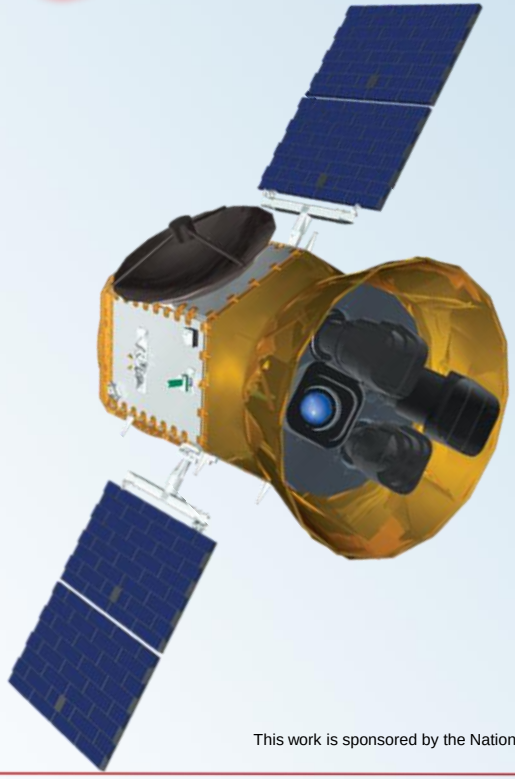
Transiting Exoplanet Survey Satellite



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

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MIT Lincoln Laboratory
July 22, 2015

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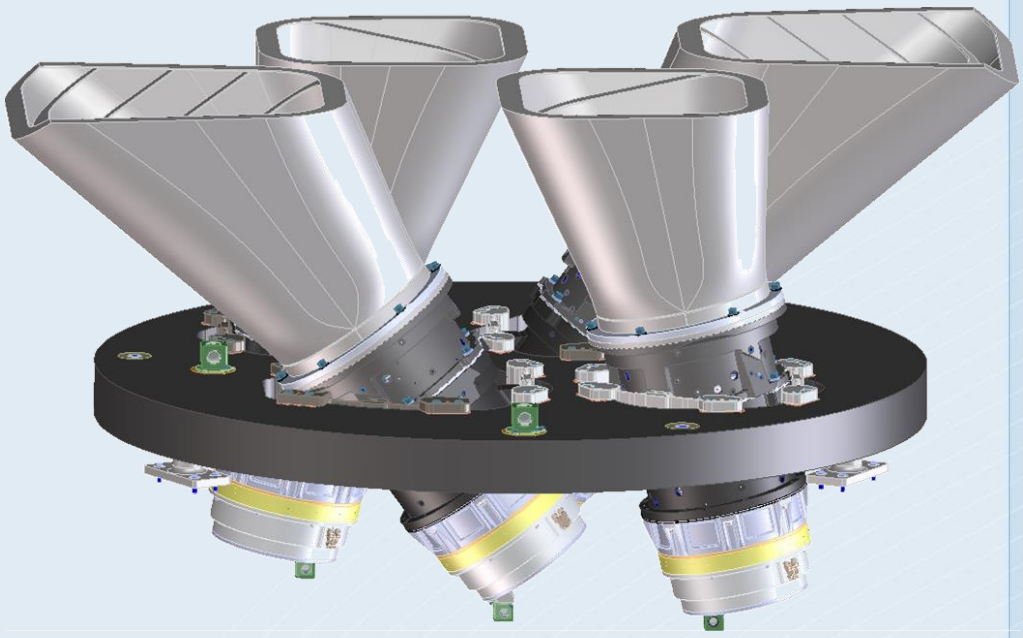
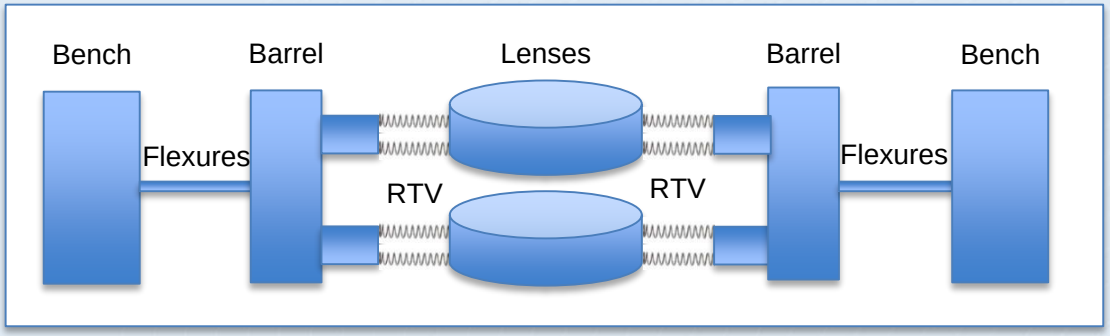
Agenda

- System Overview
- Objectives
- Key Requirements
- STOP Modeling Process
- Summary of Results
  - *Thermal*
  - *Structural*
  - *Optical*
  - *STOP*
- Path Forward

Structural Design

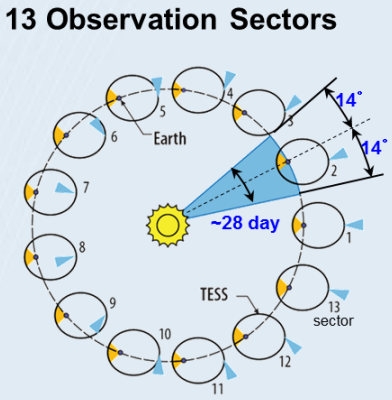
- Composite bench
- Invar camera flexures
- Aluminum lens barrel
- Composite lens hood baffle, flexure mounted to aluminum interface ring
- RTV 566 bonding pads
- Glass optics

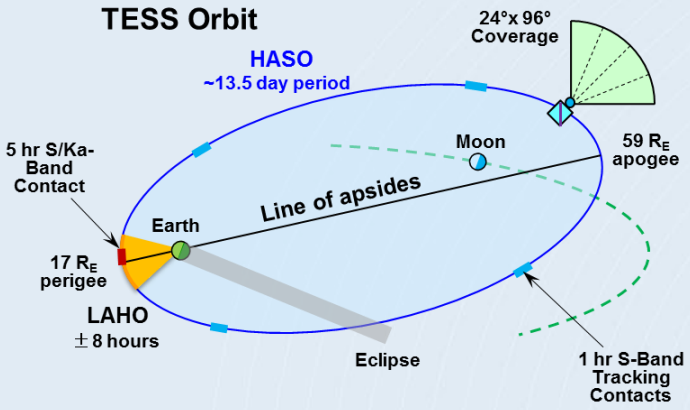


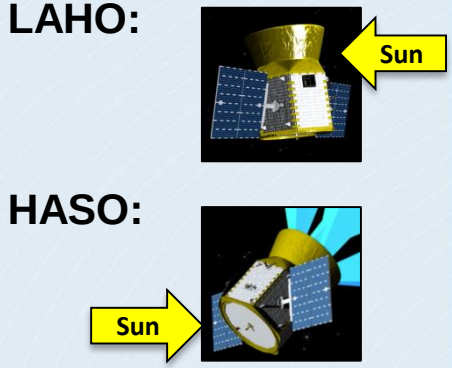


Orbital Environment

- 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° / 54° 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*

Key Requirements

Title	Requirement	Predicted Performance	Margin
Observation Settling Time	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.	5 hrs	-43%
Distortion-Induced Image Motion	The instrument shall limit distortion-induced motion of each camera boresight with respect to the instrument ensemble-average boresight to < 0.30 arc-sec over any 1 hour period during HASO.	0.16 arc-sec	+88%
Camera Boresight Deflection	The instrument shall limit distortion-induced motion of each camera boresight with respect to the instrument ensemble-average boresight to < 4.0 arcsec during HASO.	TBD	TBD
Systematic Error: Peak Temperature Effects	The instrument shall limit variation in ensquared energy of any camera relative to the camera's individual boresight to < 700 ppm over any 1 hour period during HASO, for the following apertures and field angles: Field angle (deg) — Aperture Size (microns) (0,0) — 75x75 (0,6) — 75x75 (0,11) — 75x75 (11,11) — 105x105	145 ppm	+380%

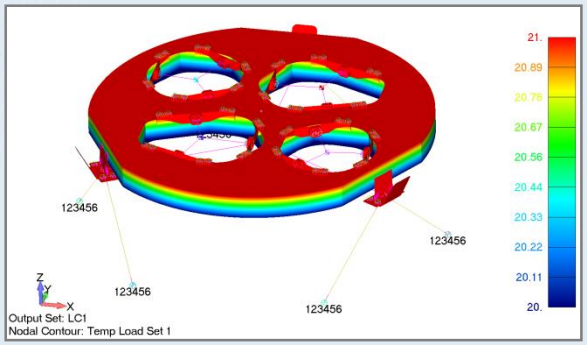
Pre-STOP Analysis Error Budget

- 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*

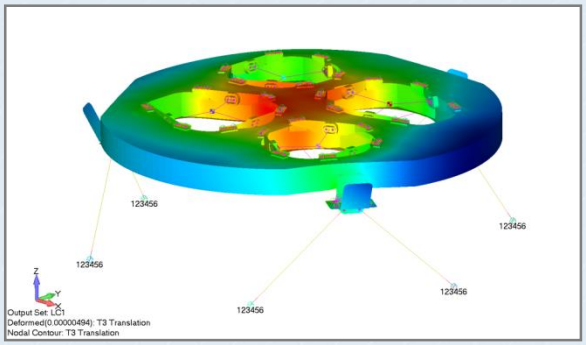
PSF Drift Initial Error Budget

	dT / 1 hr	dϕ / dT	dϕ / 1 hr
	(°C / hr)	(arcsec / °C)	(arcsec)
Mount Posts			0.05
Camera Plate (dT/dZ)	0.20	0.08	0.02
Camera Plate (dT/dr)	1.00	0.03	0.03
Camera Flexures (dT)	0.65	0.08	0.05
Camera Flexures (dT/θ)	0.25	0.10	0.02
Camera Barrel, Bezels			0.15
Harness			0.05
Lenses, RTV			0.15
RSS			0.23
Budget			0.30
Margin			0.19

$\Delta T_{applied}$ = 1 °C / depth

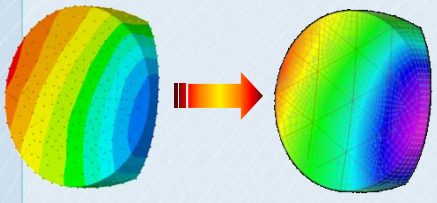


$\Delta\phi_{cameras}$ = 0.08 arcsec



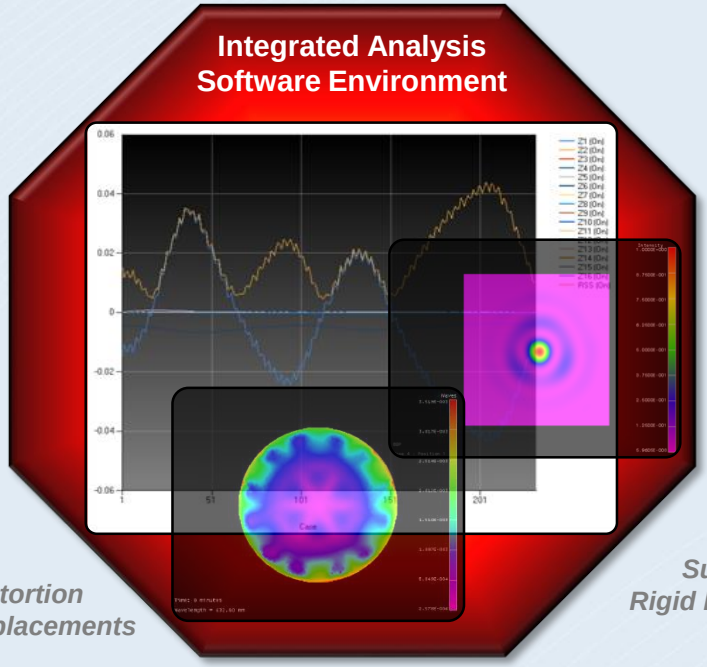
STOP Modeling Process

Thermal to Structural Temperature Mapping



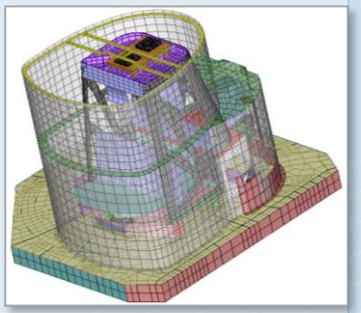
dn/dT Profiles

Integrated Analysis Software Environment



dn/dσ Profiles

Structural Loading



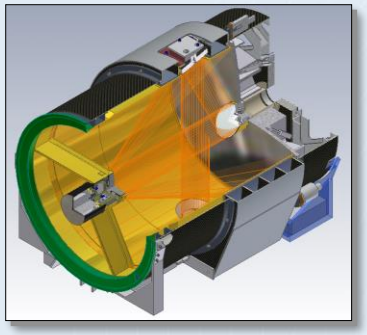
Thermo-Elastic Distortion Analysis

Surface Distortion Rigid Body Displacements

Surface Distortion Rigid Body Displacements

Structural Analysis

Ray Tracing & Optical Analysis



TESS STOP Analysis Approach

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.

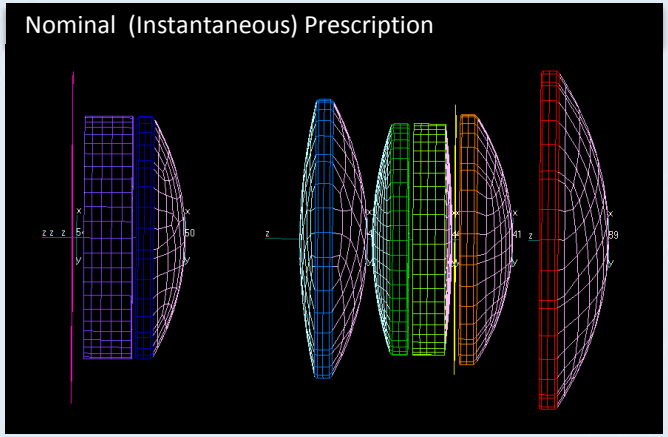
2) Perform image space LOS analyses quantifying chief ray motions on image planes relative to perturbed image plane origin.

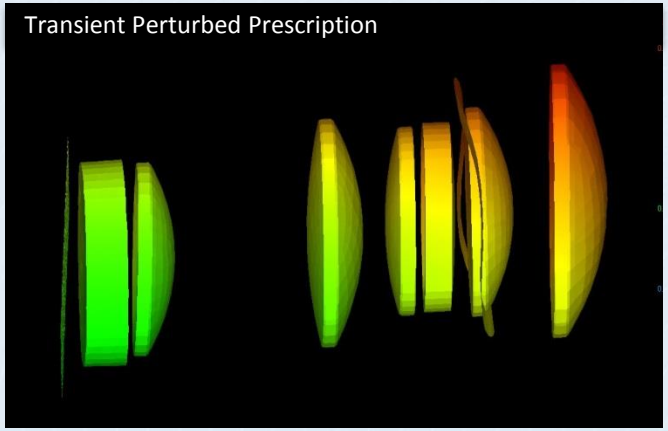
3) Perform PSF analyses characterizing centroid motion relative to the chief ray used in LOS analysis in step 2.

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)

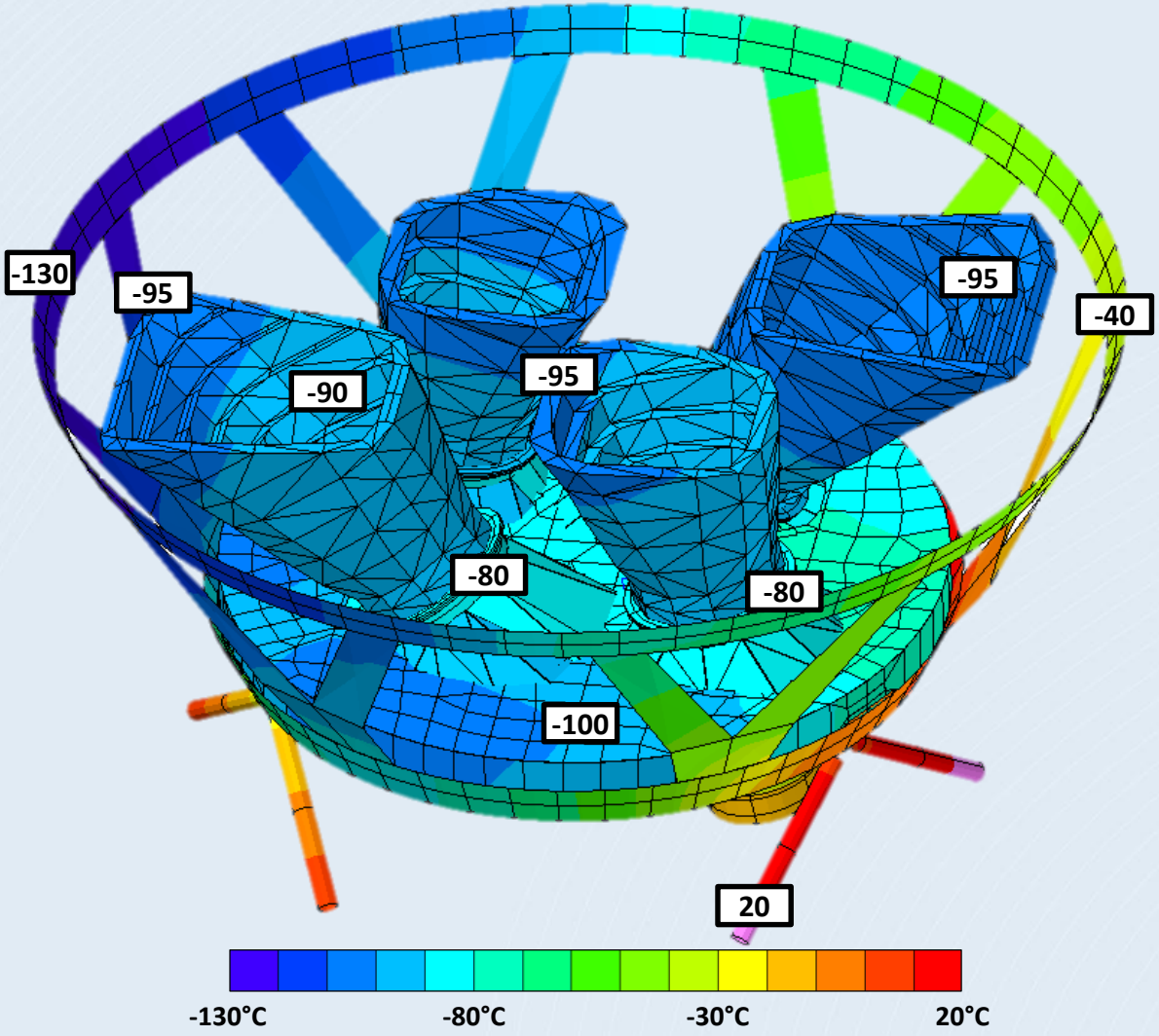
Additional Model Validation Cases

ID #	Case Description	Expected/Desired Result	Actual Result
1	0.1mm rigid body lateral translation of camera	Zero motion on image plane	✓ Confirmed
2	0.1mm rigid body lateral translation of camera	Zero motion of PSF centroid	✓ Confirmed
3	0.1mm rigid body lateral translation camera corner field (12 deg,12 deg)	No change in LOS	✓ Confirmed
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

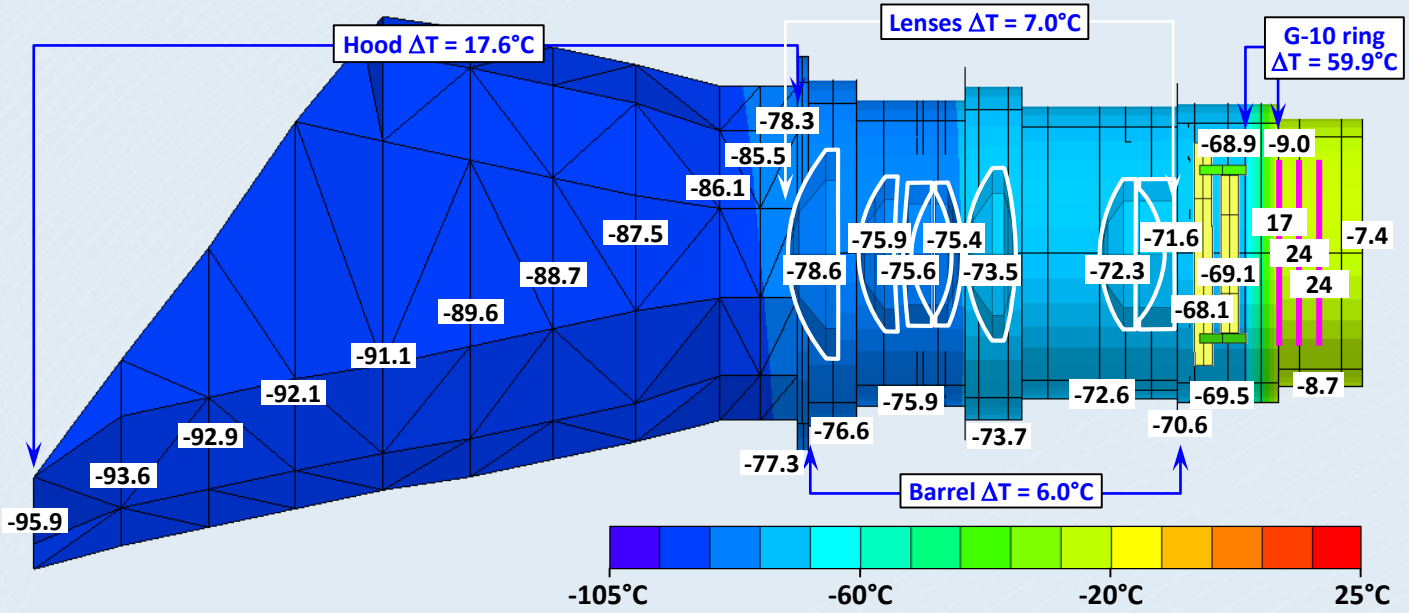
- Thermal Loads
- Transient Temperature Distributions
- Instrument Architecture
- Structural Disturbances

HASO Instrument Temperature Distribution

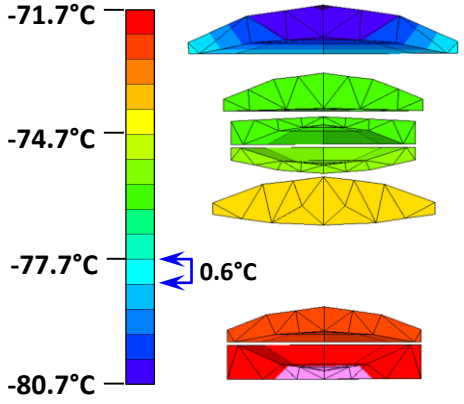


HASO Camera Temperatures

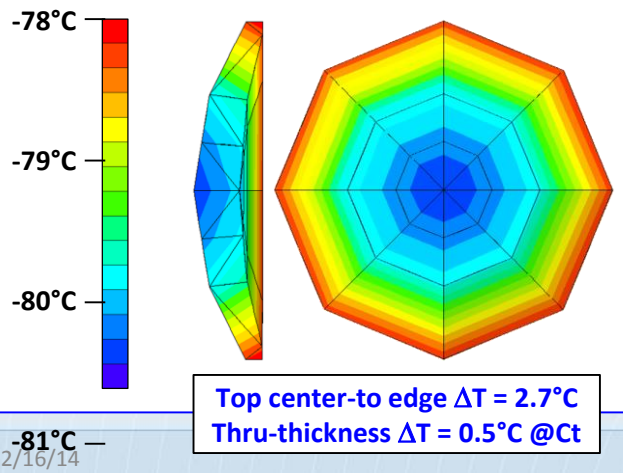
Camera 1
(Average temperatures are shown)



Camera 1, Lenses

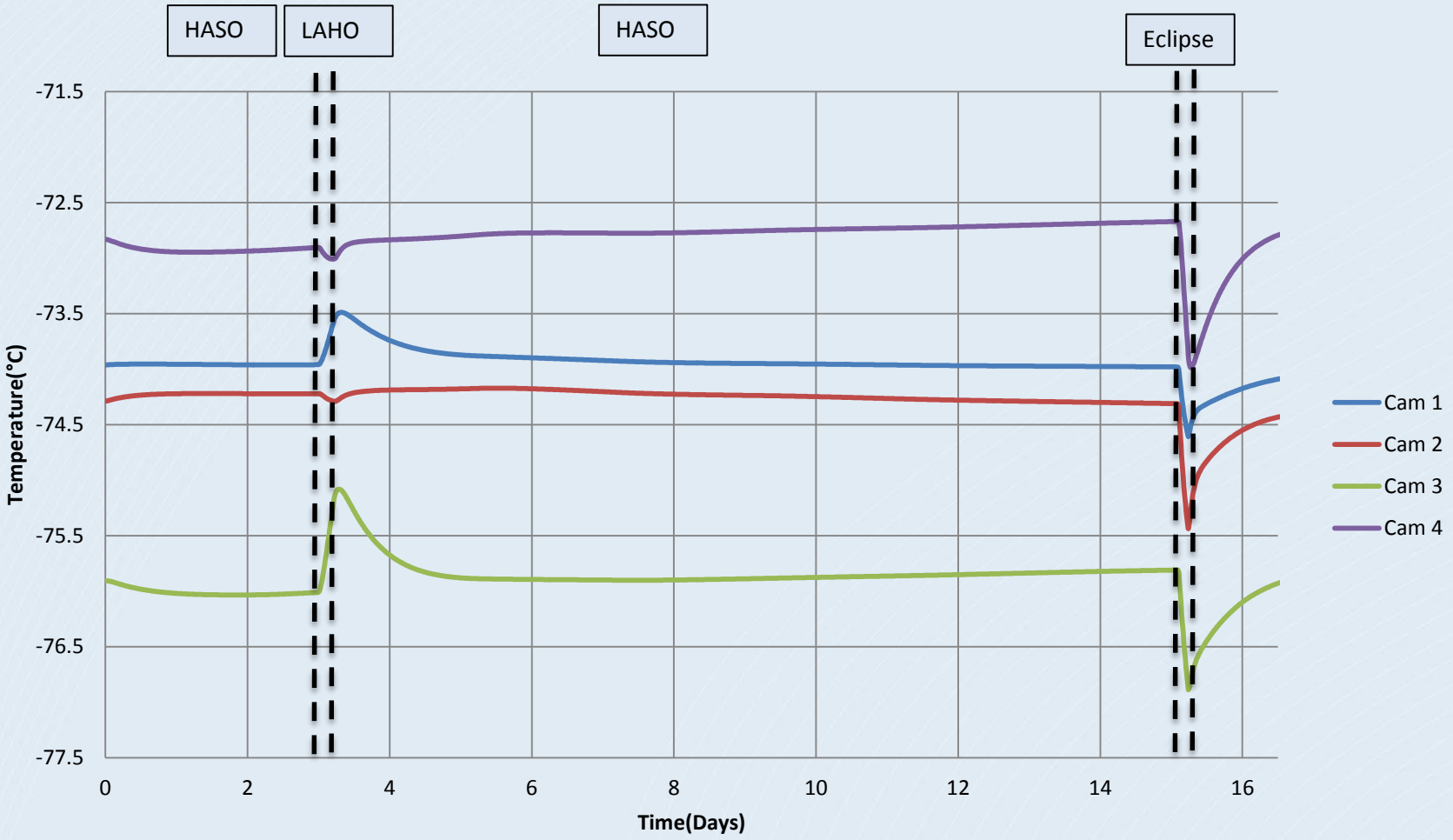


Camera 1, Lens 1



Top center-to edge ΔT = 2.7°C
Thru-thickness ΔT = 0.5°C @Ct

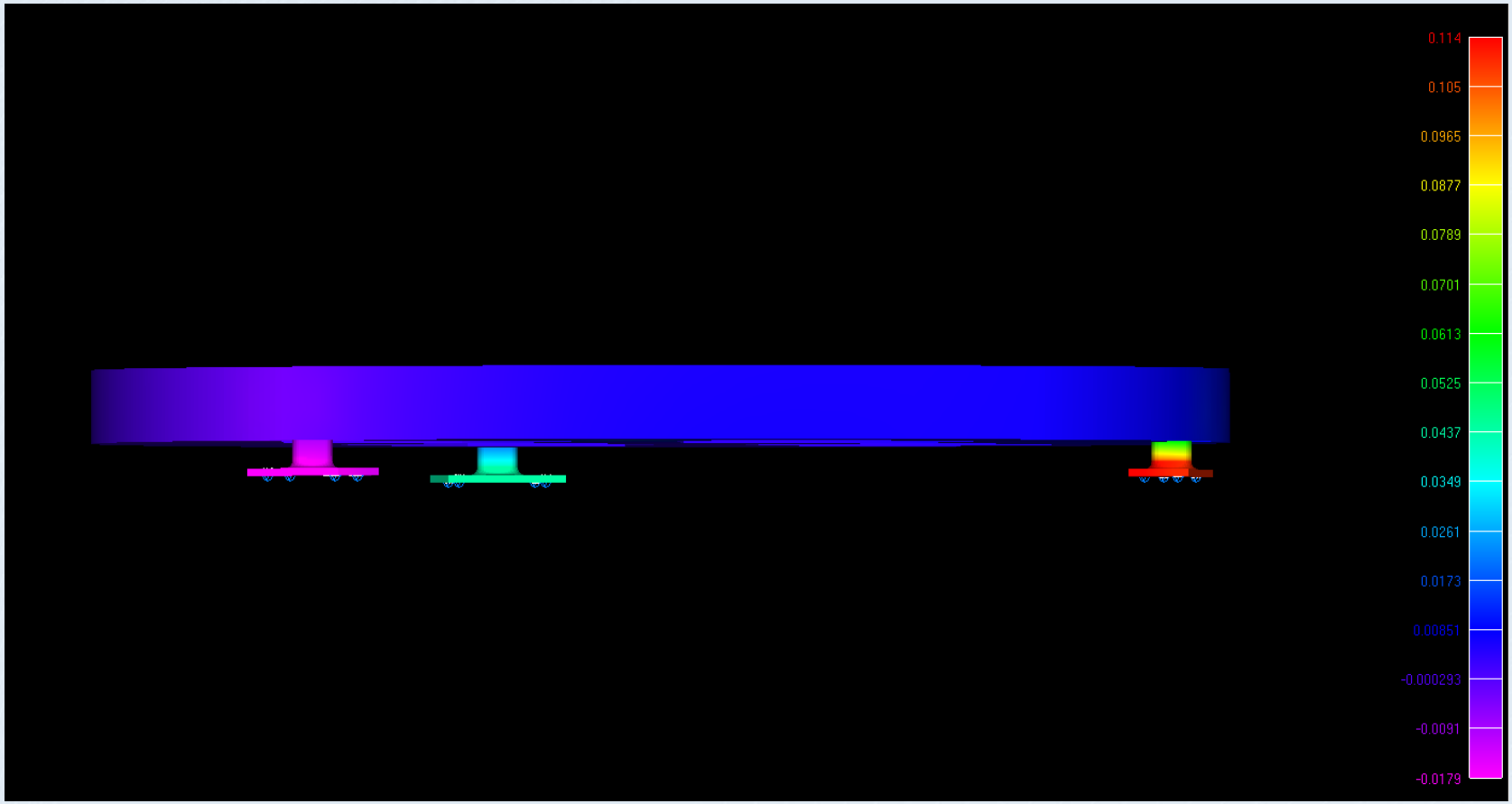
Transient (Average) Lens Temperatures



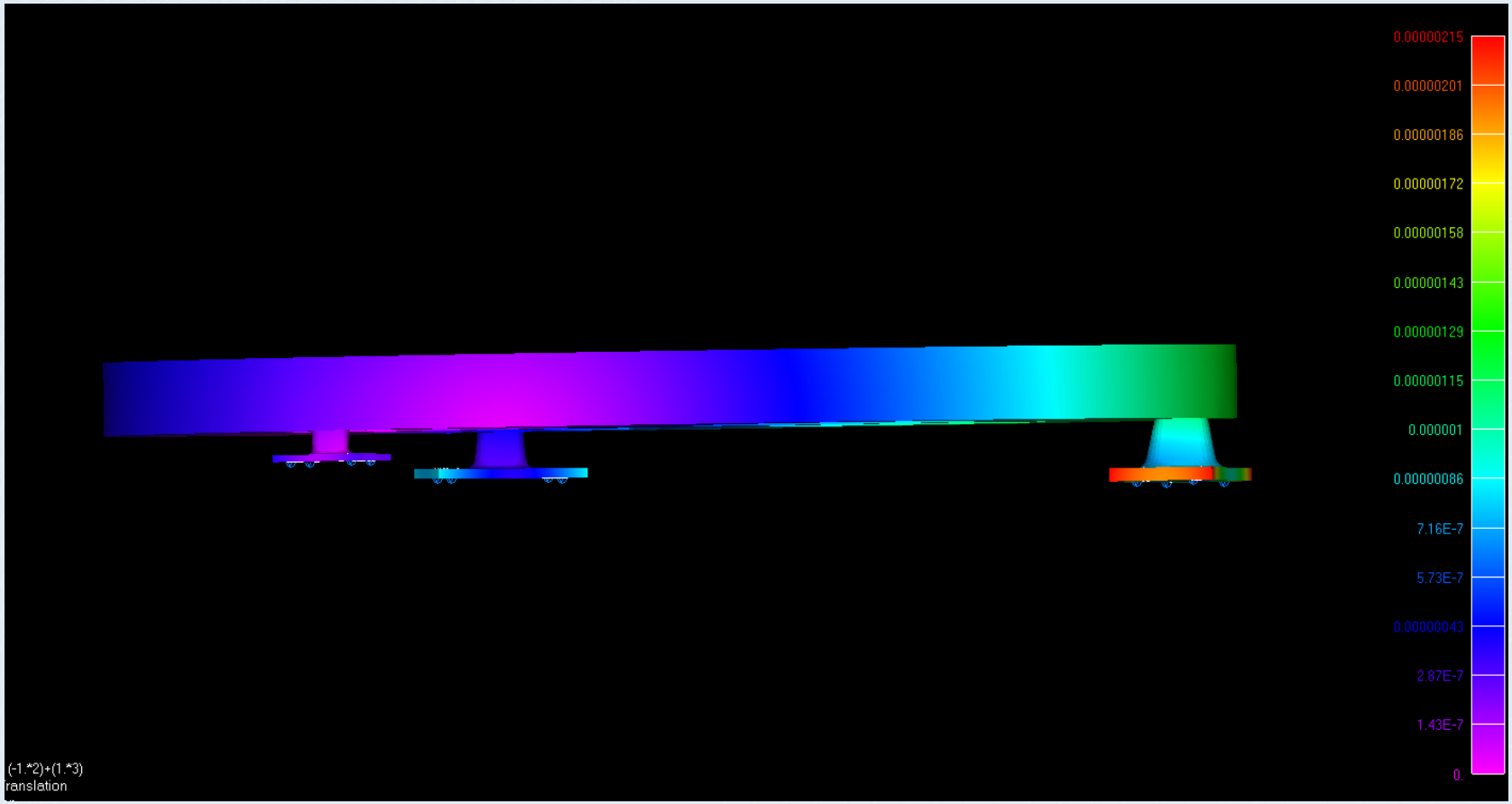
Lens temperature varies by <5°C

Transient Deformation of the Camera Plate

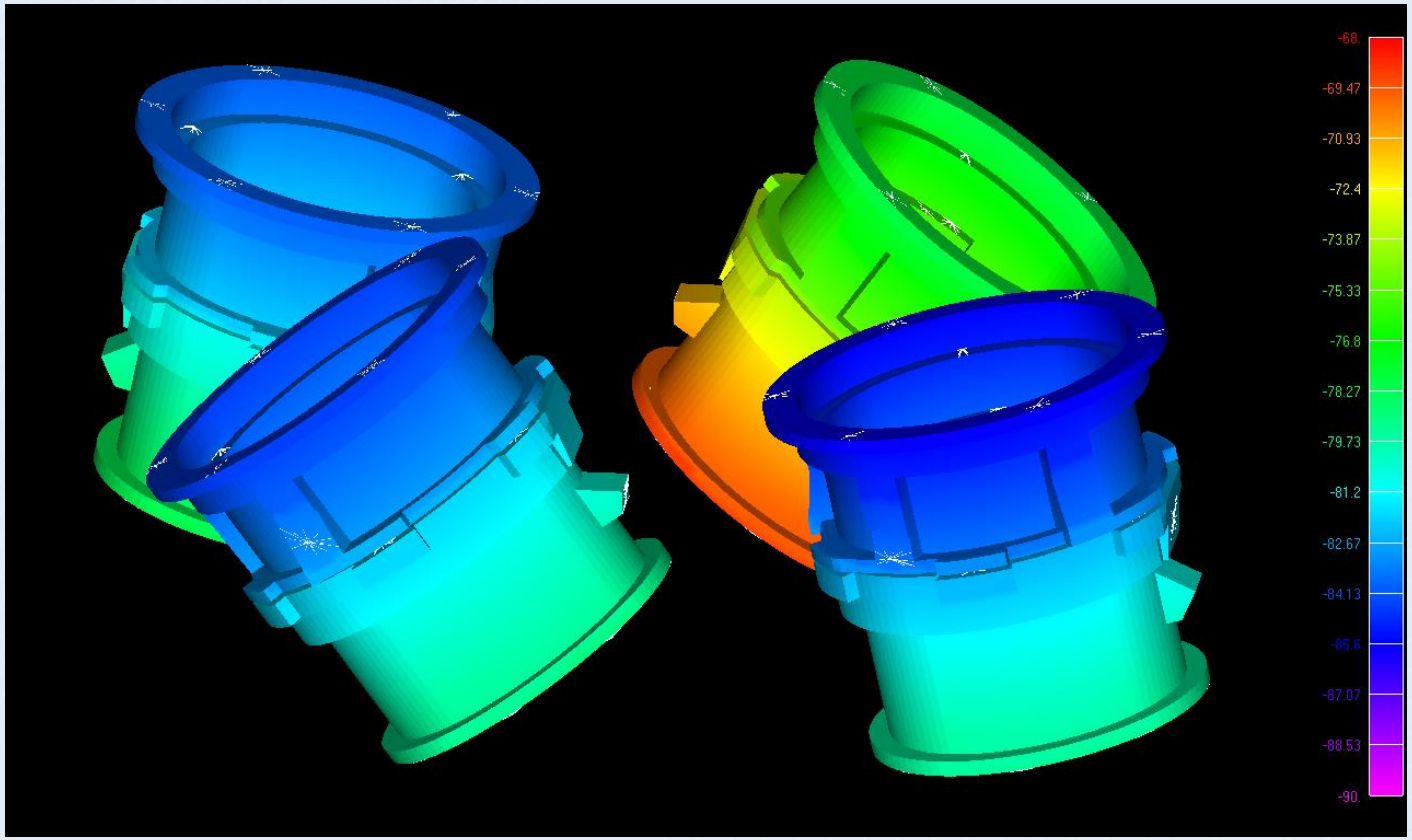
Transient ΔT of the Mount Posts



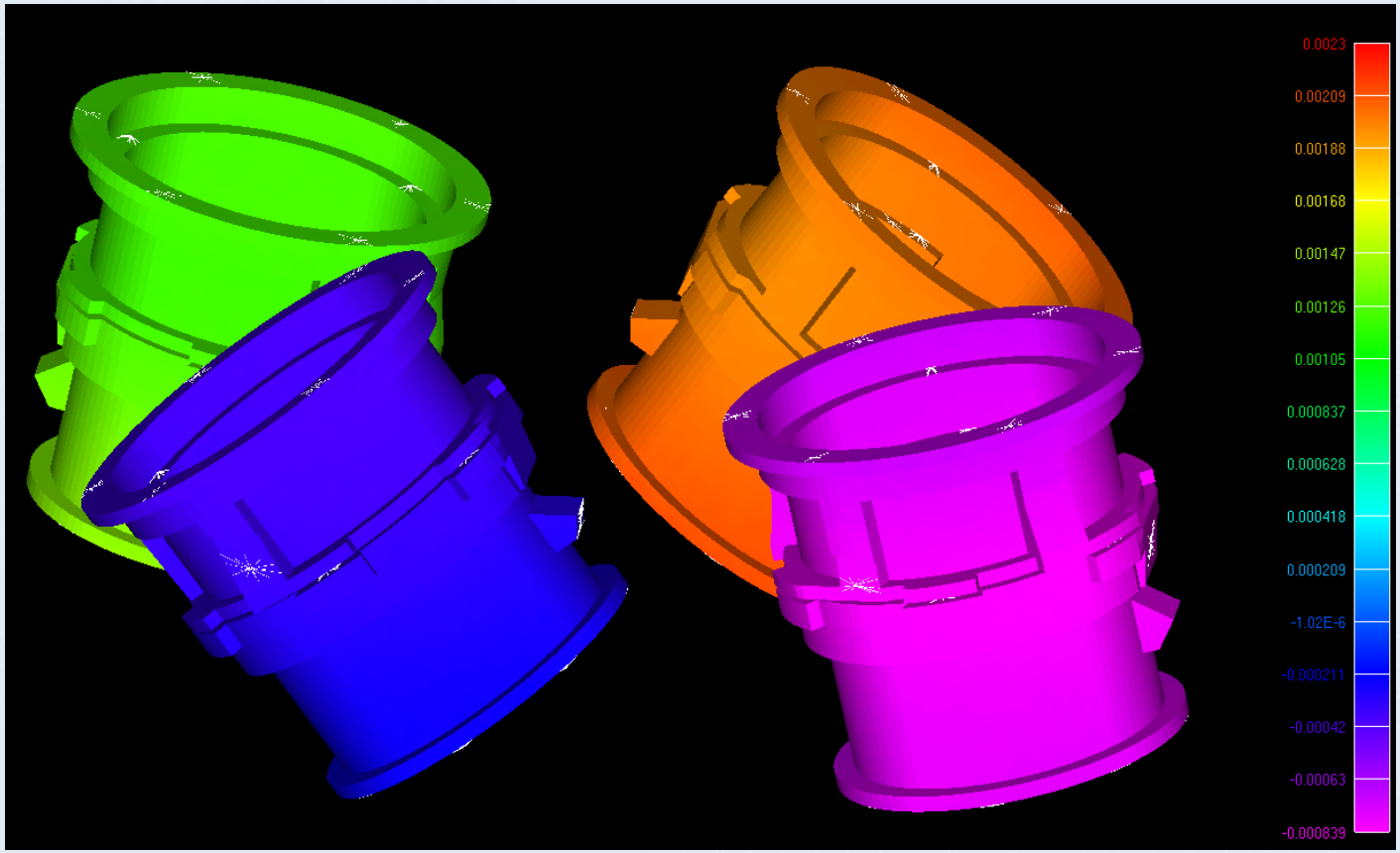
Transient Deformation of the Mount Posts



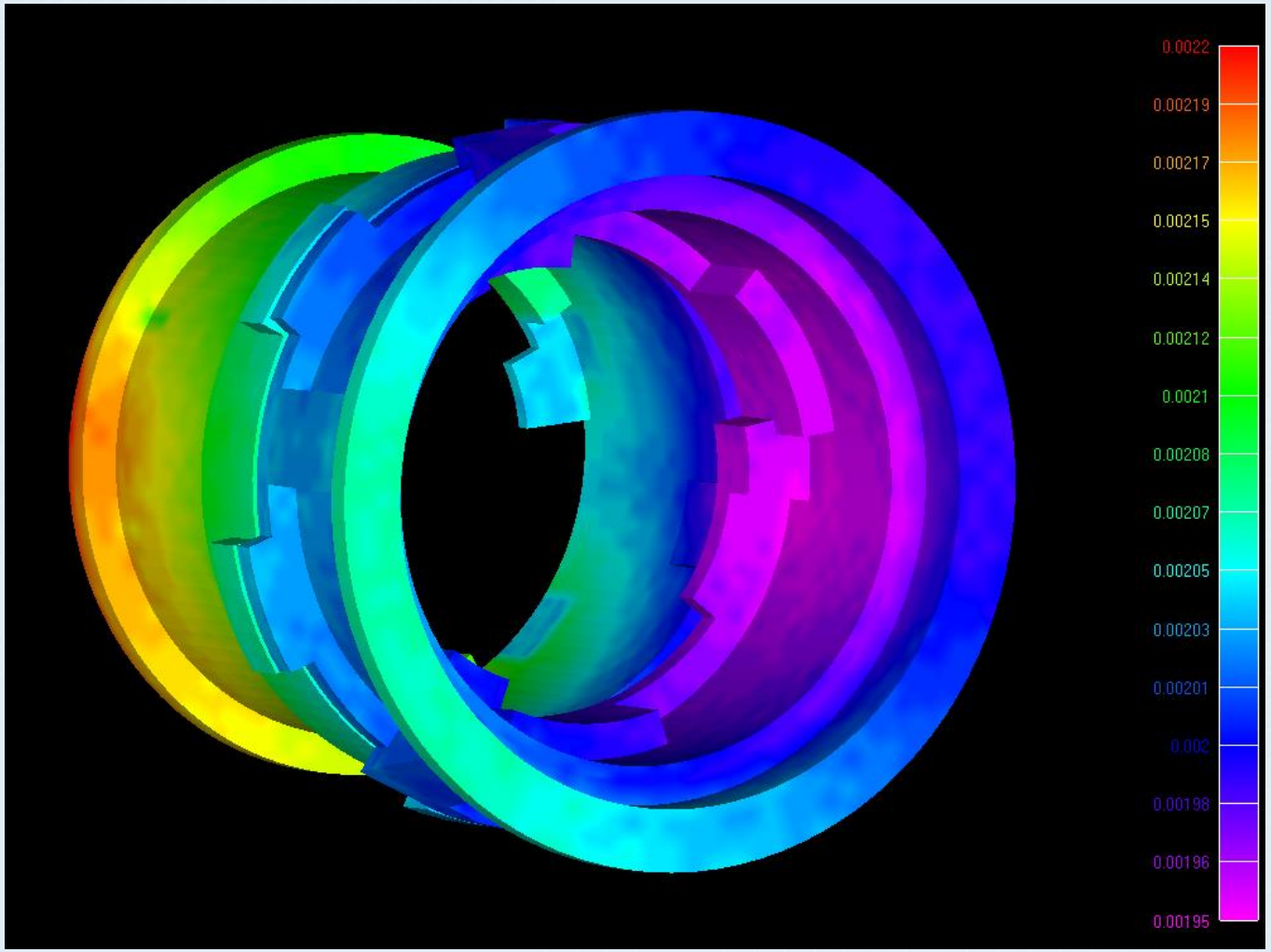
Temperatures of the Barrels at t = 3 hrs



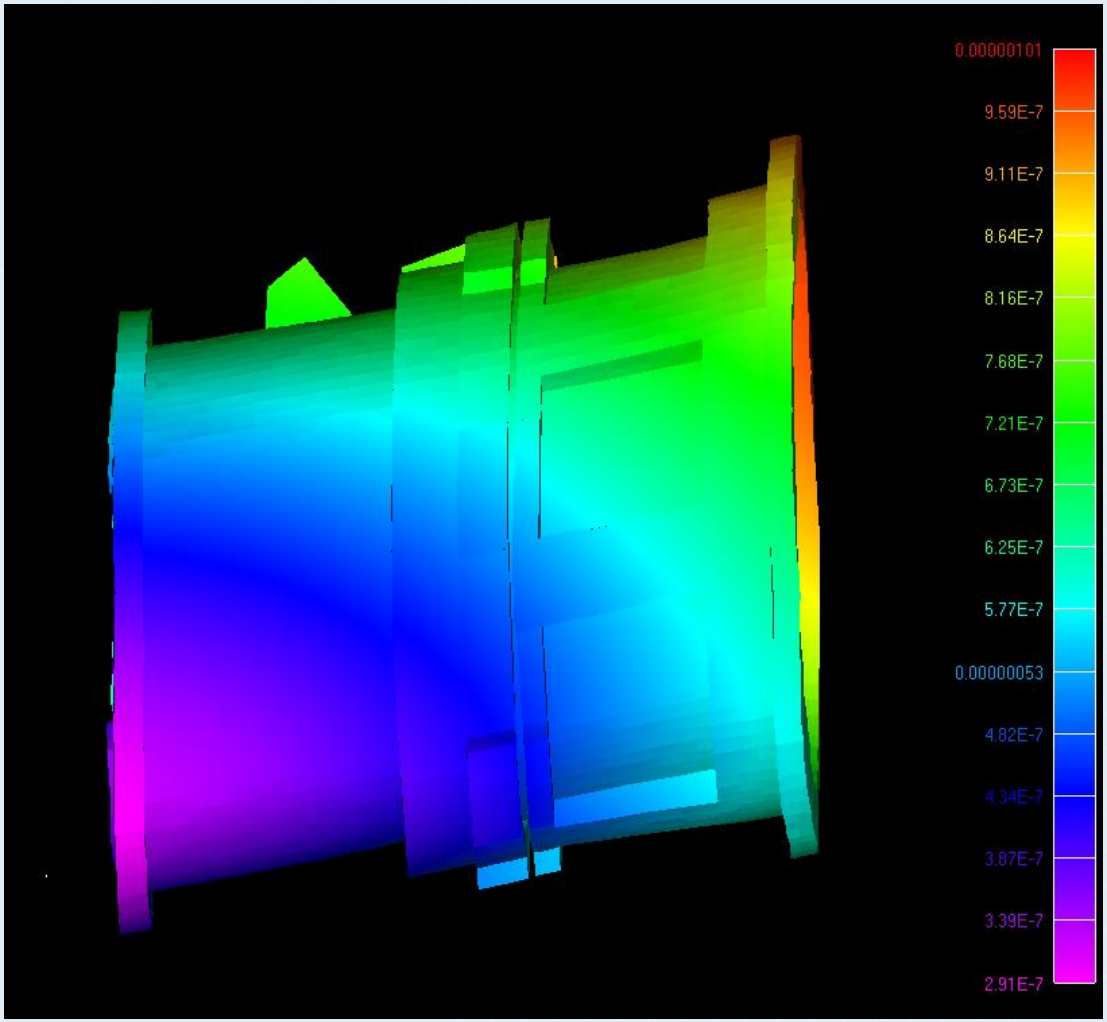
Relative Transient ΔT of the Cameras



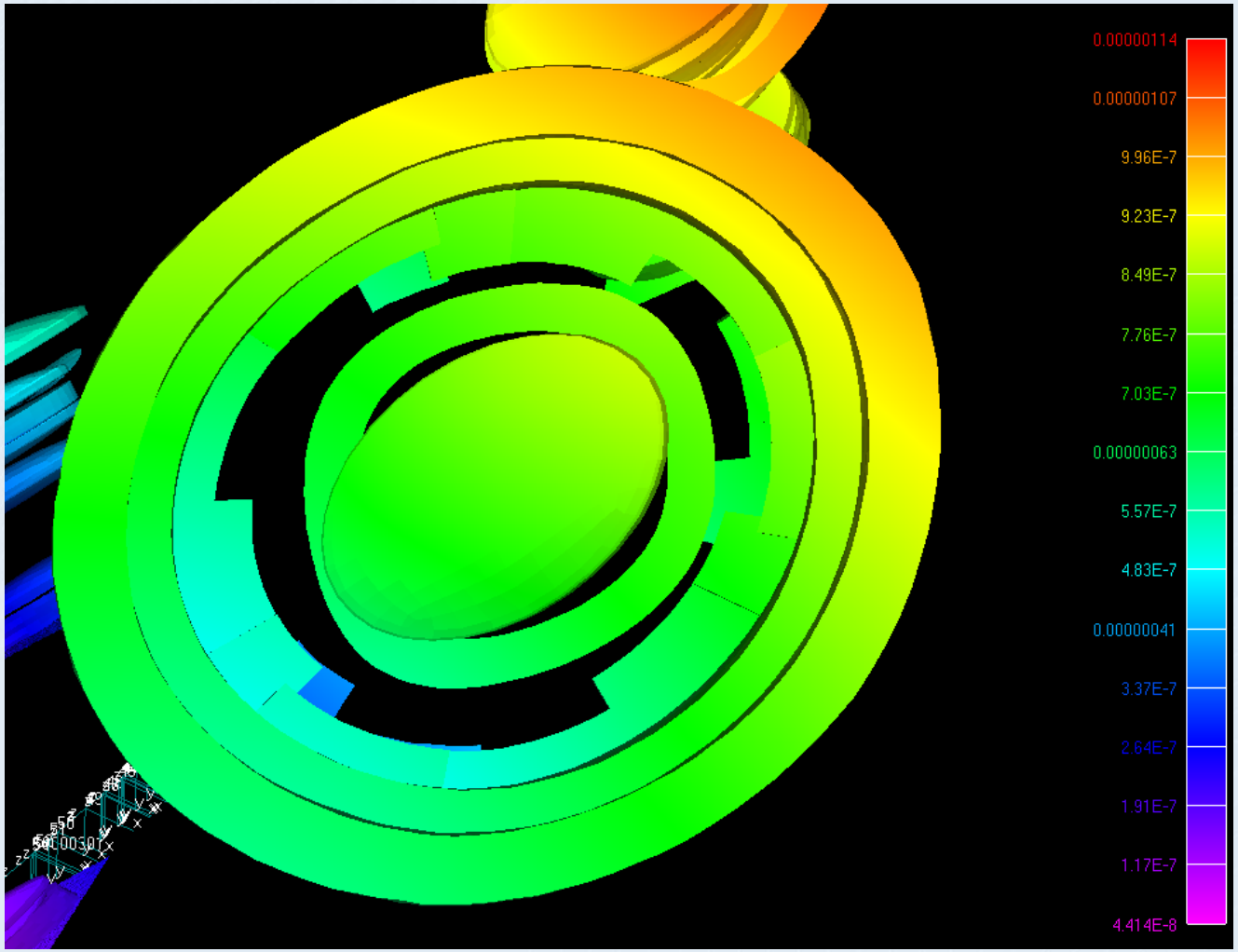
Transient ΔT of the Lens Assembly



Transient Deformation of the Lens Barrel

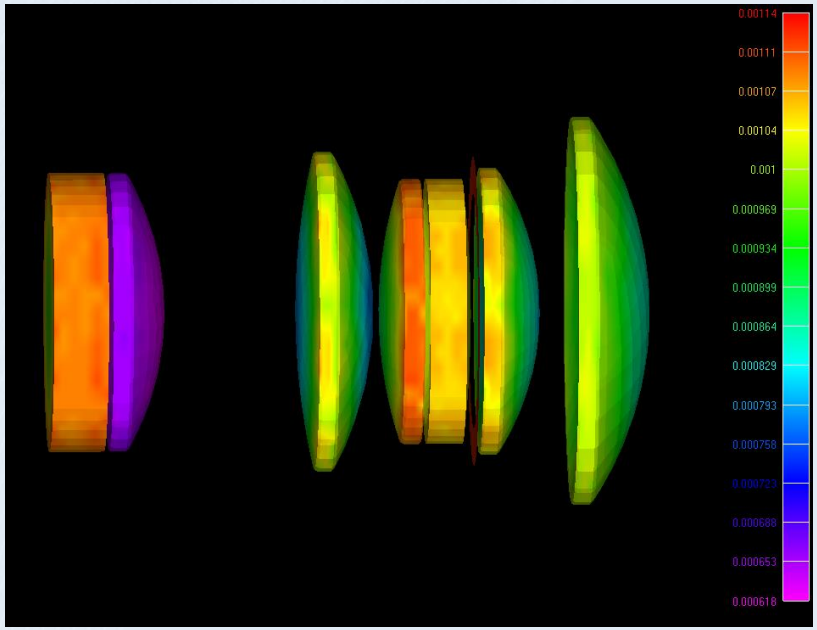


Transient Deformation of the Lens Assembly



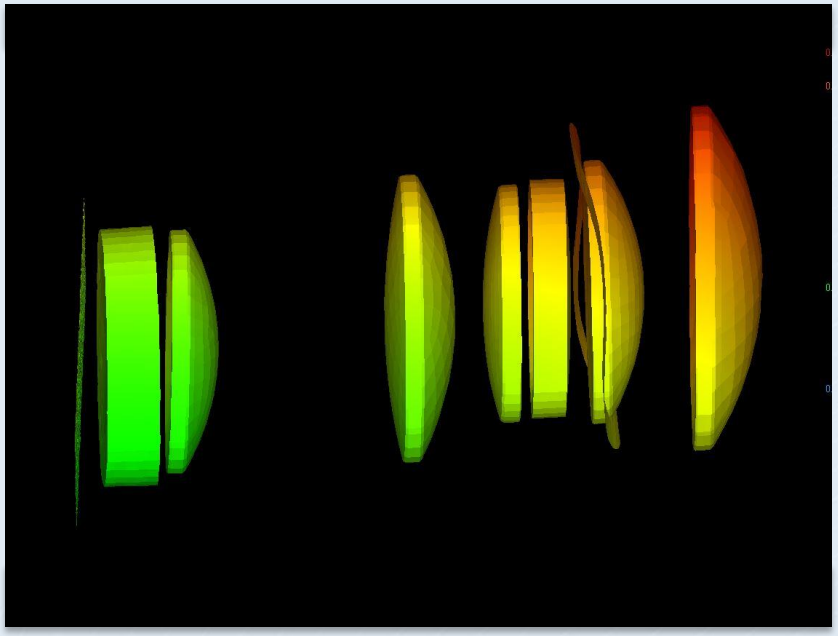
Transient Optical Perturbations

Transient Temperature Change



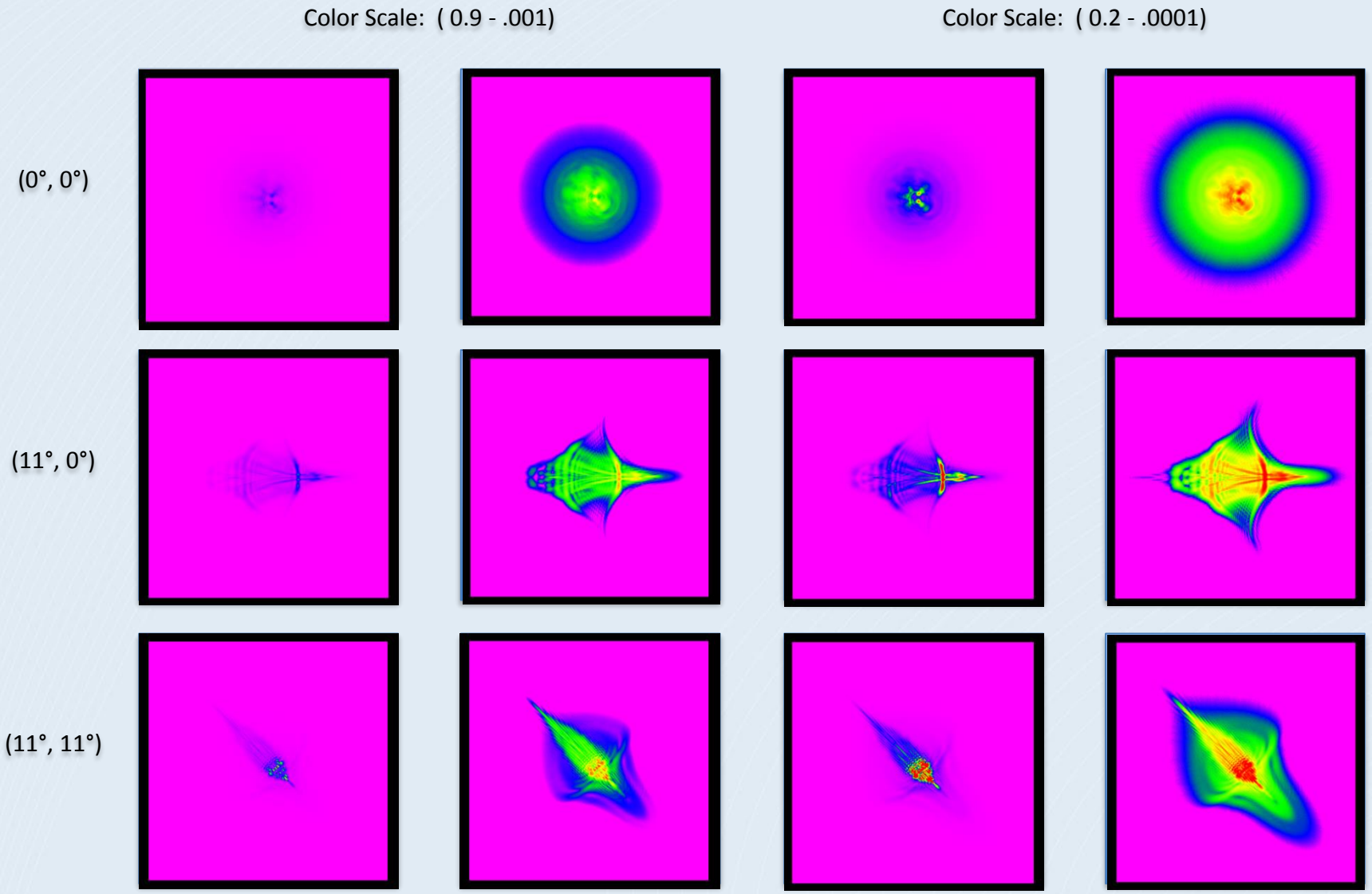
Temperature difference between t=3, t=4 hrs

Transient Displacements



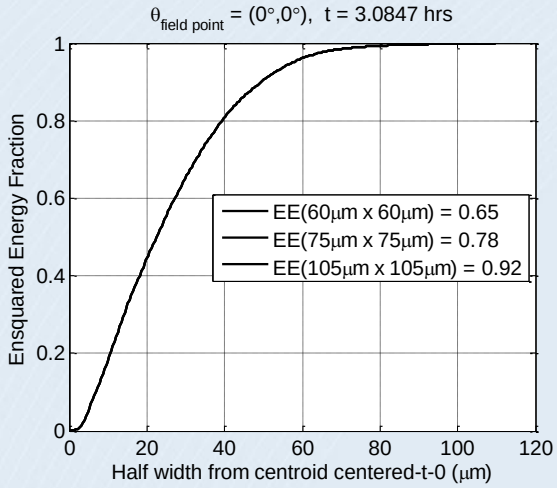
Resulting deformation

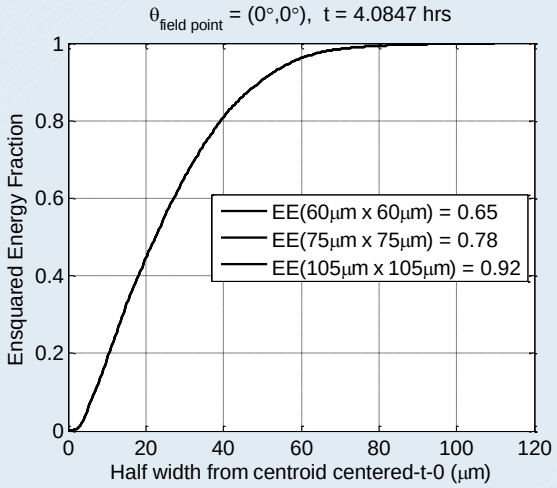
PSF plots at t = 3hrs after LAHO

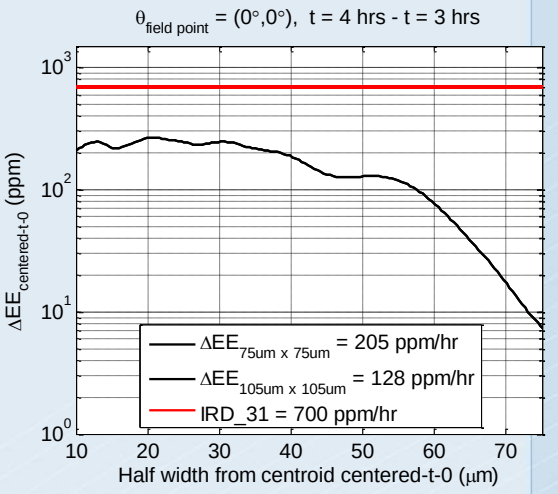


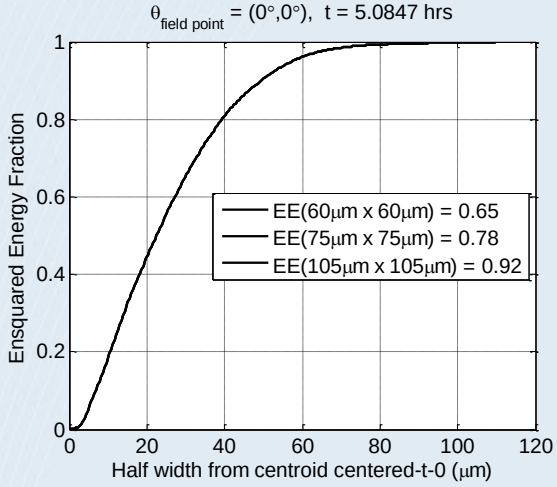
EE (0°, 0°) at t = 3 hrs, t = 5 hrs after LAHO

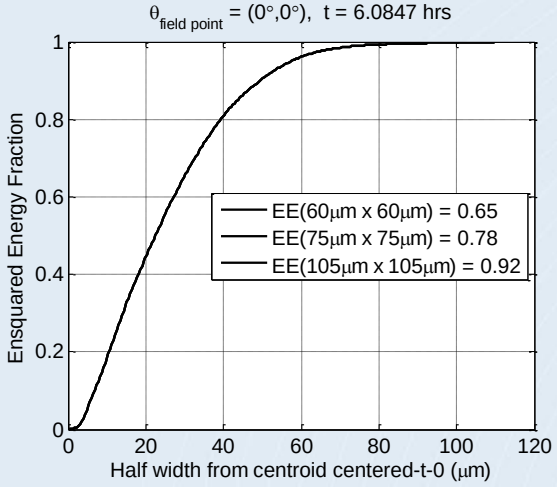
Centered about the instantaneous centroid

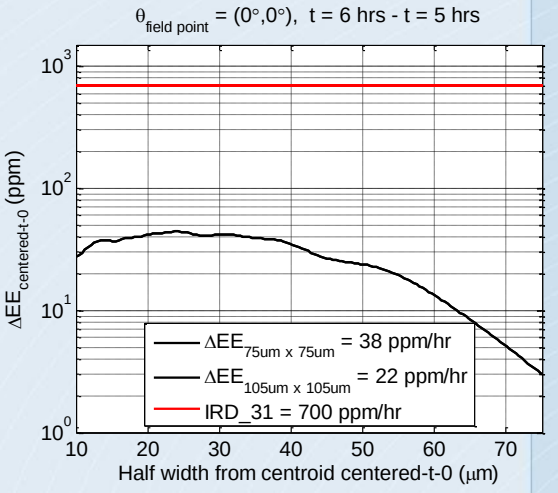






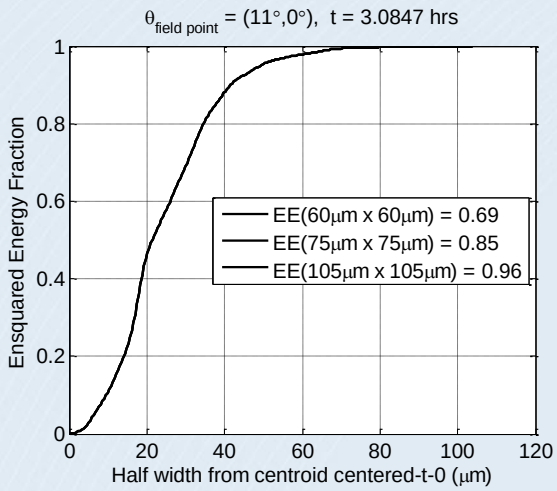


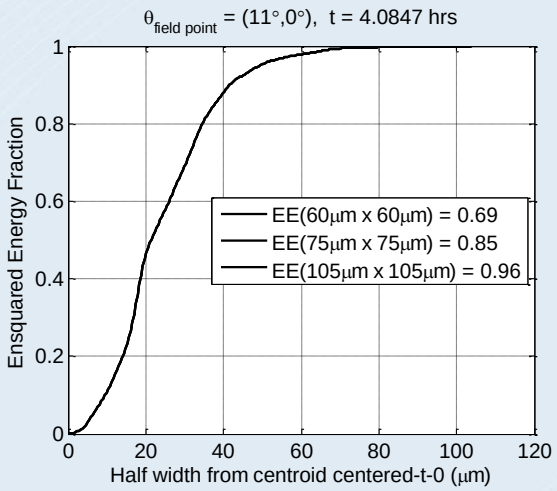


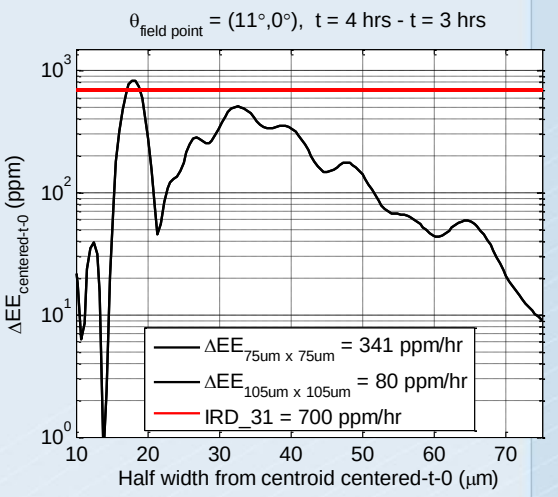


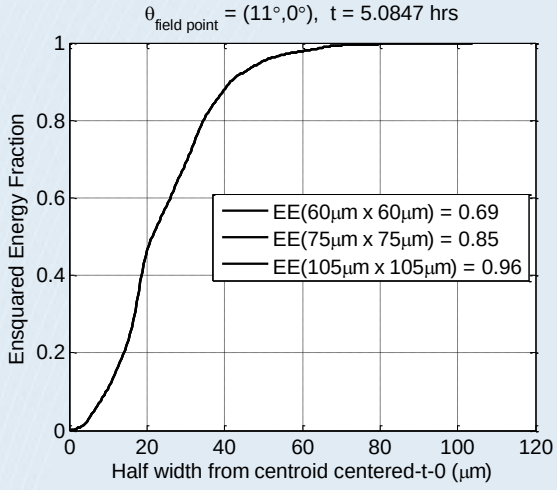
EE (11°, 0°) at t = 3 hrs, t = 5 hrs after LAHO

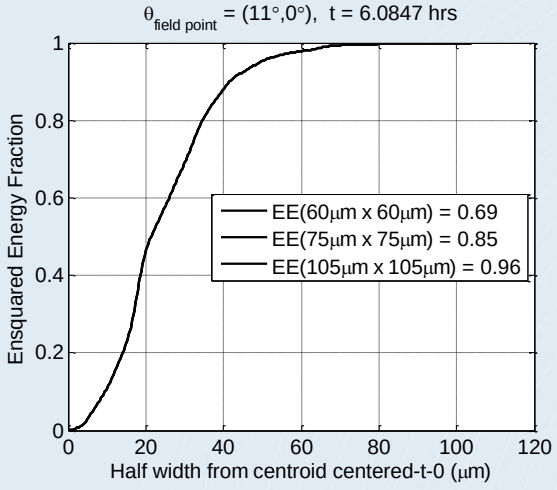
Centered about the instantaneous centroid

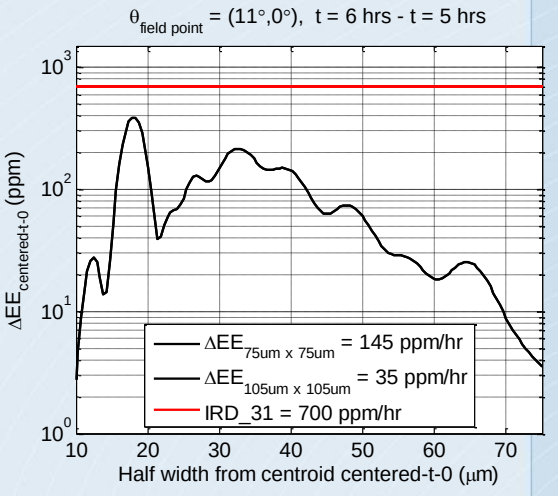






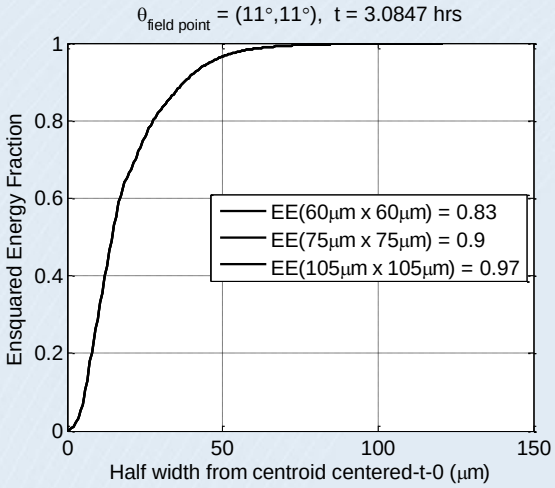


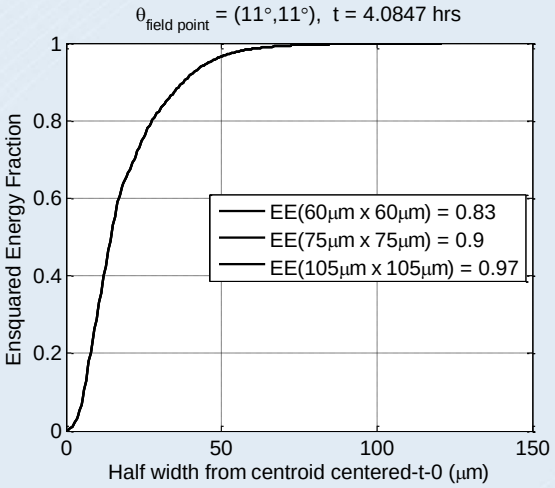


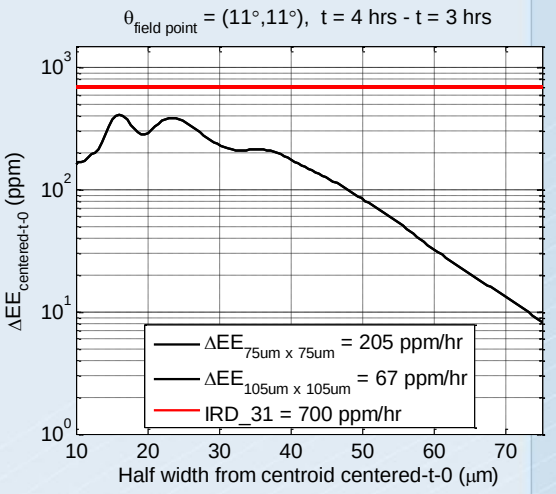


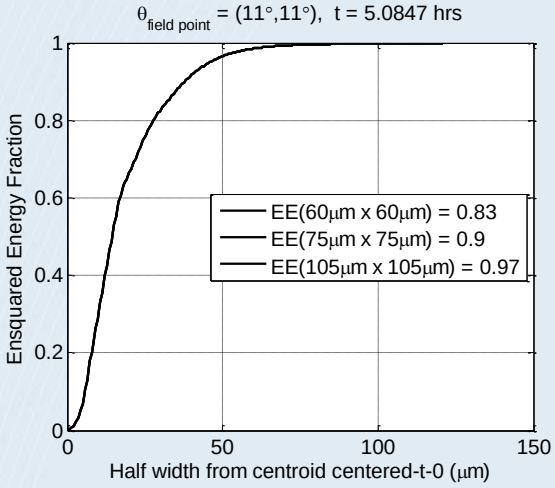
EE (11°, 11°) at t = 3 hrs, t = 5 hrs after LAHO

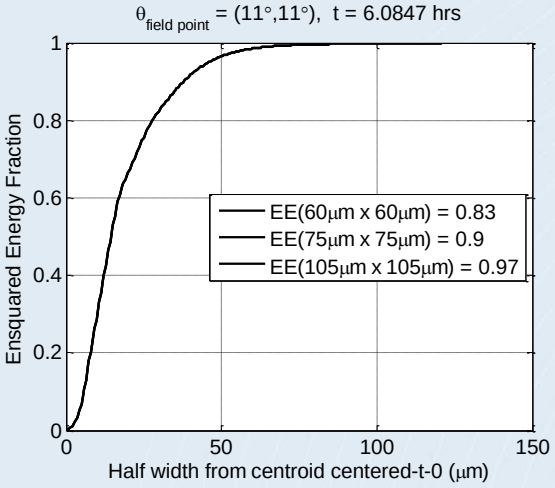
Centered about the instantaneous centroid

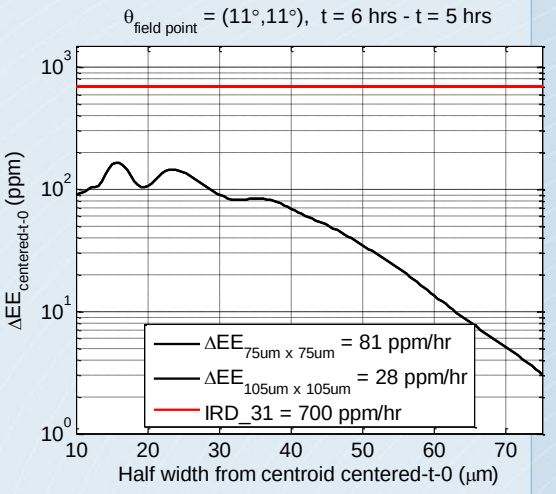






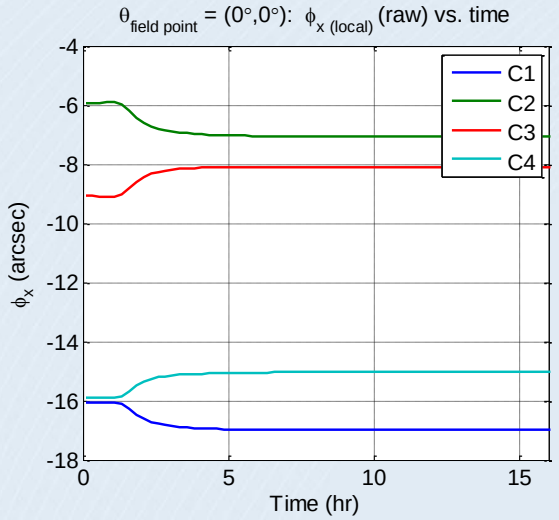


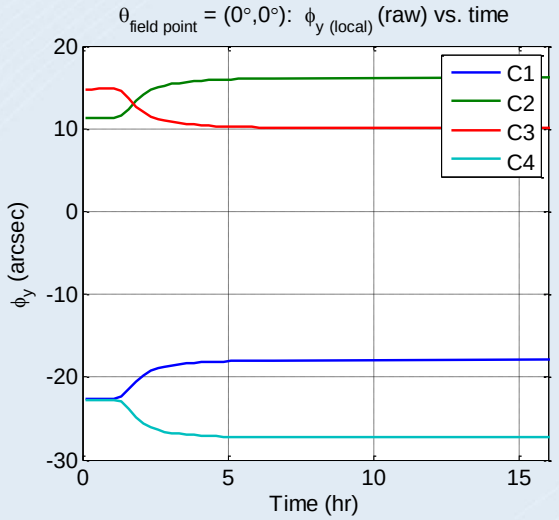


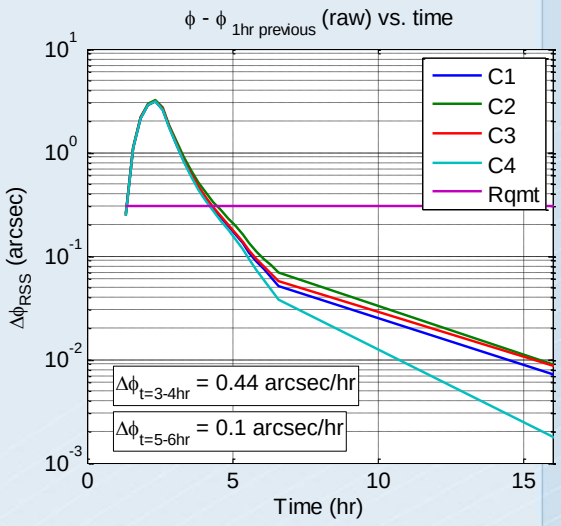


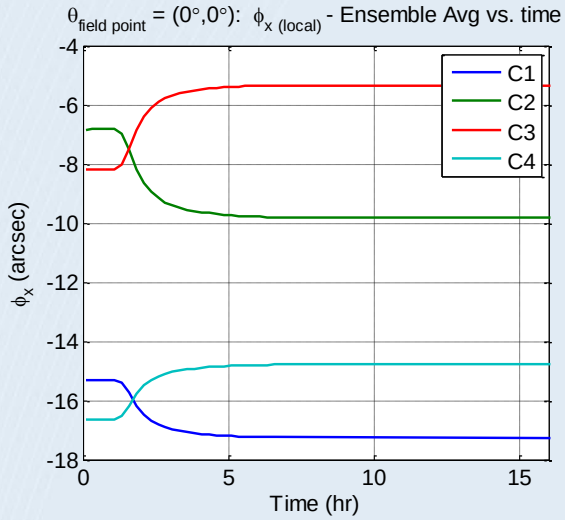
Peak PSF Motion (0°, 0°) vs. t

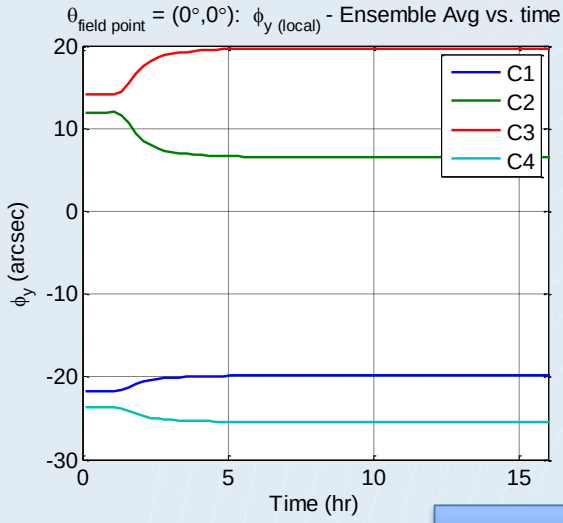
Subtracting the ensemble average does not necessarily achieve image stabilization

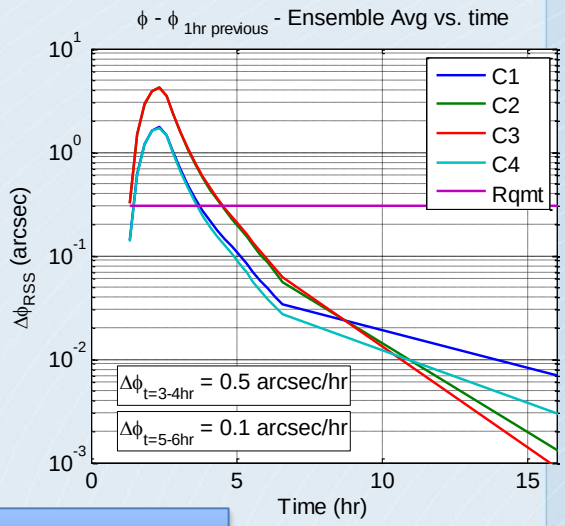








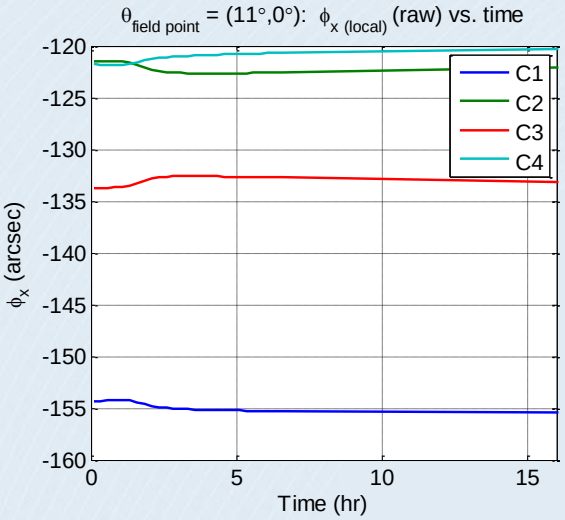


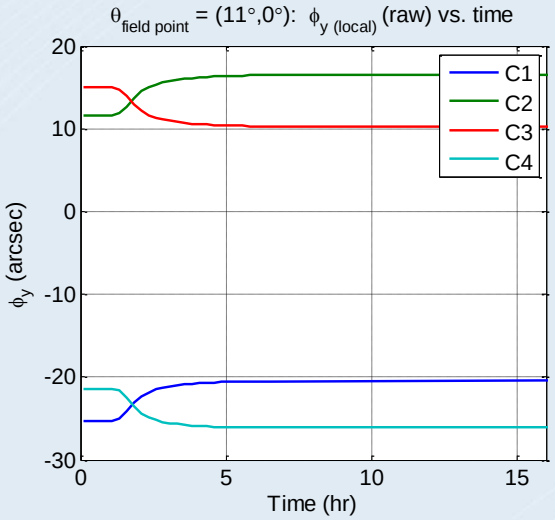


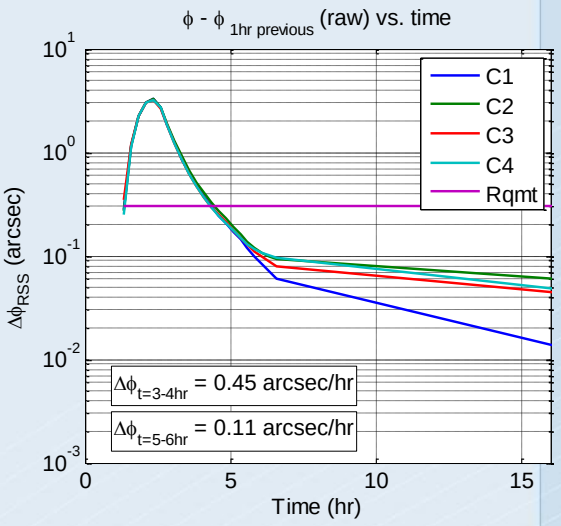
IRD_32 = 0.30 arcsec / hr

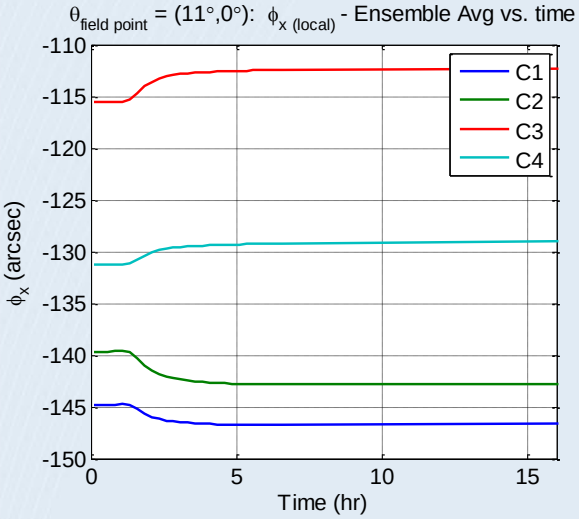
Peak PSF Motion (11°, 0°) vs. t

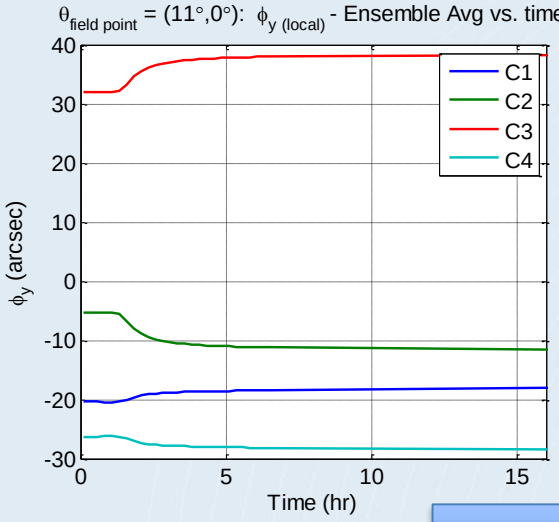
Subtracting the ensemble average does not necessarily achieve image stabilization

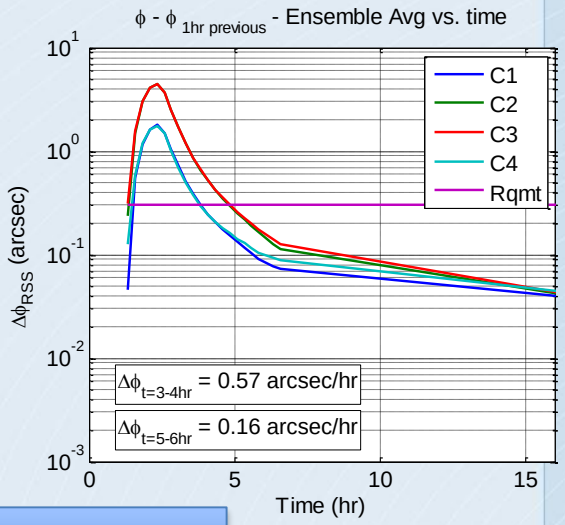








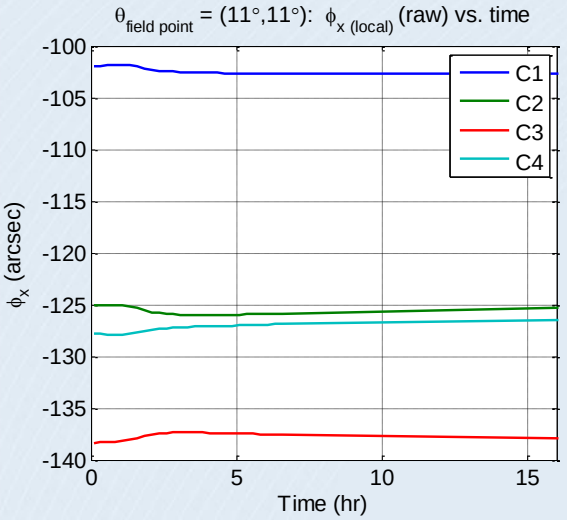


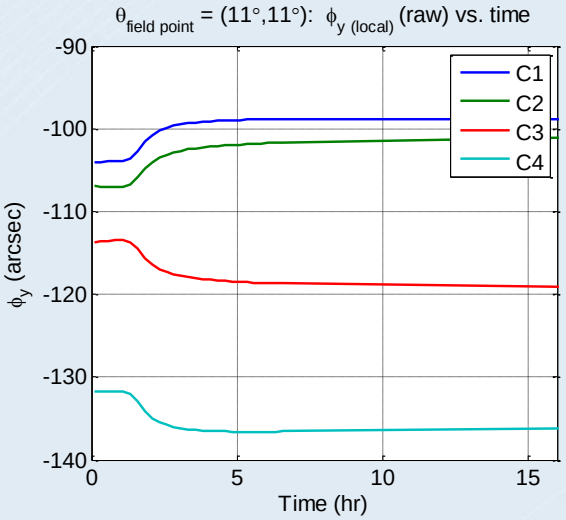


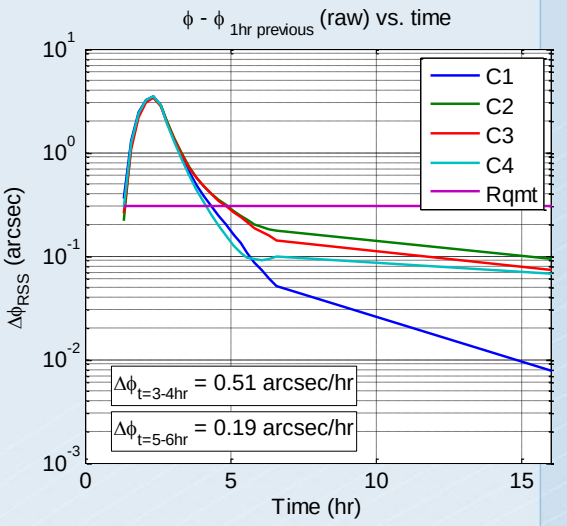
IRD_32 = 0.30 arcsec / hr

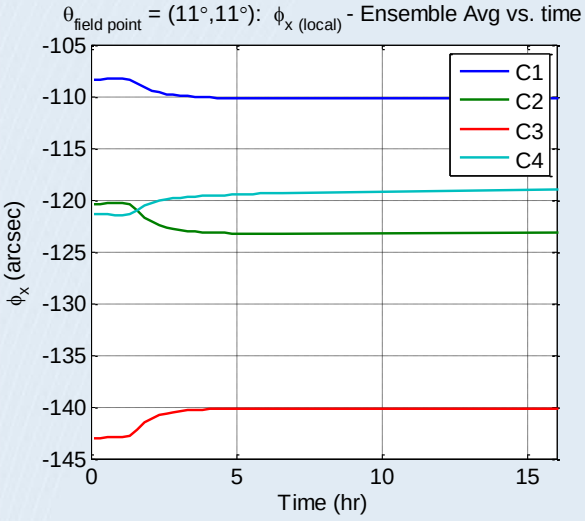
Peak PSF Motion (11°, 11°) vs. t

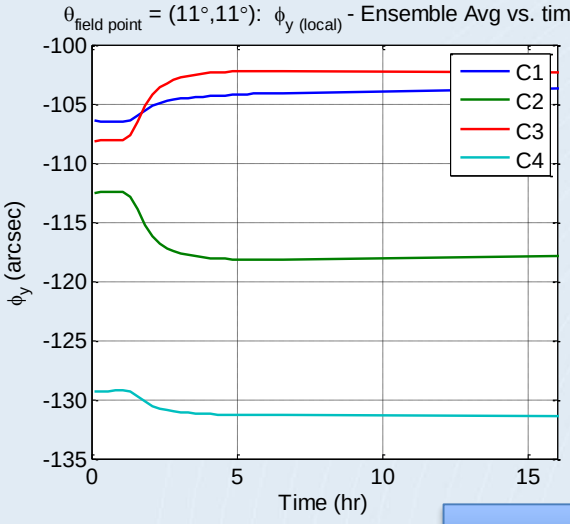
Subtracting the ensemble average does not necessarily achieve image stabilization

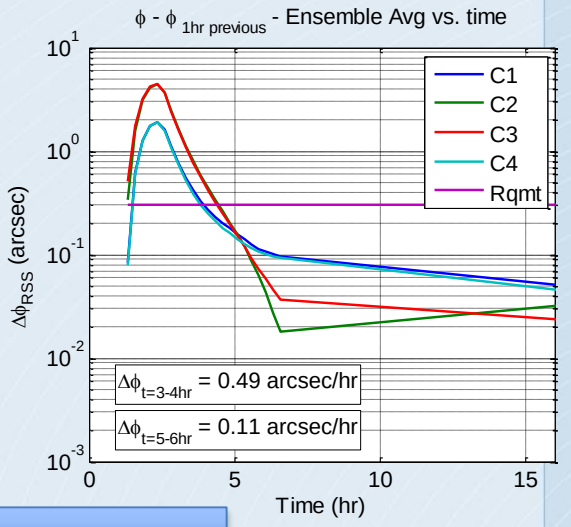












IRD_32 = 0.30 arcsec / hr

Extended Time Period PSF Motion

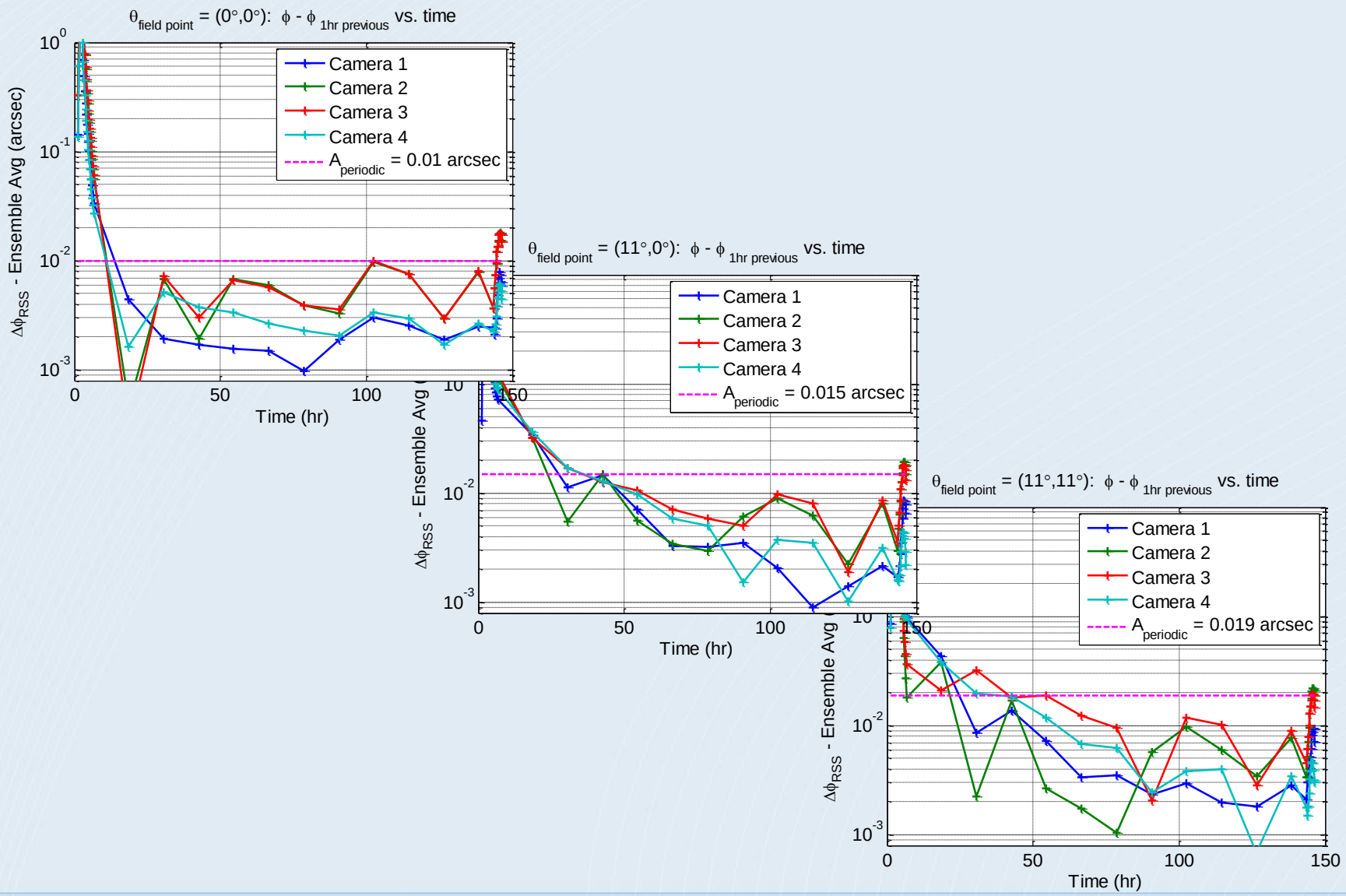
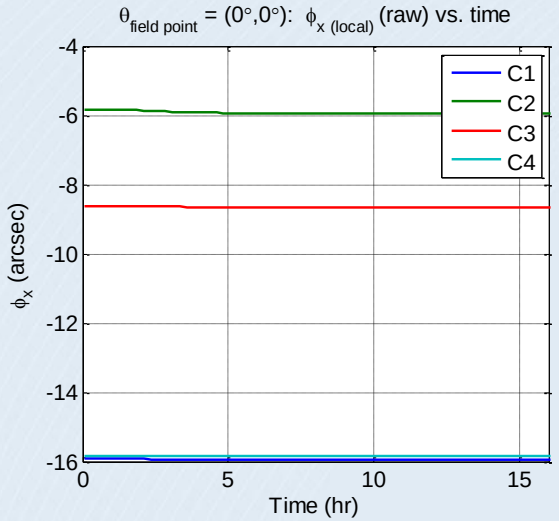
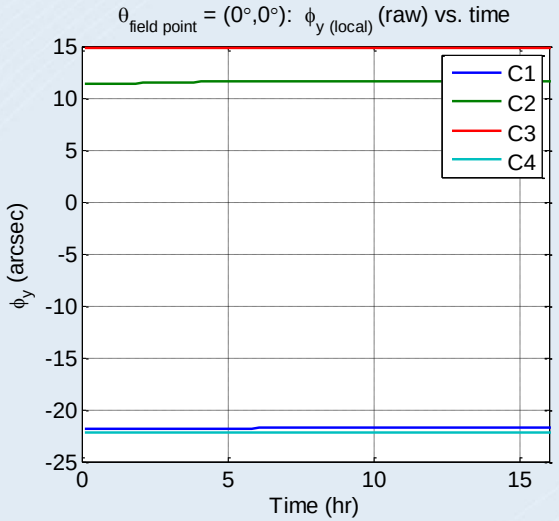
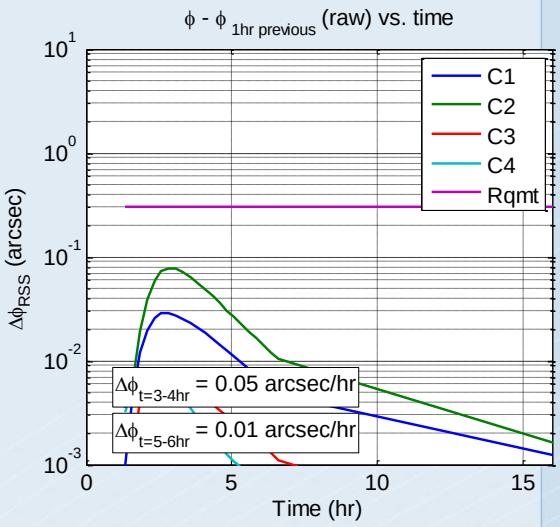


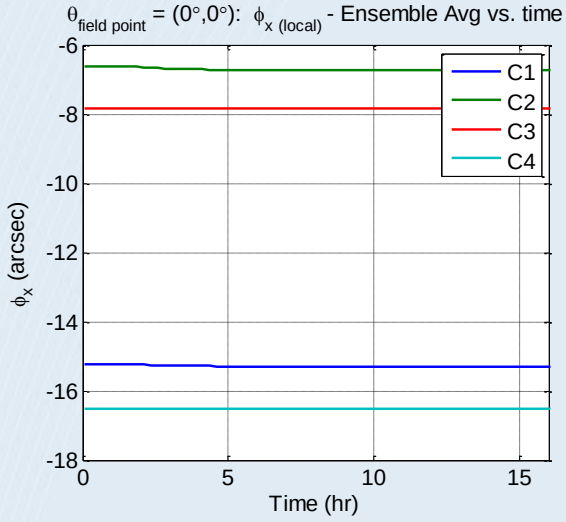
Plate (Only) Contribution to PSF Motion

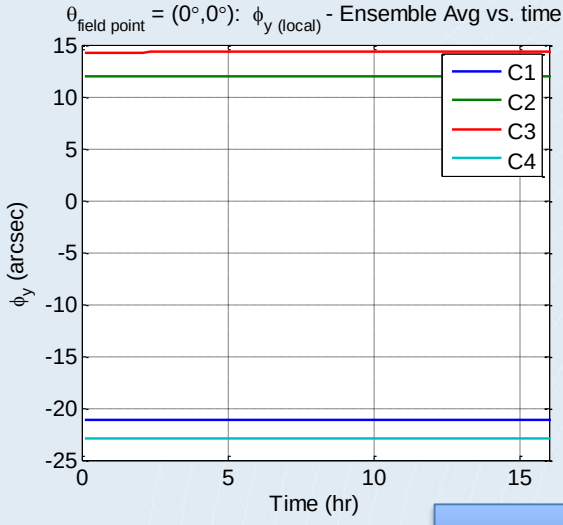
Subtracting the ensemble average does not necessarily achieve image stabilization

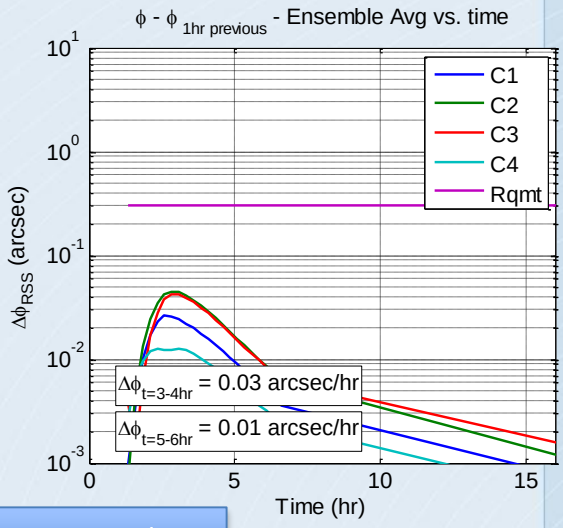








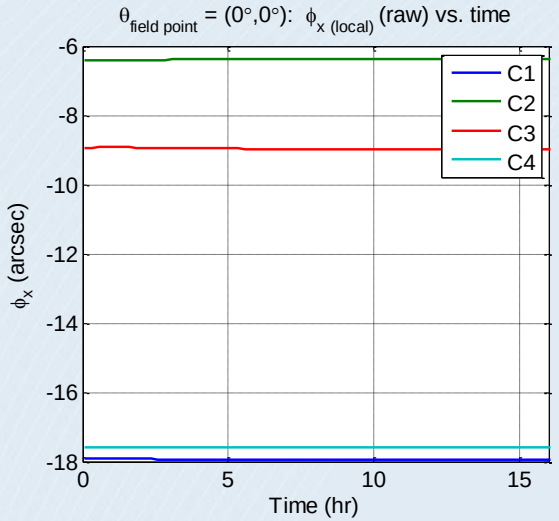


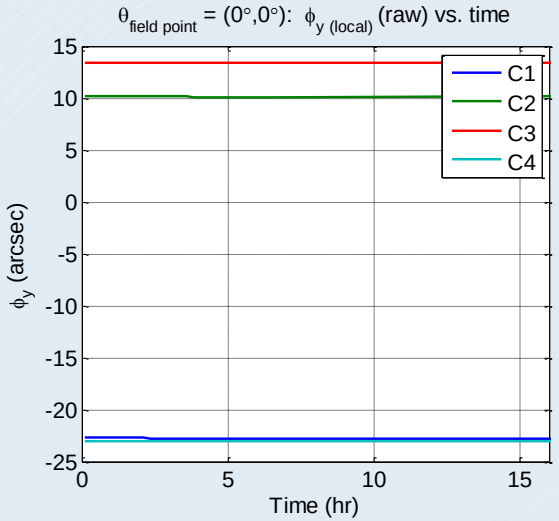


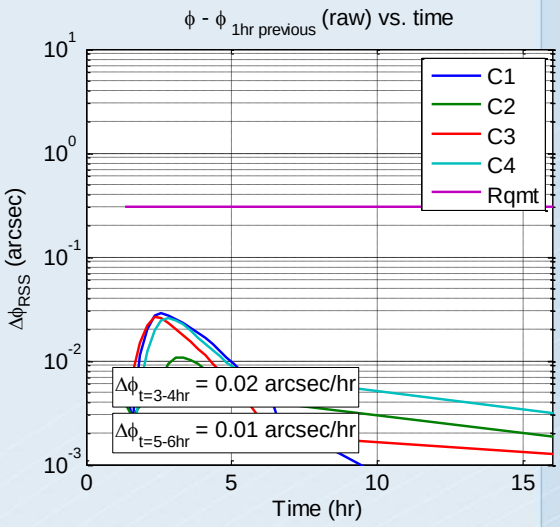
IRD_32 = 0.30 arcsec / hr

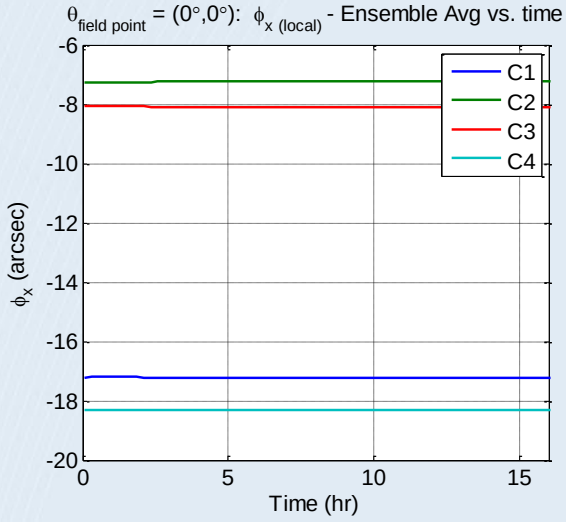
Flexures (Only) Contribution to PSF Motion

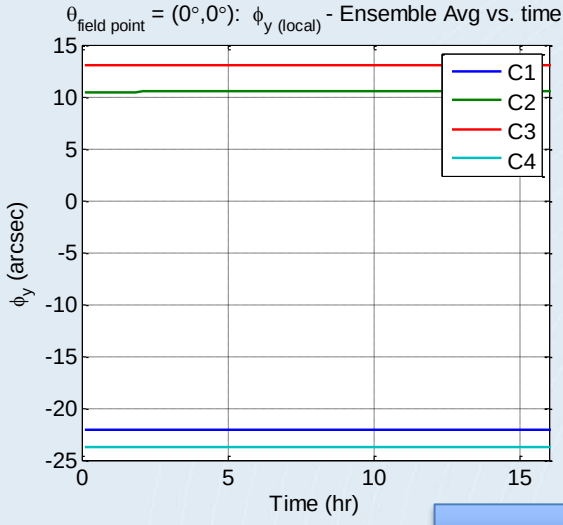
Subtracting the ensemble average does not necessarily achieve image stabilization

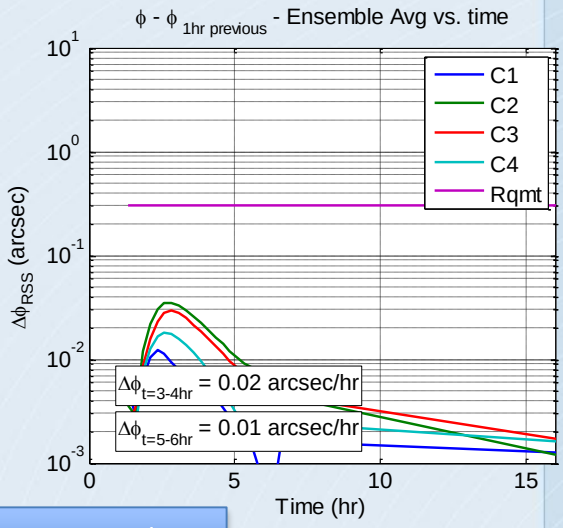








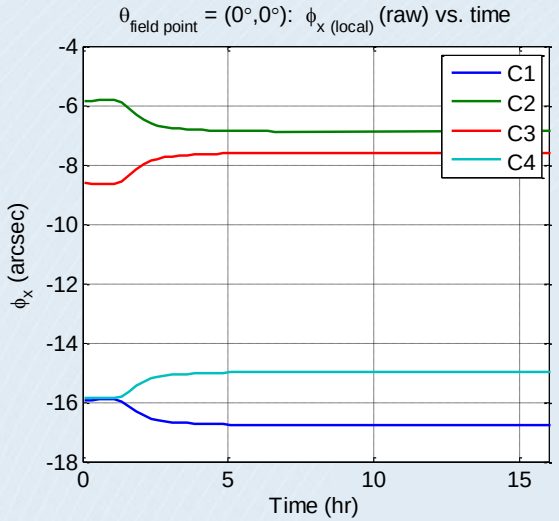


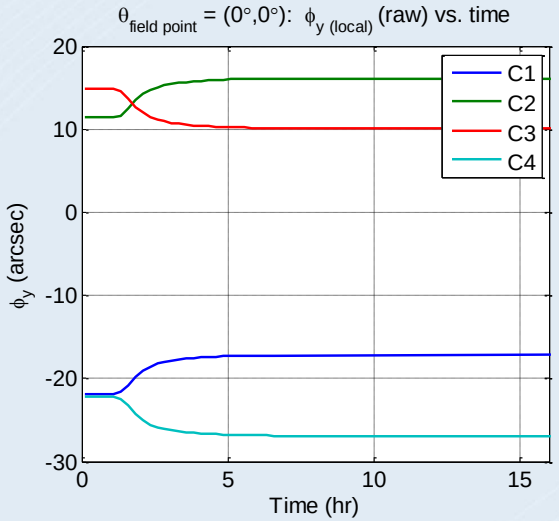


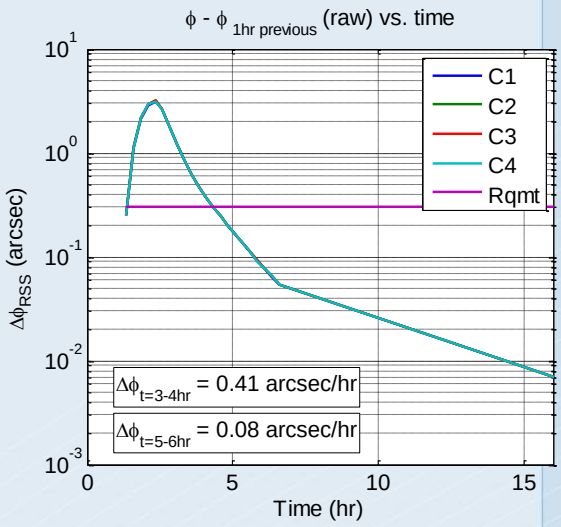
IRD_32 = 0.30 arcsec / hr

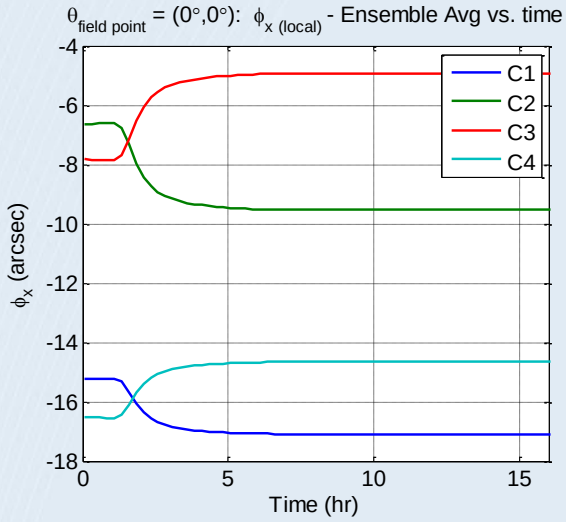
Posts (Only) Contribution to PSF Motion

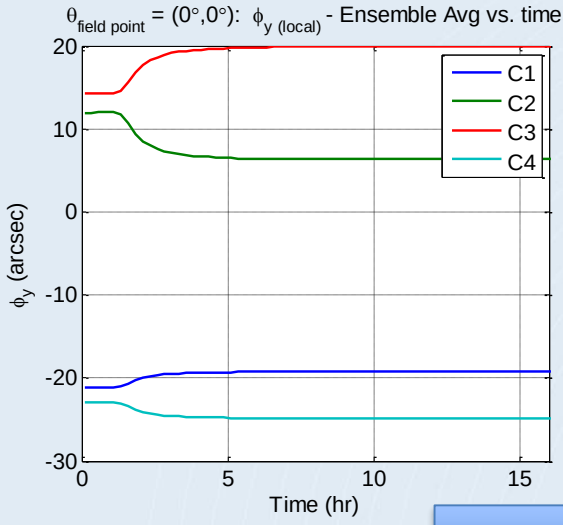
Subtracting the ensemble average does not necessarily achieve image stabilization

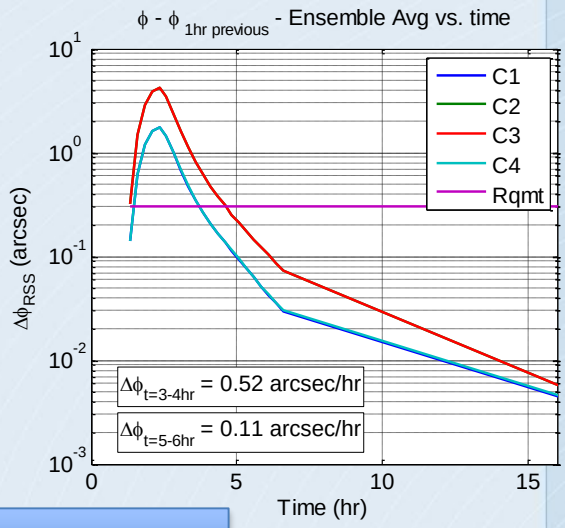












IRD_32 = 0.30 arcsec / hr

Path Forward

- Perform additional model validations
- Complete remaining thermal scenarios
- Analyze eclipse portion of orbit to characterize performance
- Release finalized STOP Analysis V&V Report

Backup