr>
<td>2.25</td>
<td>25.0</td>
</tr>
<tr>
<td>2.35</td>
<td>10.4</td>
</tr>
<tr>
<td>2.40</td>
<td>10.0</td>
</tr>
<tr>
<td>2.45</td>
<td>8.5</td>
</tr>
<tr>
<td><strong>2.50</strong></td>
<td><strong>8.0</strong></td>
</tr>
<tr>
<td>2.60</td>
<td>6.0</td>
</tr>
<tr>
<td>2.70</td>
<td>4.0</td>
</tr>
</tbody>
</table>

vectran cable
vectran epoxied into vented screw
mirror plate
clamped end
rigid mirror
Picomotors Position Control

**Encoders** help estimate mirror position within an interval

Encoder interval: $41 \mu m$
Encoder Shaft

• Established manufacture procedure to create dimension-stable encoder shafts
  – Thermally deform and bond encoder to cylindrical shaft
  – Variation of shaft outer diameter within 25 $\mu m$
  – Encoder strip interval 41 $\mu m \pm 0.5 $ $\mu m$ (post bonding)
  – Thermally loaded to $-50^\circ C$

• Created statistical calibration – actuation algorithm for picomotor position control
  – Picomotor axial precision within 221 $nm$

• Tested open loop position control with algorithm
## Systems Readiness Level

<table>
<thead>
<tr>
<th>Rigid Mirror Box</th>
<th>Deformable Mirror Box</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Completed</strong></td>
<td><strong>Completed</strong></td>
</tr>
<tr>
<td>• Assembly procedure</td>
<td>• Assembly procedure</td>
</tr>
<tr>
<td>• Successful vibration tests of box structure in all shaking directions</td>
<td>• Preliminary vibration tests (successful up to -6dB NASA standard)</td>
</tr>
<tr>
<td>• Mirror bonding procedure</td>
<td>• New mirror mounts design</td>
</tr>
<tr>
<td>• Successful bonding tests</td>
<td>Future Work</td>
</tr>
<tr>
<td>• Integration and mirror alignment on optical testbed</td>
<td>• Vibration tests with new mounts, spherical DM, and flight electronics (using PSLV standard)</td>
</tr>
<tr>
<td></td>
<td>• Integration on optical testbed</td>
</tr>
<tr>
<td></td>
<td>• Separation device tests with flight electronics, in vacuum</td>
</tr>
</tbody>
</table>

**Future Work**

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

**GLASS** free body diagram

**Equilibrium of Forces**

\[ 3F_G = 10f_{post} + mx_{\text{MAX}} + 3(f_{\text{magnet}} + f_{\text{post}}) \]

- \( F_G \) = contact force ball-bearing (assume equal at each mount)
- \( f_{\text{post}} \) = force from mirror posts (10)
- \( mx_{\text{MAX}} \) = vibrating mirror
- \( f_{\text{magnet}} \) = magnet pull force
Glass Failure Analysis

\[ f_{post} = \frac{85N}{A_{Instron}} A_{post} = 0.306N \]

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

\[ m_{x_{\text{max}}} = 45g \times 61.54g' = 27.2N \]
- Peak acceleration on mirror plate

\[ f_{\text{magnet}} = \text{from datasheet} \ 4.048N \]
- Highest measurement

Equilibrium of Forces

\[ F_G = \frac{10f_{post} + m_{x_{\text{MAX}}} + 3(f_{\text{magnet}} + f_{post})}{3} = 14.441N \]
Glass Failure Analysis

Hertzian contact stress

• Contact between a sphere and a half-space

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

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

$$a = \sqrt{Rd}$$

The applied force $F$ is related to the displacement $d$ by\textsuperscript{[16]}

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

where

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

and $E_1, E_2$ are the elastic moduli and $\nu_1, \nu_2$ the Poisson’s ratios associated with each body.

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

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

where $p_0$ is the maximum contact pressure given by

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

Hertzian contact stress
- Contact between a sphere and a half-space

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

\[ E^* = 50.65 \text{ GPa} \]
\[ p_0 = 1.0813 \text{ GPa} \]

\[ p_0 = 2.758 \text{ GPa} \]

Borosilicate Glass
Compressive Strength = 2GPa
Vibration Loads

RV test levels

- NASA - minimum workmanship
  - 6.8gRMS
- NASA - acceptance
  - 10.0gRMS
- NASA - qualification
  - 14.1gRMS
- PSLV - acceptance
  - 4.47gRMS
- PSLV - qualification
  - 6.7gRMS

Frequency [Hz]
11. How is the pull force of each magnet determined?

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

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

Needs

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

Ashish Goel
January 4th, 2017
Overview

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

Multiplexer Board

41 optoisolator switches and multiplexer for routing electrode and bias voltages

HV Board

Picomotor Drivers x3
Picomotor Power (150 V)
Mirror Variable Bias (175 V)
Mirror Variable Electrode Supply (350 V)

Microcontroller Board

Voltage Regulators
Microcontroller
XBee
Separation Device
Current Limiters

Picomotor Encoders
MirrorSat/CoreSat
Thermopiles

Caltech.edu
<table>
<thead>
<tr>
<th>Board</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirror Electronics</td>
<td></td>
</tr>
<tr>
<td>Multiplexer board</td>
<td>Flight boards ready and tested</td>
</tr>
<tr>
<td>HV board</td>
<td>V1.0 functional, V2.0 currently under testing</td>
</tr>
<tr>
<td>Microcontroller board</td>
<td>V1.0 functional, V2.0 currently under testing</td>
</tr>
<tr>
<td>Camera Electronics</td>
<td></td>
</tr>
<tr>
<td>Motherboard</td>
<td>Debugging issues in V1.0</td>
</tr>
<tr>
<td>Shack-Hartmann board</td>
<td>Yet to be fabricated</td>
</tr>
</tbody>
</table>
Multiplexer Board
Distributes HV to mirror electrodes through 41 optoisolator switches

Optoisolator switch

FFC connector for electrode routing layer on the mirror

Multiplexer
Microcontroller Board

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

- Current Sensor
- Separation Device
- Temp. Sensor
- Current limiting switch
- Thermopile connector
- Voltage regulator
- Encoder connector
- MirrorSat/CoreSat Interface
- Current source
- Programming header
- Microcontroller
- XBee

Caltech
Power Distribution

- Voltage Regulators
- Current Limiting Switch x3
- Control Switch
- Separation Device Power

MCU Board

- 2.8V
- 3.3V
- 5V
- 12V

Fixed 100V Supply

Variable HV Supply

Fixed 150V Supply

HV Board
Power Control & Monitoring

MCU Board

1. ADC
2. MCU Board
3. Current Switch 1

HV Board

1. Fixed 100V Supply
2. Variable HV Supply
3. Fixed 150V Supply

PWR IN

EN
## Connectors and Cabling

<table>
<thead>
<tr>
<th>End 1 Connection</th>
<th>End 2 Connection</th>
<th>End 1 Connector</th>
<th>End 2 connector</th>
<th># Wires</th>
<th>Qty</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV board</td>
<td>Picomotor</td>
<td>DF13</td>
<td>Patch cable</td>
<td>2</td>
<td>3</td>
<td><img src="picomotor_patch_cable.png" alt="Image" /></td>
</tr>
<tr>
<td>μC board</td>
<td>Separation device</td>
<td>JST rectangular</td>
<td>Soldering or Brazing</td>
<td>2</td>
<td>1</td>
<td><img src="separation_device.png" alt="Image" /></td>
</tr>
<tr>
<td>μC board</td>
<td>Encoder sensor</td>
<td>DF13</td>
<td>Direct solder</td>
<td>4</td>
<td>3</td>
<td><img src="encoder_sensor.png" alt="Image" /></td>
</tr>
<tr>
<td>μC board</td>
<td>Thermopile</td>
<td>DF13</td>
<td>Direct solder</td>
<td>4</td>
<td>3</td>
<td><img src="thermopile.png" alt="Image" /></td>
</tr>
<tr>
<td>μC board</td>
<td>Mirrorsat</td>
<td>Harwin M80</td>
<td>TBD</td>
<td>4</td>
<td>1</td>
<td><img src="mirrorsat.png" alt="Image" /></td>
</tr>
<tr>
<td>μC board</td>
<td>Limit Switch</td>
<td>DF13</td>
<td>Direct Solder</td>
<td>2</td>
<td>1</td>
<td><img src="limit_switch.png" alt="Image" /></td>
</tr>
<tr>
<td>μC board</td>
<td>Desktop computer</td>
<td>3 x 2 header</td>
<td>N/A</td>
<td>6</td>
<td>1</td>
<td><img src="desktop_computer.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Custom cabling using PTFE wires through DigiKey

caltech.edu
Motherboard - Layout

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

Top side
Bottom side
Camera Motherboard
Based on Atmel Cortex A5 ARM processor development board
Components:
- M80 to communicate with CoreSat
- 2 Hirose Plugs to receive SHWS signals
- 1 Hirose Receptacle for Baumer camera
- 21 pin MDM connector for mask motor, contact detectors, 3 temperature sensors
- 4 LVDS switches
- Mask motor driver circuit
## Connectors and Cabling - Camera

<table>
<thead>
<tr>
<th>End 1 Connection</th>
<th>End 2 Connection</th>
<th>End 1 Connector</th>
<th>End 2 connector</th>
<th># Wires</th>
<th>Qty</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motherboard</td>
<td>Science Camera</td>
<td>Locking USB</td>
<td>Patch cable</td>
<td>4</td>
<td>1</td>
<td><img src="image1.jpg" alt="Image" /></td>
</tr>
<tr>
<td>Motherboard</td>
<td>Boom Inspection Camera</td>
<td>Locking USB</td>
<td>Patch cable</td>
<td>4</td>
<td>1</td>
<td><img src="image2.jpg" alt="Image" /></td>
</tr>
<tr>
<td>Motherboard</td>
<td>Baumer Camera</td>
<td>GigE</td>
<td>GigE</td>
<td>1</td>
<td>1</td>
<td><img src="image3.jpg" alt="Image" /></td>
</tr>
<tr>
<td>Motherboard</td>
<td>Baumer Camera</td>
<td>Direct Solder</td>
<td>JST 03</td>
<td>2</td>
<td>1</td>
<td><img src="image4.jpg" alt="Image" /></td>
</tr>
<tr>
<td>Shack Hartmann Board</td>
<td>Temp. sensors, mask motor, contact detectors</td>
<td>MDM</td>
<td>Direct Solder</td>
<td>20</td>
<td>1</td>
<td><img src="image5.jpg" alt="Image" /></td>
</tr>
<tr>
<td>Shack Hartmann Board</td>
<td>CoreSat</td>
<td>Harwin M80</td>
<td>Harwin M80</td>
<td>4</td>
<td>1</td>
<td><img src="image6.jpg" alt="Image" /></td>
</tr>
<tr>
<td>Shack Hartmann Board</td>
<td>Shack Hartmann Sensor</td>
<td>Hirose FX12</td>
<td>Hirose FX12</td>
<td>1 (Flex)</td>
<td>2</td>
<td><img src="image7.jpg" alt="Image" /></td>
</tr>
<tr>
<td>Shack Hartmann Board</td>
<td>Baumer Camera</td>
<td>Hirose FX12</td>
<td>Hirose FX12</td>
<td>1 (Flex)</td>
<td>1</td>
<td><img src="image8.jpg" alt="Image" /></td>
</tr>
</tbody>
</table>
RMB and DMB Interface

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

<table>
<thead>
<tr>
<th>Mode</th>
<th>Power Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activate release mechanism</td>
<td>0.7 A / 3.5 W</td>
</tr>
<tr>
<td>Picomotor actuation</td>
<td>0.44 A / 2.2 W</td>
</tr>
<tr>
<td>Mirror Actuation</td>
<td>0.44 A / 2.2 W</td>
</tr>
</tbody>
</table>
Questions?
Backup Slide
PCB Layout for Shack Hartmann
Motherboard Block Diagram

- Baumer camera
- Boom Inspection camera
- Pupil Mask Motor Driver
- Imaging camera
- Contact detectors
- Temperature sensors
- Camera CPU
- Spacecraft
- XBee Transceiver

Connections:
- GigE: Baumer camera to Camera CPU
- GPIO x1: Boom Inspection camera to Camera CPU
- USB 2.0: Baumer camera, Boom Inspection camera, Spacecraft to Camera CPU
- UART: Camera CPU to Spacecraft, XBee Transceiver
- GPIO x4: Pupil Mask Motor Driver to Camera CPU
- USB 2.0: Imaging camera to Camera CPU
- I2C: Temperature sensors to Camera CPU
Camera Boards Stackup

OPTICS

12 lines of I2C to 3 temperature sensors
8 Lines to Mask Motor & Contact detectors

Baumer Flex cable from SHWS 1
Baumer Flex cable from SHWS 2

USB from Imaging & Boom inspection camera

SHWS BOARD

Baumer Flex Cable

MOTHERBOARD

12 V

Support BOARD

XBEE

BAUMER CAMERA

Power (12V)

GigE

Chassis

131
Presentation Agenda

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

Thibaud Talon
Yuchen Wei
Ashish Goel
Outline

• Requirements
• Mirror box
  – Software architecture
  – Driver update
• Camera
  – Software architecture
  – Driver update
• Telescope startup procedure
• Error handling
• Future work
Requirements of AAReST OBSW

• Mirror software
  – Communicate with camera through XBee and with MirrorSat through UART as backup
  – Automated failure detection and safe mode reset
  – Actuate picomotors and electrodes

• Camera software
  – Communicate with CoreSat through UART (ssh protocol)
  – Communicate with 4 mirrors through XBee
  – Automated failure detection and safe mode reset
  – Take images and analyze them

Both software run in non hard real time mode
Mirror Box Software
Architecture

1. Execute action function
2. Send feedback
3. Report in Register file

Register file

Data parsing
1. Save data
2. Error check
3. Parsing

Update Scheduler List

Execute Schedule

Mirror Scheduler

Command from camera
0x05 0x01 0x01 0x0000064 0x01

Loaded by boot loader from external EEPROM

Data parsing
1. Save data
2. Error check
3. Parsing

Update Scheduler List

Execute Schedule
1. Execute action function
2. Send feedback
3. Report in Register file

Register file

Algorithm
Position a picomotor
Actuate an electrode
Health keeping

Driver
Picomotor driver
HV driver
Multiplexer driver
Temperature driver

Interface
SPI Interface
I2C Interface
UART Interface
ADC Interface

Caltech.edu
Mirror Box Scheduler

High priority tasks:
- Health keeping
- Temp sensor check
- Payload voltage/current check

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

• Picomotor controller
  – Open loop actuation tested
  – Feedback algorithm to position each picomotor with ~50nm precision (from simulations): to be tested

• Electrode controller
  – Apply variable HV to each electrode: to be tested

• XBee
  – Independent communication established with Camera

• Temperature sensor
  – Need to ensure reliability of measurements
Mirror Box Software Test

• Bootloader
  – Loads code from an external EEPROM during each boot up
  – Starts code if no issue, otherwise allow camera to upload a new code to the Mirror via Xbee/MirrorSat
  – Tested on flight board

• Scheduler
  – Tested on development board with simple tasks (data transfer through UART)
• Each layer creates independent processes; monitored by telescope "scheduler", terminal itself at end of execution
• Each process owns a dedicated log
• Each layer accessible through CoreSat – camera interface
Camera Driver Update

• Science Camera
  – Connection, taking images and check proper functioning
  – Tested on flight CPU

• SHWFS
  – Connection, taking images and check proper functioning
  – Need to be tested on flight CPU
  – Need to include switching of image detector

• XBee
  – Connection to device and comms to 4 remote mirrors
  – Need to check proper functioning in flight

• Temperature sensors
  – Need to ensure reliability of measurements
Camera Software Test

• Google test
  – Framework to test software
  – Tested all image processing functions

• Telescope testbed GUI
  – Created a GUI to control the testbed and test the code

• Driver test
  – Science camera, SHWS and XBee/Mirror comms tested on the testbed through the GUI
  – Initial tests, in the process of improving the drivers
Cmd flow example: Calibration

- **Cmd handling process**: read command script
- **Call target algorithm** (start calibration process)
- **Compute voltage map**
- **Pipe voltage map to Xbee process**
- **Parse voltage map to atom commands**
- **Scheduler task receives voltage value**

### Diagram Details

- **Command script**: `Calibration` (Task Name: Calibration, UTC 00:00)
- **Voltage map**: `Voltage_map_Time.csv`
- **Atom command file**: `mirrorbox_No_log_Time.csv`
- **Command Handler**
- **Bash script**
- **Voltage map computation**
- **Pipe to Xbee process**
- **Parse to atom commands**
- **Scheduler task**
- **Actuation task**
- **Send feedback**

---

caltech.edu  Jan 2017  AAReST Telescope  143
Cmd flow example: Calibration

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

Telescope Scheduler turns off all processes
Camera and mirror boxes idle state

- Definition of telescope “idle” state:

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

  **Mirror side**
  - Power: MCU board, XBee module and temperature sensors
  - Monitor power supply
  - Send house keeping info of power supply and peripheral sensors to camera
  - Check for incoming command to update scheduler task list
Camera and mirror boxes boot process

- Independent processes
- Processes communication through pipe/files
- Processes monitored by OS
- Run in infinite loop
- Check command periodically
- Task protected by watchdog timer
Error handling strategy

• Definition of camera/mirror safe mode:
  – Turn off all science payloads
  – Microcontroller/Camera CPU monitor temp & voltage
  – Keep camera - mirrobox communications
  – Keep communications with coresat & mirrorsat
  – 4 mirror boxes and camera have independent safemodes

• Automated safe mode trigger of camera/mirror:
  – Camera: system monitor process turns off payloads; command mirror boxes to disable payload; write system log
  – Mirror boxes: error handling task disable payload power supply; feed back to camera; write system log
Mirror error handling strategy

- House keeping task check for current periodically
- Disable voltage automatically / by command

- Automatically shut down HV board power supply
- Re-enable by command

+ 2.8V, 5V, 12V power supply

- Mirror Box CPU

- Separation device
  - Current monitor

- Voltage enabler

- Voltage enabler

- HV Supply
  - Current switch

- Voltage regulator
  - Current monitor

- Mirror sat power supply
  - Automatically shut down HV board power supply
  - Re-enable by command
Camera error handling strategy

- System monitor process check for current & temp periodically
- Disable voltage automatically / by command

- Camera power switch board
Conclusion

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

• Camera side
  – Implementation of camera scheduler layer
  – Finish and test camera drivers on telescope CPU
  – Tailoring of Linux kernel

• Mirror side
  – Test mirror actuation driver
  – Packaging of mirror tasks
  – Test of scheduler on telescope testbed
Presentation Agenda

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

Christophe Leclerc
Subsystem Overview

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

**Main components:**
- Kinematic mounts
- Separation device
- Composite boom
## Boom Subsystem Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length [1]</td>
<td>1163 ± 1 mm</td>
</tr>
<tr>
<td>Maximum admissible lateral offset [2]</td>
<td>± 3 mm</td>
</tr>
<tr>
<td>Maximum admissible angular offset [2]</td>
<td>± 1°</td>
</tr>
<tr>
<td>Maximum lateral tip deflection (dynamic) [3]</td>
<td>± 0.20 mm / s</td>
</tr>
<tr>
<td>Maximum longitudinal tip deflection (dynamic) [3]</td>
<td>± 0.05 mm / image</td>
</tr>
</tbody>
</table>

System Overview

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

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

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

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

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

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

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

**Results expected:**
- ~12% decrease in reaction force over 4 months;
- ~14% decrease in reaction force over 8 months;
- ~16% decrease in reaction force over 1 year.
Vibration Testing Objectives

Survive launch vibration phase
Acceptance level test
(10 gRMS, 30g peak)

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

Accurate position of the camera
Vibration induced displacements of the adjustable components

Separation device functional
Evolution of the Vectran cable tension

System undamaged
Structural integrity and mechanical response
Vibration Testing Results

Thorough visual inspection
No damage was observed

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

Faro arm measurements:
relative displacements
Displacements measured well within requirements

Accelerometers:
Structural integrity
No major frequency shift were observed

Transfer function overlay top collar mount

Transfer function

Frequency (Hz)

Pre-12dB RV White
Pre-6dB RV White
Pre-3dB RV White
Pre-0dB RV White
Post-0dB RV White
Stage 1 Deployment

Objectives:
- Demonstrate reliable and repeatable stage 1 deployment
- Validate the kinematic mount and the separation device
Stage 1 Deployment
Stage 2 Deployment Test

Objectives:

• Ensure a reliable and repeatable stage 2 deployment
• Determine maximum acceleration due to deployment
Stage 2 Deployment
Stage 2 Deployment

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

Objectives:
• Ensure a reliable and repeatable positioning of the camera after aging in the stowed configuration

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

<table>
<thead>
<tr>
<th></th>
<th>Length Change</th>
<th>Lateral Change</th>
<th>Angular Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requirement</td>
<td>± 1mm</td>
<td>± 3mm</td>
<td>± 1º</td>
</tr>
<tr>
<td>Folding</td>
<td>0.1 mm</td>
<td>0.5 mm</td>
<td>0.1º</td>
</tr>
<tr>
<td>Aging</td>
<td>0.1 mm</td>
<td>1.1 mm</td>
<td>0.2º</td>
</tr>
</tbody>
</table>

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

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

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

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