The Vision
**Objective:**

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

1. Mission Overview (15 mins)
   – Telescope overview

2. Spacecraft Design (150 mins)
   < Coffee Break>

3. Telescope Design (150 mins)
   a) Telescope Concept of Operation (Melanie)
   b) Camera (Manan)
   c) Mirrors (John)
   d) Electronics (Yamuna)
   e) Boom (Lee)
   f) Telescope System Modelling (Lee / Marie)
   g) Telescope Breadboard/Test (Marie)

4. Summary & wrap up (15 mins)

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

- NanoSat and MirrorCraft
- Docking system
- Integrated spacecraft & mission ops
- Deformable mirrors
- Telescope system
- Optical focus algorithm
- Boom w/AFRL
- Composite Boom

Launch

Class instructors

Manufacturing facilities

*Planning to have discussions with ISRO*
Project Approach

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

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

- 80% encircled energy
- Rendezvous & docking
- Lifetime

Telescope
- Optical Design

Spacecraft
- Pointing knowledge, control & stability
- Jitter
- Docking port vertical offset
- Reconfiguration
- Lifetime (90 days)
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.
1. **MirrorSat (x2)** – 3U cubesats with deformable mirrors on top with rendezvous and docking capability

2. **CoreSat** – main spacecraft with primary power, communications, primary ACS, docking capability

**Payload**

1. **Mirror assemblies** – 2 active deformable mirrors, 2 fixed glass reference mirrors with tip/tilt positioning

2. **Instrumentation package** – Telescope optics, detectors, wave front sensor, aperture mask

3. **Boom** – 1.2m deployable composite
Operation timeline

Pre-launch & Launch

Deployment

Calibration

Imaging

Reconfiguration

Calibration

Imaging

Extended mission

Desorbit
Deployment

- Launch
- Detach from launcher & Verify orbit
  - Turn on satellite
    - Turn on low voltage
    - Switch from battery to solar power
  - Verify and stabilize satellite
    - Power, Thrusters, Communications
    - Tumble rate, Temperature, Attitude
    - Camera functioning (dark measurement)
- Telescope deployment
  - 1st stage boom deployment
  - 2nd stage boom deployment w/ camera
  - Uncage DM1, DM2, RM1 & RM2
- Adjust and stabilize satellite attitude
- Point spacecraft to first target and begin telescope calibration
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

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

UHF

S-Band ISL

VHF

Univ of Surrey

JPL

Caltech
Information System

CAMERA CONTROLLER
- Store & compute position, size, shape, SNR, EE for each spot => Piston/Tip/Tilt of each segment
- Store & Compute WF slope for each segment
- ⇒ Voltage maps of each DM
- Store data

Science detector images
SH detector images
Camera state variables (mask config, T, status, ...)
Inspection camera images
Boom state variables (T)
Mirror state variables (T, V, config, status, ...)
S/C status (attitude, attitude rate, config, ...)

RM Board (x2)
DM Board (x2)

S/C CPU

Images, telemetry

Commands

Earth
Reconfiguration

1. Power up MirrorCraft1
   Verify thrusters, T, communication and attitude control
2. Undock MC1: free-flyer
   Check MC1 properties
   Move MC1
3. Rotate spacecraft
4. Capture and lock MC1
   Check spacecraft
   Power up MirrorCraft2
   Check MC2 properties
5. Undock MC2: free-flyer
   Move MC2
6. Rotate spacecraft
7. Capture and lock MC2
   Check spacecraft
Accomplishments in the Past Year

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

Melanie Delapierre, Marie Laslandes, Eric Grohn
Telescope control

• **Purpose:** Automatically correct in space for deployment imprecision, manufacture errors and thermal disturbances with active calibration.

• **Degrees of freedom:**
  - 3 Rigid Body Motion actuators per segment (control through imaging detector)
  - 41 piezo-electric actuators per deformable mirror (control through Shack Hartmann)
Concept of operations

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

Step 2: Point telescope to a star.

Step 3: Space Calibration concept

1. **Blind search** to bring spot on detector
   - Using 2 Rigid Body Motion Actuators

2. **Centering** to center the spot on the detector
   - Using 2 Rigid Body Motion Actuators

3. **Focusing** to minimize the spot size on the imaging detector
   - Using 3 Rigid Body Motion Actuators

4. **Shape control** to minimize the wave-front error on the Shack Hartmann
   - Using 41 embedded mirror actuators
# Calibration operations

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

**TIME ~10 min**

- **IF NECESSARY**

- **Start Calibration**
**Blind Search algorithm**

**Aim**: Put the optical image in the image detector.

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

**Detector**: Image detector

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

**Aim:** Center optical image on image detector.

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

**Detector:** Image detector

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

Find $l_1,l_2$ s.t. \( \{ X(l_1,l_2) \} = \{ 0 \} \)

Uses a standard **Newton Method**

\[
\begin{pmatrix}
\Delta X \\
\Delta Y
\end{pmatrix}
= 
\begin{bmatrix}
\frac{\delta X}{\delta l_1} & \frac{\delta X}{\delta l_2} \\
\frac{\delta Y}{\delta l_1} & \frac{\delta Y}{\delta l_2}
\end{bmatrix}
\begin{pmatrix}
\Delta l_1 \\
\Delta l_2
\end{pmatrix}
\]

\=> About 1 min algorithm

Experimental centering
Focusing algorithm

**Aim**: Translate mirror to put its focal plane in the image detector plan.

**Actuators**: three picomotors (to piston without tip and tilt, 1 dof)

**Detector**: Image detector

**Closed loop**: Find the minimum radius $R$ of optical image according to the length of the actuators $l$.

$$\min_l R(l)$$

**Method 1**: Impose small increments $\delta l$ in the direction that decreases $R$ and stop when it changes direction: Long, imprecise

**Method 2**: Experimentally evaluate the convexity of $R(l)$ and implement better minimization algorithms (convex ?...)

Shape control algorithm

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

- Knowing the influences of the $n=41$ actuators of the system, the optimal voltages can be deduced:
  
  - Influence Functions: $A = [a_1, a_2, ..., a_n]$, $a_i \in \mathbb{R}^m, m \approx 176$ (# lens on SHWS)
  
  - Measured WFE slopes: $d \in \mathbb{R}^m$
  
  $\Rightarrow$ Voltages: $\delta v = \min_x \| d - Ax \|_{rms}$ ,
  
  with $-v_l - v_n < x < v_l - v_n$

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

- **Control loop**
  
  - Input: influence matrix $(A)$
    voltage limit $(v_l)$
    loop gain $(\alpha)$
  
  - Output: corrected WF
Conclusion

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

- Shape control algorithm could be needed after each pointing because of different thermal disturbances.
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Please send comments to Dr. Greg Davis
(Gregory.L.Davis@jpl.nasa.gov)
Camera

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

Caltech
Telescope Optical Overview

Ø 0.405 m aperture (narrow), f/D = 2.87

Ø 0.100 m segments, masked to Ø 0.090 m

Ø 0.530 m aperture (wide), f/D = 2.19

Primary Mirror (M1)

M1 focal length: 1.163 m

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

Camera
Camera Requirements

• Functional
  – Image star field using sparse aperture primary mirror (M1)
  – Provide feedback for primary mirror segment calibration
    • Deformable mirror (DM) wavefront errors (WFE)
    • Segment rigid body motions (RBM)
  – Take engineering images of CoreSat during MirrorCraft reconfiguration

• Performance
  – 80% encircled energy (EE) diameter at image plane < 50 µm
  – Full field-of-view (FoV) > 0.3°
  – Signal-to-Noise Ratio (SNR) > 100
  – Optical bandwidth: 465 nm – 615 nm (540 nm center)

• Constraints
  – Mass < 4 kg
  – Volume < 10 × 10 × 35 cm
  – Power < 5 W
Camera Optical Design

Primary Mirror (M1)

DM1

RM1

RM2

DM2

Shack-Hartmann Wavefront Sensor (SHWS) 1

Cube beamsplitter × 2

Pupil mask

Imaging detector

Collimator

Imaging lens

SHWS 2

Prime focus

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

- MLA: EO #64-476
  - 10 × 10 mm, 300 µm pitch
  - 5.1 mm focal length
  - ~177 WF slope samples per segment

- Image sensor: CMOSIS CMV4000
  - CMOS imager
  - 11.26 × 11.26 mm active area
  - 5.5 µm pixel pitch
  - 2048 × 2048 pixels, 4.2 Mp
  - (QE)\text{peak} = 0.57 at 537 nm
SHWS Spilt

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

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

36 mm x 24 mm sensor active area (KAI-16070)

DM2 (wide)

11 mm x 11 mm

DM1 (wide)

11 mm x 11 mm
SHWS Prototype

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

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

[Diagram showing MLA, MLA mount, Tip/tilt/piston positioners × 3, Reference flat WF, Image sensor, SHWS raw output]
• Aptina MT9P031 CMOS sensor
  – 2592 × 1944 pixels, 5 Mp
  – 2.2 µm square pixels oversample the Ø14.2 µm spot from a single primary mirror segment
  – 5.70 × 4.28 mm active area
  – 0.34° FoV (diagonal)
  – (QE)_{peak} = 0.62 at 482 nm

• Prototype: Ximea MU9PM-MBRD camera
Telescope CPU

• Atmel SAMA5D35 ARM Cortex-A5 MPU
  – 536 MHz, 512 Mbyte DRAM
  – Arch-based Linux kernel
    • Leverage existing libraries (OpenCV), drivers (I²C, SPI, UART), file system, etc.
  – Using evaluation board for prototyping; will adapt evaluation board design for flight
Pupil Mask Configuration

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

Selector wheel
Fixed plate
Stepper motor
Spur gear
Hard stop + limit switch

Compact configuration
Wide configuration
Lens Barrel Design

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

Collimator 1 resting on spacer

Assembled Collimator

Radial tab

Steel barrel

Aluminum spacers
Lens Group Testing

Geometric spot size estimated using raytracing $\phi$ 25.8 $\mu$m

Measured spot size $\sim\phi$ 17.6 $\mu$m
Camera Mechanical Design

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

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

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

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

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

<table>
<thead>
<tr>
<th></th>
<th>On-axis</th>
<th>Worst off-axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Narrow</td>
<td>33.4</td>
<td>42.4</td>
</tr>
<tr>
<td>Wide</td>
<td>36.0</td>
<td>44.2</td>
</tr>
</tbody>
</table>

80% EE 

Fraction of encircled energy

80% EE diameter (µm)

DL

Narrow configuration: on-axis
Narrow configuration: off-axis worst case
Wide configuration: on-axis
Wide configuration: off-axis worst case

Spot diameter [µm]
SNR Considerations

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

\[
SNR = \frac{N}{N_{RON} + N_{poisson}}
\]

\[
N_{poisson} = \sqrt{N}
\]

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

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

\[
T_{int} = 50ms
\]

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

\[
n_{lenslets} = 177
\]

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

\[
F = 3.4 \times 10^6 photons/cm^2/s
\]
# Camera Mass Budget

<table>
<thead>
<tr>
<th>Part</th>
<th>Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collimator barrel assembly</td>
<td>750</td>
</tr>
<tr>
<td>Imaging barrel assembly</td>
<td>754</td>
</tr>
<tr>
<td>Metrology plate</td>
<td>683</td>
</tr>
<tr>
<td>Mask mechanism</td>
<td>77</td>
</tr>
<tr>
<td>SHWS</td>
<td>136 × 2</td>
</tr>
<tr>
<td>Front Baffle</td>
<td>26</td>
</tr>
<tr>
<td>Electronics</td>
<td>188</td>
</tr>
<tr>
<td>Radiation shielding</td>
<td>126</td>
</tr>
<tr>
<td>Beamsplitter assembly</td>
<td>71</td>
</tr>
<tr>
<td>Boom inspection camera</td>
<td>53</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3000</strong></td>
</tr>
<tr>
<td>+ Margin (10.0%)</td>
<td><strong>3300</strong></td>
</tr>
</tbody>
</table>

< 4000 g requirement
# Camera Power Budget

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

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

• SHWS detector readout electronics and software
  – Reduce power consumption
  – Challenging to design FPGA for readout

• SHWS alignment and calibration
  – Need to decouple piston from tip/tilt positioners
Camera Future Work

• Mature prototype
  – Metrology plate + lens barrel mounts
  – Pupil mask
  – SHWS
  – B/S mounts
  – Frangibolt interface
  – Integrate electronics and software prototypes

• Test stray light control strategies
  – Build front baffle
  – Select optical black coatings
  – Test mask optical properties
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Deformable Mirrors

John Steeves
Erin Evans, Marie Laslandes
Problem Description

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

• Physical:
  – Mirror diameter: 100 mm
  – Nominal ROC: 2.326 m
  – Total hardware volume: ~1U (10 x 10 x 10 cm)
  – Manufacturing tolerances:
    • 3 μm RMS aspheric figure error

• Actuation:
  – Capable of achieving $\lambda/10$ (50 nm) RMS figure accuracy
    • Accommodate both wide and compact telescope configurations (2.7 μm RMS)
    • Correction of manufactured shape errors (3 μm RMS)
    • Correction of deformations due to thermal imbalance (3μm RMS focus)
  – Stable shape deformation over exposure time (~50 ms)

• Environment:
  – Vibration:
    • Survival of launch loads (Delta IV Heavy test case)
    • Low excitation from S/C during imaging
  – Thermal:
    • Survival: -40 to +80 °C
    • Operational: -20 to +20 °C
Actuation Specifications

- Rigid body actuation (required for launch stowage, initial calibration, reconfiguration)
  - Piston: ± 10 mm
  - Tip/tilt: ± 0.1 rad

- Figure correction
  - Off axis shape generation
  - Manufacturing error correction
  - Thermal imbalance

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

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

<table>
<thead>
<tr>
<th>Zernike</th>
<th>[µm RMS]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focus</td>
<td>±6</td>
</tr>
<tr>
<td>Astigmatism3</td>
<td>±3</td>
</tr>
<tr>
<td>Coma3</td>
<td>±1</td>
</tr>
<tr>
<td>Spherical3</td>
<td>±1</td>
</tr>
<tr>
<td>Trefoil5</td>
<td>±1</td>
</tr>
<tr>
<td>Tetrafoil7</td>
<td>±0.5</td>
</tr>
<tr>
<td>Astigmatism5</td>
<td>±0.5</td>
</tr>
<tr>
<td>Higher order</td>
<td>±0.1</td>
</tr>
</tbody>
</table>
Deformable Mirror Overview

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

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

*Indicates conditions that are ongoing.
Mirror Mounting

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

Mirror box prototype with rigid glass mirror

Baffle
Def. Mirror
Launch Restraint
Board
Picomotor
Multiplexer Board
HV Amplifier Board

Rigid body actuation scheme
Current Mirror Prototype

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

Example influence function measurements
• High correctability for low-order Zernike Modes
• Large actuator strokes before saturation
Flight Qualification

• Material Characterization
  – Piezopolymer material data

• Thermal Analysis & Testing
  – Quantification of survival and operating temperature limits
  – Thermal-vac testing of mirror laminates

• Vibrational Tests
  – Survival of launch loads
  – Mirror vibrations during imaging
P(VDF-TrFE) Material Characterization

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

- **Critical temperatures**
  - \( T_g \): -40°C, glass transition (ill-defined)
  - \( T_c \): +110°C, Curie
  - \( T_m \): >140°C, melting
  - \( T_d \): >400°C, decomposition

- **Very low moisture absorption** (<0.01%)

- **Viscoelasticity**
  - Stiff for a polymer but still viscoelastic
  - Creep master curve to be measured
  - Good news: glass substrate will dominate shape over time and maintain molded shape
Thermal Environment

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

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

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

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

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

Mode 1
$\omega = 69.672$ Hz

Mode 2
$\omega = 72.217$ Hz

Mode 3
$\omega = 72.217$ Hz

Mode 4
$\omega = 208.47$ Hz

Mode 5
$\omega = 267.75$ Hz

3 point mount

Modes 1-3 (73Hz)

Mode 4 (219Hz)
Launch Survival

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

- Mirror
- Microphone
- Amplifier
- Waveform Generator
- Vibrometer
- DAQ/D2A
- Laser
• 125 dB overall sound pressure level (OASPL) achieved
• Signal broken into sections in order to deliver proper SPL across all frequencies
• > 300 \( \mu m \) RMS center deflection measured at 125 dB
  – Good agreement with model predictions (< 10 %)
  – Restraint system required
Restraint System

- Deformable Mirror Package
- Restraint Plate
- Metal Pillar
- Damping Material
- Restraint Peg
- Silicone Rubber
- Silicone Foam
- Styrene
• Lab implementation:
  – Holes drilled through mirror PCB in order to accommodate various restraint configurations
  – Mirror seated against silicone pads atop shoulder bolts
Vibration Suppression

- Mirror response measured at 115dB (low signal distortion)
  - ~75x reduction in RMS response
  - More broad-band response due to constrained configuration
  - Values to be measured at higher SPLs (TBD)
Vibration During Imaging

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

• Design of deformable mirrors complete
  – Fabrication process (almost) finalized
    • Still working on obtaining slumped glass substrates
  – Design of flight package complete
  – Flat prototypes constructed

• Flight qualification of mirrors
  – Extensive material data gathered for piezoelectric polymer
  – Thermal-vac chamber commissioned
    • Thermal balancing of mirror laminates (TBD)
    • Optical performance during thermal cycling (TBD with figured mirrors)
  – Launch survival
    • Data gathered for reduced SPL inputs
    • Restraint system constructed in order to mitigate mirror vibrations
1. Mission Overview (15 mins)
   - Telescope overview
2. Spacecraft Design (150 mins)
   < Coffee Break>
3. Telescope Design (150 mins)
   a) Telescope Concept of Operation (Melanie)
   b) Camera (Manan)
   c) Mirrors (John)
   d) Electronics (Yamuna)
   e) Boom (Lee)
   f) Telescope System Modelling (Lee / Marie)
   g) Telescope Breadboard/Test (Marie)
4. Summary & wrap up (15 mins)

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

Yamuna Phal,
Melanie Delapierre, Eric Grohn
Mirror Electronics - Overview

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

PURCHASED → TESTED
DESIGNED → IMPLEMENTED → TESTED
TO BE RE-DESIGNED
DESIGNED → IMPLEMENTED → TESTED
Mirror Electronics - Requirements

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

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

  - HV DC output for driving picomotors (*Translation*)
    ▪ 0-110V range for driving 3 modes
    ▪ Required SR – 0.6 V/\(\mu\)s(*transient*)
Lab-prototype - Design Decisions

- **ATMEL MCU**
  - RAD tolerant – used in INSPIRE mission

- **DAC needed**
  - 16-bit DAC for a resolution of 61 mV
  - I²C or SPI – SPI Interface
  - Could be interfaced for bipolar output range

- **Power Amplifier selection - HV board** *(Picomotors)*
  - Gain of X100
  - Output swing of +/-500 V DC as required

- **Power Amplifier selection - HV board** *(Mirror actuators)*
  - 10KHz capacity and swing 0-110 V (SR ~0.6 V/μs)
  - Output current of 120 mA rms max

- **HV DC-DC converter selection**
  - 1 W dissipation each with 1.67 mA input current

- **Temperature sensors + Telemetry channels**
Lab-prototype - Controller board

Summary

- 12 V power supply for board operation (3.3-5 V desired)
- UART interface (RS232) for sending program and feedback (needed)
- I²C/SPI interfaces (needed)
- ANALOG INPUT (present)/ANALOG OUTPUT interfaces (absent)
- On-board switches and other interfaces (not needed)
Lab-prototype - HV board
(Mirror actuators)

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

**Design Summary**

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

*TO BE RE-DESIGNED*
HV board (*Picomotors*) - Open Issues

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

- I²C interfacing with the Controller board
- Provides optical isolation between LV-HV signals
- A single HV line could be used for driving 41 channels
## Mirror Electronics - Power Budget

<table>
<thead>
<tr>
<th>LAB PROTOTYPE (TESTED)</th>
<th>POWER RATING (NO LOAD)</th>
<th>POWER RATING (FULL LOAD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONTROLLER BOARD</td>
<td>0.1 W</td>
<td>2.76 W</td>
</tr>
<tr>
<td>HV BOARD (Mirror actuators)</td>
<td>0.4 W</td>
<td>TBD</td>
</tr>
<tr>
<td>HV BOARD (Picomotors)</td>
<td>0.4 W</td>
<td>TBD</td>
</tr>
<tr>
<td>MUX BOARD</td>
<td>0.1 W</td>
<td>0.8 W</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1 W</td>
<td>TBD</td>
</tr>
</tbody>
</table>
Lab-prototype - Components used

• Controller board
  - MCU - ATMEGA 1284
  - DAC - Maxim MAX542
  - Zigbee
    ▪ XBEE-ZB – XBP24BZ7SIT-004J (63mW RPSMA Router/End Device)
    ▪ Antenna – A24HASM450 (2.4 GHz RPSMA)

• HV board (Mirror actuators)
  ▪ Power Amplifier - Apex PA79
  ▪ HV DC-DC converter - EMCO FS10-CT

• HV board (Picomotors)
  ▪ Power Amplifier - Apex PA78
  ▪ HV DC-DC converter - EMCO FS02-CT

• MUX board
  - PhotoMOS relay - Panasonic AQV258
  - LED driver IC - Maxim MAX6956

• Temperature sensor
  - TI TMP006
Plan Forward

- Designing appropriate driver board for picomotors
- Validate the use of HV board (mirror actuators) and MUX board for in-flight operation
- Design a customized controller board for in-flight operation with a new controller
  - 5 V (3.3 V) power supply
  - UART interface (RS232)
  - I²C/SPI/ANALOG INPUT-OUTPUT interfaces

TO BE DESIGNED
Camera Electronics

Manan Arya,
Melanie Delapierre, Yamuna Phal, Eric Grohn
Camera Electronics - Overview

• Requirements
• Lab-prototype block diagram
• Lab-prototype design
  – Power budget
  – Components used
• Open Issues
• Plan Forward
Camera Electronics - Requirements

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

- **SHWS1 Microlens Array**: EO #64-476
- **SHWS1 Detector**: CMOSIS CMV4000 CMOS
- **SHWS1 Driver**: Xilinx Virtex 4 FPGA (TBC)
- **Boom Inspection Camera**: LinkSprite JPEG Color Camera
- **Motor Driver**: Allegro A4988 (TBC)
- **Telescope CPU**: Atmel SAMA5D35 ARM Cortex-A5
- **Imaging Detector**: Aptina MT9P031 CMOS
- **ZigBee Transceiver**: XBee ZB
- **Collimator**: Light from M1
- **Cube beamsplitter × 2**: SPI + TBD serial
- **Pupil Mask**: Imaging lens
- **Mask Motor**: Faulhaber ADM1220S
- **Limit Switches**: GPIO
- **SPI + TBD serial**: SPI
- **GPIO**: SPI, UART
- **UART**: SPI + TBD serial
- **I²C + power**: UART
- **ZB wireless**: Analog
- **S/C**: I²C + power
- **RMx, DMx**: ZB wireless

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## Camera Power Budget

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

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

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

• SHWS detector readout electronics and software
  - Reduce power consumption
  - Challenging to design FPGA for readout

• SHWS alignment and calibration
  - Need to decouple piston from tip/tilt positioners
Plan forward

- Validate the use of components for in-flight operation
- Design a customized controller board for in-flight operation
- Reduce power consumption by reducing the interfacing electronics on the Atmel SAMA5D35 evaluation board
1. Mission Overview (15 mins)
   - Telescope overview
2. Spacecraft Design (150 mins)
   < Coffee Break>
3. Telescope Design (150 mins)
   a) Telescope Concept of Operation (Melanie)
   b) Camera (Manan)
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   d) Electronics (Yamuna)
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   g) Telescope Breadboard/Test (Marie)
4. Summary & wrap up (15 mins)

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

Lee Wilson,
John Steeves, Erin Evans
Boom Requirements

• Functional
  – Enable 1.16m telescope focal length ✓
  – Compact launch configuration ✓
  – Can self deploy ✓

= Requirement Completed

= Additional testing required

• Performance
  – Boom elongation
    • Static: < 500µm (can handle with rigid body mirror actuators) ✓
    • During imaging: < 50 µm ✓
  – Boom lateral deflection
    • Static: < 2mm (keep image on detector) ?
    • During imaging: < 200 µm/s (avoid image smearing) ✓
  – ACS
    • Boom deployment within ACS control authority ✓
    • Avoid coupling between S/C and ACS system ?
Boom Architecture

• Hollow cylindrical boom wrapped around S/C via folding-tape-spring hinges
  – 4 hinges total
  – Bonded to S/C and Camera

• Two stage unconstrained deployment process

Stage 1

Stage 2

Root
Camera
Package

1.16m
1.35m
Boom Lay-up

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

- Extra 90° layup on outer side of hinge regions
- Dimensions
  - 210 µm total thickness
  - 38 mm diameter
- Cutting pattern
  - “Dog-bone” hinge cutting pattern
  - D = 15mm, L=90mm, SW = 8mm
- Structural optimisation techniques used to develop design

Hinge Characterization

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

Hinge Test
[32x speed]
Hinge Characterization

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

Deployed configuration

Locked configuration

Moment-Angle Relation

Manufacturing Line Defects

Hinge A (shifted line defect)
Hinge B (best boom)
Dynamic Stage 2 Deployment Test

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

Deployed configuration:
- Coresat
- Boom
- Camera

Stowed configuration:
- J-rail (12 ft)
- 2.9 m
- 0.25 m
- 0.68 m
Dynamic Stage 2 Deployment Test
Stage 2 Deployment Test Results

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

Stage 2 deployment lasts 7s
Stage 2 Finite Element Simulation

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

Experiment - First latch at 2s

Simulation - First latch at 2.89s

Shock G’s similar to experiment
Simulated Thermal Profile Summary

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

### Boom nodal temperatures over multiple orbits

<table>
<thead>
<tr>
<th>Case</th>
<th>Axial Deflection</th>
<th>Lateral Deflection</th>
<th>Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot</td>
<td>25 μm</td>
<td>625 μm</td>
<td>0.04°</td>
</tr>
<tr>
<td>Cold</td>
<td>-127 μm</td>
<td>97 μm</td>
<td>0.006°</td>
</tr>
</tbody>
</table>

### Boom CTE

<table>
<thead>
<tr>
<th></th>
<th>Axial</th>
<th>Circum</th>
</tr>
</thead>
<tbody>
<tr>
<td>~ 1.0 ppm/°C</td>
<td>21 ppm/°C</td>
<td></td>
</tr>
</tbody>
</table>

< 500 μm  < 2 mm
Boom Interfaces
CoreSat-Boom Interface

• Boom bonded on to mandrel

• Features
  – Cradles support boom during launch
  – Kinematic mount
    • For boom alignment during assembly
  – Stage 1 separation device

• Camera mount similar but more compact & no separation device
Kinematic Mount

- **Components**
  - 4 ball tipped screws
  - 3 flats
  - 1 cone
  - 3 screws on base plate control rotation about x, y
  - 4\textsuperscript{th} screw controls rotation about z

- **Clamping Method**
  - Two springs hold plates together during alignment
  - Three nuts hold plates together after alignment
Kinematic Mount

- **Components**
  - 4 ball tipped screws
  - 3 flats
  - 1 cone
  - 3 screws on base plate control rotation about x, z
  - 4th screw controls rotation about y

- **Clamping Method**
  - Two springs hold plates together during alignment
  - Three nuts hold plates together after alignment
Separation Device

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

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

• Prototype testing is needed for:
  – Stage 1 burn wire cutting release mechanism
  – Shake test for boom alignment & survivability
    • Will determine if additional cradles / damping material is needed to support boom in launch configuration
    • Confirm dimensional accuracy needed from kinematic mount is attainable

• Redo stage 2 deployment tests with final boom layups
  – Integrate boom cabling into the tests
Future Work

• Utilize cyanate ester resin in boom
  – Improved thermal properties
  – Low outgassing

• Quantify viscoelasticity of boom material

• Monitor damage of hinges due to multiple folding/deployment processes
1. Mission Overview (15 mins)
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Please send comments to Dr. Greg Davis (Gregory.L.Davis@jpl.nasa.gov)
Telescope System Modelling

Lee Wilson, Marie Laslandes
Dynamic Pointing Control

• MATLAB Simulink model of S/C control system was developed
  – Prove pointing requirements can be met with given reaction wheel disturbances
  – Only example control system – Surry with implement actual system
  – Assume optical axis = principle S/C inertia axes

• Requirements
  – Camera jitter from pixel size and exposure time: dθ/dt, dφ/dt < 0.02 °/s
  – Image remains on detector during calibration: θ, φ constant to within 0.1° for 600s
Control Loop

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

- Version 1 unbalanced RW prototype had disturbance amplitude of $F = 11 \, \mu\text{Nm/Hz}^2*\omega^2$
  - Assume here $1.1 \, \mu\text{Nm/Hz}^2$
  - Estimate wheels will operate at $< 650 \, \text{rpm}$ during imaging
- Sensor (ie, MEMS gyro) noise – assume white noise with variance $3.5\times10^{-4} \, \text{rad}^2$
- System meets requirements with these assumptions

**RW Speeds**

**S/C Jitter ($< |0.02| \, ^\circ/\text{s}$)**

**S/C Orientation ($< 0.1\, ^\circ$ for 600s)**
Telescope closed loop modeling

• Objective: validate optical performance and control concept

• Modeling of a 1 segment telescope, on axis observation at 540 nm

• Code V + Matlab + Abaqus for an end to end simulation
  – Inject a set of perturbations into optical model (Monte Carlo)
  – Ray trace: degraded performance
  – Compute correction commands and inject into optical model (5 iterations)
  – Ray trace: corrected performance

• Statistics on 500 Monte Carlo trials give the expected performance of the telescope
Injected errors

- Mirror initial shape error (< 4.5 µm RMS)
  - Off-axis shape generation + manufacturing errors correction
  - Defined by set of Zernike (Z4-66)

- Boom deflections (±0.04° / ±0.6mm)
  - Induce camera translation and rotation

- Thermal effects (±20°C)
  - Mirror curvature depends on temperature
  - Spacing between elements depends on temperature (CTE mismatch)
Correction loops

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

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

Initial error, measured on the Shack Hartmann

Error measured on the Shack Hartmann at each iteration

Spot on imaging detector

Mirror voltages

Spot size (µm)

WFE (µm RMS)
Telescope closed loop results

• Narrow configuration: performance meet requirements
  – Mean wave-front error: 43.5 nm rms \( \sim \lambda/10 \) RMS
  – Mean spot diameter (80% EE): 31.4 \( \mu \)m < 50 \( \mu \)m required
Telescope closed loop results

• Wide configuration: more challenging but acceptable
  – Mean wave-front error: 89.7 nm rms ~ λ/6 RMS
  – Mean spot diameter (80% EE): 69.0 μm slightly above requirement

• Conclusion
  – The system should be able to correct efficiently the expected errors
  – Validate optical design and control scheme
  – Validate chosen hardware
  – Validate requirements on the deformable mirror initial shape error
1. Mission Overview (15 mins)
   – Telescope overview
2. Spacecraft Design (150 mins)
   < Coffee Break>
3. Telescope Design (150 mins)
   a) Telescope Concept of Operation (Melanie)
   b) Camera (Manan)
   c) Mirrors (John)
   d) Electronics (Yamuna)
   e) Boom (Lee)
   f) Telescope System Modelling (Lee / Marie)
   g) Telescope Breadboard/Test (Marie)
4. Summary & wrap up (15 mins)

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

Marie Laslandes, Manan Arya, Eric Grohn
Objective

• Provide a set-up in which the different components of the telescope can be integrated and tested as a whole
  – Verify interfaces
  – Verify optical alignment
  – Verify calibration process

• Breadboard requirements
  – Simulate the interfaces between spacecraft and telescope
    • Mechanical, power supply, communication
  – Simulate the observation of a star
    • Feed the primary mirror segment with a large collimated beam
Optical design

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

**Breadboard elements**

**Telescope elements**

- Mirror Segment, mounted in its mirror box
- Source (currently at 633 nm, should be switched to 540 nm for final test)
- Pellicle Beam Splitter (minimizing aberrations)
- Spacecraft interface plate (representing mechanical interfaces between mirror boxes and spacecraft)
- Camera

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

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

• Measurements on different areas of the mirror

• Qualitative analysis: Fringes look straight everywhere => no obvious shape error

• Quantitative analysis with automatic image processing could be implemented if needed
Breadboard Alignment

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

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

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

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

=> Breadboard alignment is satisfactory for preliminary testing
Telescope Integration & Tests

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

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

- **Procedure**
  - Insert collimating group according to prime focus
  - Insert refocusing group
  - Insert imaging detector
  - Insert cube beam splitter
  - Insert Shack Hartmann

- **Objectives**
  - Minimize wave-front error on Shack Hartmann
  - Minimize spot size on imaging detector

- **Degrees of freedom for each elements**
  - Translation along optical axis
  - Height
  - Tip/Tilt

Source and Pellicle BS (breadboard elements)
Camera on Breadboard

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

• When Shack-Hartmann implemented: measured and simulated wave-front error must be compared
Other segments integration

• Only 2 segments can be tested in the same time (due to flat mirror size)

• Procedure
  – Mount segment on mirror box
  – Mount mirror box on interface plate
  – Set piston/tip/tilt using the imaging detector measurement (blind search, centering and focusing algorithms)
  – Set shape of deformable mirror using the Shack-Hartmann measurement (shape control algorithm)

• Validation: measurement vs breadboard optical modelling
  – Spot measured on imaging detector and wave-front error on Shack-Hartmann
  – Will validate both optical alignment and control functioning
Rigid Body Motion control

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

![Diagram showing the configuration with a laptop, Newport Picomotor Drivers, Picomotors, and an Image Detector (Ximea Camera).]
Rigid Body Motion control

- Hardware will gradually be switched to a flight-like configuration:
RBM control loop - results

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

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

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

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

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4. Summary & wrap up (15 mins)

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Plans for Next Year

John Baker
Plan for next year

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

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