Using Integrated Optomechanical Modeling to Assess Performance of the Transiting Exoplanet Survey Satellite

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System Overview

Objectives

Key Requirements

STOP Modeling Process

Summary of Results
- Thermal
- Structural
- Optical
- STOP

Path Forward
- Composite bench
- Invar camera flexures
- Aluminum lens barrel
- Composite lens hood baffle, flexure mounted to aluminum interface ring
- RTV 566 bonding pads
- Glass optics
- HEO orbit, 13.75 day period
- CONOPS consist of: 325 hr science phase (HASO) + 5 hr non-science phase (LAHO)
  - Exact durations vary slightly over operational life
  - For analysis purposes, this is treated as fully cyclic symmetry (conservative)
- Attitude change during LAHO creates a temperature pulse
  - This is the peak disturbance on the camera system
  - Worst case performance is expected to occur immediately after LAHO
Objectives

- Report predicted system capability vs. requirements
  - PSF drift / PSF spreading
  - $78^\circ / 54^\circ$ observatory attitude
  - Eclipse / Non-eclipse periods
  - Max / Min FPE power dissipation assumptions
  - Hot / Cold-sided thermal property assumptions

- Provide detailed explanations of the results
  - Transient Temperature Gradients
  - Transient Mechanical Deformations
  - Camera Body Steering vs. Refractive Steering
  - Isolated contributions of individual components
<table>
<thead>
<tr>
<th>Title</th>
<th>Requirement</th>
<th>Predicted Performance</th>
<th>Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observation Settling Time</td>
<td>The Instrument shall comply with all observing requirements starting no later than 170 minutes after slewing activity, and continue uninterrupted until the next slewing activity.</td>
<td>5 hrs</td>
<td>-43%</td>
</tr>
<tr>
<td>Distortion-Induced Image Motion</td>
<td>The instrument shall limit distortion-induced motion of each camera boresight with respect to the instrument ensemble-average boresight to &lt; 0.30 arc-sec over any 1 hour period during HASO.</td>
<td>0.16 arc-sec</td>
<td>+88%</td>
</tr>
<tr>
<td>Camera Boresight Deflection</td>
<td>The instrument shall limit distortion-induced motion of each camera boresight with respect to the instrument ensemble-average boresight to &lt; 4.0 arcsec during HASO.</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Systematic Error: Peak Temperature Effects</td>
<td>The instrument shall limit variation in ensquared energy of any camera relative to the camera’s individual boresight to &lt; 700 ppm over any 1 hour period during HASO, for the following apertures and field angles:</td>
<td>145 ppm</td>
<td>+380%</td>
</tr>
<tr>
<td>Field angle (deg)</td>
<td>Aperture Size (microns)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(0,0)</td>
<td>75x75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(0,6)</td>
<td>75x75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(0,11)</td>
<td>75x75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(11,11)</td>
<td>105x105</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Initial budget used to guide design decisions

- Preliminary budget shown
- Full verification performed with integrated STOP analysis
- Additional requirements exist for PSF variation and periodic drift
- Assume similar proportions exist for these, as shown in table

\[ \Delta T_{\text{applied}} = 1 \, ^\circ C / \text{depth} \]

\[ \Delta \phi_{\text{cameras}} = 0.08 \, \text{arcsec} \]
STOP Modeling Process

Thermo-Elastic Distortion Analysis

Surface Distortion
Rigid Body Displacements

Ray Tracing & Optical Analysis

Thermal to Structural Temperature Mapping

Integrated Analysis
Software Environment

Structural Loading

Structural Analysis

dn/dT Profiles

dn/dσ Profiles

Surface Distortion
Rigid Body Displacements
1) Generate all thermo-elastic deformations in the Instrument level FEM and apply as perturbations to 4 separate optical models, including each camera’s rigid body motion.

2) Perform image space LOS analyses quantifying chief ray motions on image planes relative to perturbed image plane origin.

3) Perform PSF analyses characterizing centroid motion relative to the chief ray used in LOS analysis in step 2.

4) Sum motion from steps 2 and 3 to obtain total image space motion.

5) Convert image space motion to angular object space change using static nominal EFL (146mm).

6) Transform angular change to a global reference and assess relative motions between cameras.
Model Validation Process

- Thermal & structural models reviewed / validated
- IA-STOP tool accurately transfers the data from here to Code V
- Extensive low-level checks with Code V
  - Rigid body motions transform from local to global coordinate systems correctly
  - Combination of coincident rigid body motion and deformations of surfaces produce correct net change in lens thicknesses
  - Multi-dimensional interpolation of index of refraction as a function of wavelength, temperature and spatial position is performed correctly
  - Zernike polynomials adequately fit surface deformation shapes
  - Unit decenters / rotations of optics produce expected LOS shifts
- Check optimized design of cold focus shim produces improved performance at cold soak temperature
- Bulk soak temperature case matches with stand-alone Code V predictions
- PSF grid has adequate resolution (no mirroring in PSF transform)
## Additional Model Validation Cases

<table>
<thead>
<tr>
<th>ID #</th>
<th>Case Description</th>
<th>Expected/Desired Result</th>
<th>Actual Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1mm rigid body lateral translation of camera</td>
<td>Zero motion on image plane</td>
<td>✓ Confirmed</td>
</tr>
<tr>
<td>2</td>
<td>0.1mm rigid body lateral translation of camera</td>
<td>Zero motion of PSF centroid</td>
<td>✓ Confirmed</td>
</tr>
<tr>
<td>3</td>
<td>0.1mm rigid body lateral translation camera corner field (12 deg,12 deg)</td>
<td>No change in LOS</td>
<td>✓ Confirmed</td>
</tr>
</tbody>
</table>
| 4a   | 0.1mm lateral translation of stop only                                           | Very small change in chief ray position on image plane | ✓ 0.06 µm (0.09 arcsec)  
✓ Confirmed, due to “blended focus” optical design |
| 4b   | 0.1mm lateral translation of stop only                                           | Small change in PSF centroid wrt chief ray      | ✓ 0.05 mm (0.07 arcsec)                                                     |
| 5    | 0.1mm lateral translation of image plane only                                    | 1mm change in chief ray position on image plane | ✓ Confirmed                                                                 |
| 6    | 0.001 deg rigid body rotation of camera (on-axis field point)                    | 0.001 deg change in LOS                          | ✓ Confirmed                                                                 |
| 7    | 0.001 deg rigid body rotation of camera (on-axis field point)                    | Zero motion of PSF centroid wrt chief ray        | ✓ Confirmed                                                                 |
| 8    | 0.001 deg rigid body rotation of camera corner field (12deg,12deg)              | 0.001 deg change in LOS                          | ✓ Confirmed                                                                 |
Analysis Background

- Thermal Loads
- Transient Temperature Distributions
- Instrument Architecture
- Structural Disturbances
HASO Instrument Temperature Distribution

-130 °C - 130 °C - 80 °C - 30 °C

-95 °C - -95 °C - -80 °C - -80 °C

-90 °C - -100 °C

20 °C
HASO Camera Temperatures

Camera 1
(Average temperatures are shown)

Hood $\Delta T = 17.6^\circ C$

Lenses $\Delta T = 7.0^\circ C$

G-10 ring $\Delta T = 59.9^\circ C$

Barrel $\Delta T = 6.0^\circ C$

Camera 1, Lenses

Camera 1, Lens 1

Top center-to-edge $\Delta T = 2.7^\circ C$

Thru-thickness $\Delta T = 0.5^\circ C @ Ct$
Transient (Average) Lens Temperatures

-77.5 -76.5 -75.5 -74.5 -73.5 -72.5
Temperature (°C)

0 2 4 6 8 10 12 14 16
Time (Days)

Cam 1 Cam 2 Cam 3 Cam 4

HASO LAHO HASO Eclipse

Lens temperature varies by <5°C
Transient Deformation of the Camera Plate
Transient $\Delta T$ of the Mount Posts
Transient Deformation of the Mount Posts
Temperatures of the Barrels at $t = 3$ hrs
Relative Transient $\Delta T$ of the Cameras
Transient $\Delta T$ of the Lens Assembly
Transient Deformation of the Lens Barrel
Transient Deformation of the Lens Assembly
Transient Optical Perturbations

**Transient Temperature Change**

Temperature difference between \( t=3, \ t=4 \) hrs

**Transient Displacements**

Resulting deformation
PSF plots at $t = 3\text{hrs after LAHO}$

Color Scale: (0.9 - 0.001)

(0°, 0°)

(11°, 0°)

(11°, 11°)

Color Scale: (0.2 - 0.0001)
EE (0°, 0°) at t = 3 hrs, t = 5 hrs after LAHO

Centered about the instantaneous centroid

- t = 3.0847 hrs
- t = 4.0847 hrs
- t = 6.0847 hrs

Ensquared Energy Fraction

\[ \text{field point} = (0^\circ, 0^\circ), \ t = 3.0847 \text{ hrs} \]

\[ \text{field point} = (0^\circ, 0^\circ), \ t = 5.0847 \text{ hrs} \]

\[ \text{field point} = (0^\circ, 0^\circ), \ t = 4 \text{ hrs} - t = 3 \text{ hrs} \]

\[ \text{field point} = (0^\circ, 0^\circ), \ t = 6 \text{ hrs} - t = 5 \text{ hrs} \]
EE (11°, 0°) at t = 3 hrs, t = 5 hrs after LAHO

Centered about the instantaneous centroid

- θ field point = (11°,0°), t = 3.0847 hrs
- θ field point = (11°,0°), t = 4.0847 hrs
- θ field point = (11°,0°), t = 5.0847 hrs
- θ field point = (11°,0°), t = 6.0847 hrs

Ensquared Energy Fraction

Half width from centroid centered t-0 (µm)

<table>
<thead>
<tr>
<th>µm</th>
<th>60</th>
<th>75</th>
<th>105</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>0.69</td>
<td>0.85</td>
<td>0.96</td>
</tr>
<tr>
<td>75</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>105</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

IRD_31 = 700 ppm/hr

ΔEE(75µm x 75µm) = 341 ppm/hr
ΔEE(105µm x 105µm) = 80 ppm/hr
IRD_31 = 700 ppm/hr
EE (11°, 11°) at t = 3 hrs, t = 5 hrs after LAHO

Centered about the instantaneous centroid

\[ \theta_{\text{field point}} = (11°, 11°), \ t = 3.0847 \text{ hrs} \]

\[ \theta_{\text{field point}} = (11°, 11°), \ t = 4.0847 \text{ hrs} \]

\[ \theta_{\text{field point}} = (11°, 11°), \ t = 5.0847 \text{ hrs} \]

\[ \theta_{\text{field point}} = (11°, 11°), \ t = 6.0847 \text{ hrs} \]

\[ \theta_{\text{field point}} = (11°, 11°), \ t = 6 \text{ hrs} - t = 5 \text{ hrs} \]

\[ \theta_{\text{field point}} = (11°, 11°), \ t = 4 \text{ hrs} - t = 3 \text{ hrs} \]

\[ \Delta EE_{75 \mu m \times 75 \mu m} = 205 \text{ ppm/hr} \]

\[ \Delta EE_{105 \mu m \times 105 \mu m} = 67 \text{ ppm/hr} \]

\[ \text{IRD}_31 = 700 \text{ ppm/hr} \]
Subtracting the ensemble average does not necessarily achieve image stabilization.
Peak PSF Motion \((11^\circ, 0^\circ)\) vs. \(t\)  

Subtracting the ensemble average does not necessarily achieve image stabilization

IRD\(_{32} = 0.30\) arcsec/hr
Peak PSF Motion (11°, 11°) vs. t

Subtracting the ensemble average does not necessarily achieve image stabilization.

\[ \theta_{\text{field point}} = (11°, 11°): \phi_x (\text{local}) \text{ (raw) vs. time} \]

\[ \theta_{\text{field point}} = (11°, 11°): \phi_y (\text{local}) \text{ (raw) vs. time} \]

\[ \phi - \phi_{1\text{hr previous}} \text{ (raw) vs. time} \]

\[ \phi - \phi_{1\text{hr previous}} \text{ - Ensemble Avg vs. time} \]

\[ \Delta \phi_{\text{mess (arcsec)}} \]

\[ \Delta \phi_{1\text{hr previous}} = 0.51 \text{ arcsec/hr} \]

\[ \Delta \phi_{1\text{-}3\text{hr previous}} = 0.49 \text{ arcsec/hr} \]

\[ \Delta \phi_{1\text{hr previous}} = 0.19 \text{ arcsec/hr} \]

\[ \Delta \phi_{1\text{hr previous}} = 0.11 \text{ arcsec/hr} \]

IRD_32 = 0.30 arcsec / hr
Extended Time Period PSF Motion
Subtracting the ensemble average does not necessarily achieve image stabilization.
Flexures (Only) Contribution to PSF Motion

Subtracting the ensemble average does not necessarily achieve image stabilization.
Subtracting the ensemble average does not necessarily achieve image stabilization.

IRD_{32} = 0.30 \text{ arcsec/ hr}
- Perform additional model validations
- Complete remaining thermal scenarios
- Analyze eclipse portion of orbit to characterize performance
- Release finalized STOP Analysis V&V Report