UC Observatories
Laboratory for Adaptive Optics

ShaneAO

ShaneAO
Final Design Review

(Architecture & Optomechancial)

UC Observatory

April 26, 2012

Introduction to the team

- Optical design
  - Renate Kupke (+Proj Mgr)
- Science Camera
  - Prof. Connie Rockosi
  - Michael Peck
  - Rosalie McGurk
- Mechanical design
  - Jerry Cabak
  - Chris Ratliff
  - Daren Dillon
- Electrical systems
  - Barry Alcott

- *Thank you* to our reviewers
  - Bruce Macintosh, LLNL
  - Brian Bauman, LLNL
  - Les Saddlemyer, HIA
  - Michael Fitzgerald, UCLA

Your expertise is and advice is highly valued

Introducing ShaneAO: The new Adaptive Optics System for Lick Observatory

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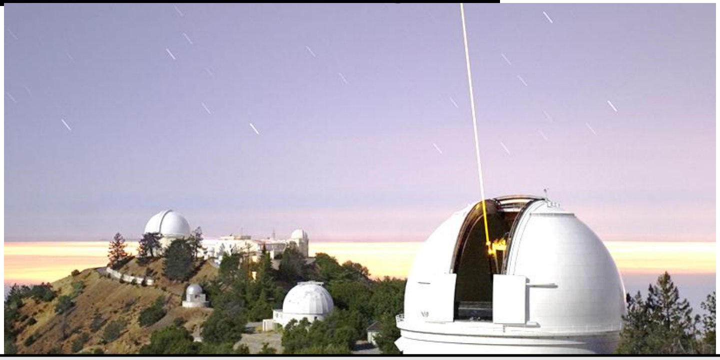
What the new system provides in comparison to the old:



Old System	ShaneAO
High Strehl in K band J and H accessible	High Strehl in J, H, and K bands I band accessible
Diffraction-limited imaging in K 19 arcsec FOV 76 mas/pix	Diffraction-limited in J, H, and K 20 arcsec FOV 33 mas/pix more sensitive science detector
Limited to short exposures	4-hour exposures enables dim object spectra
Fixed on-sky orientation	Instrument can rotate to set the spectrograph slit angle

Expanded Science

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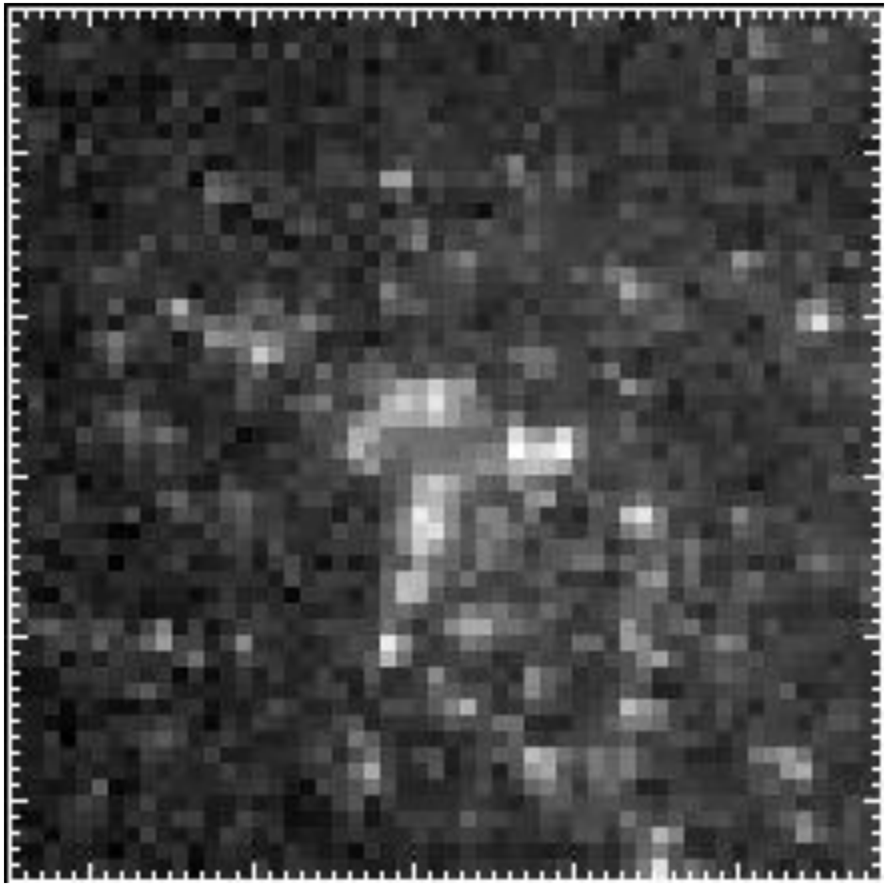
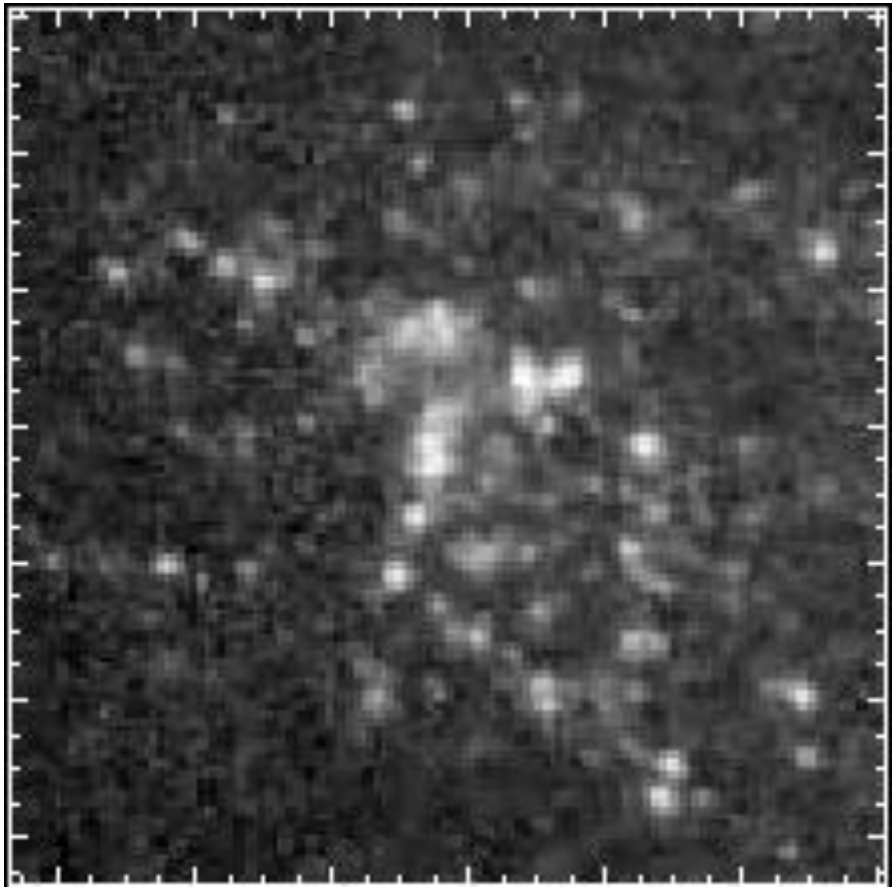
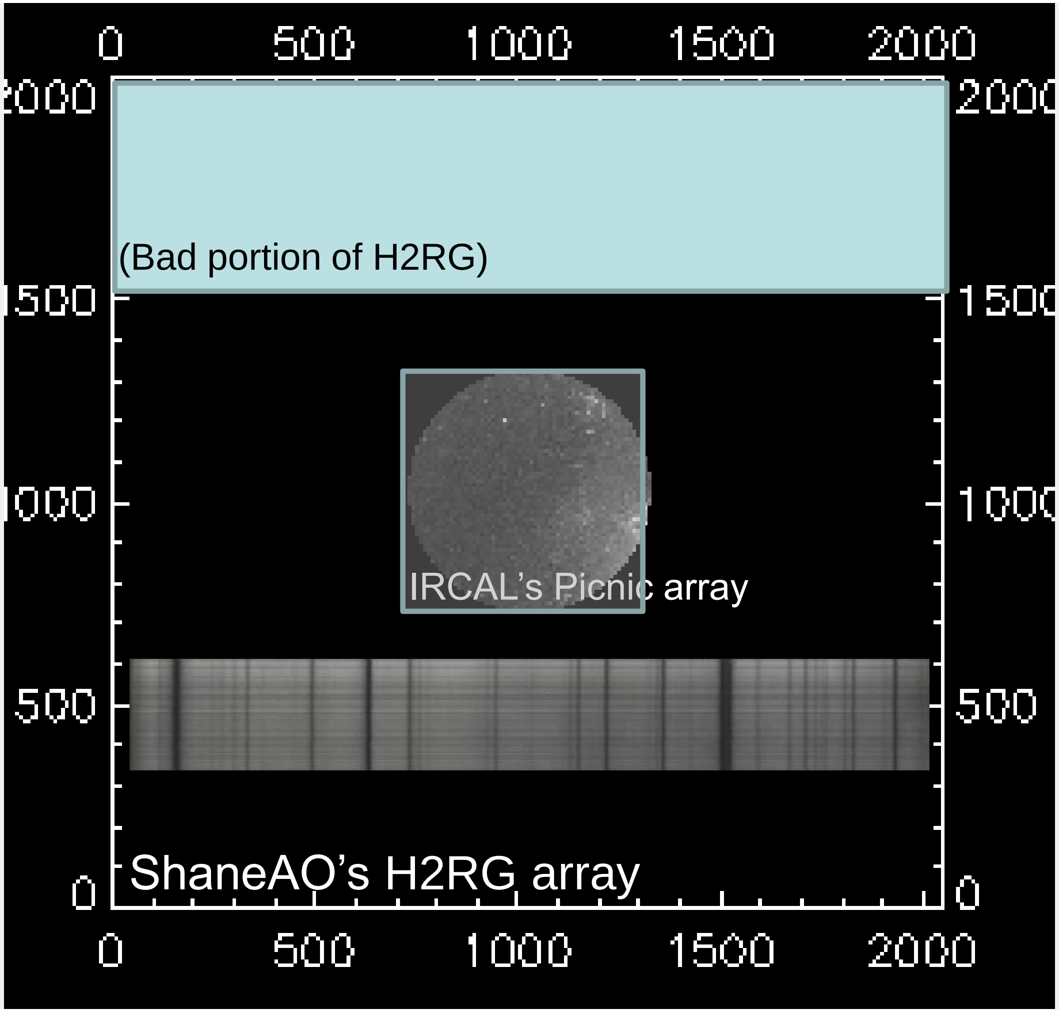
Lick AO science pixels



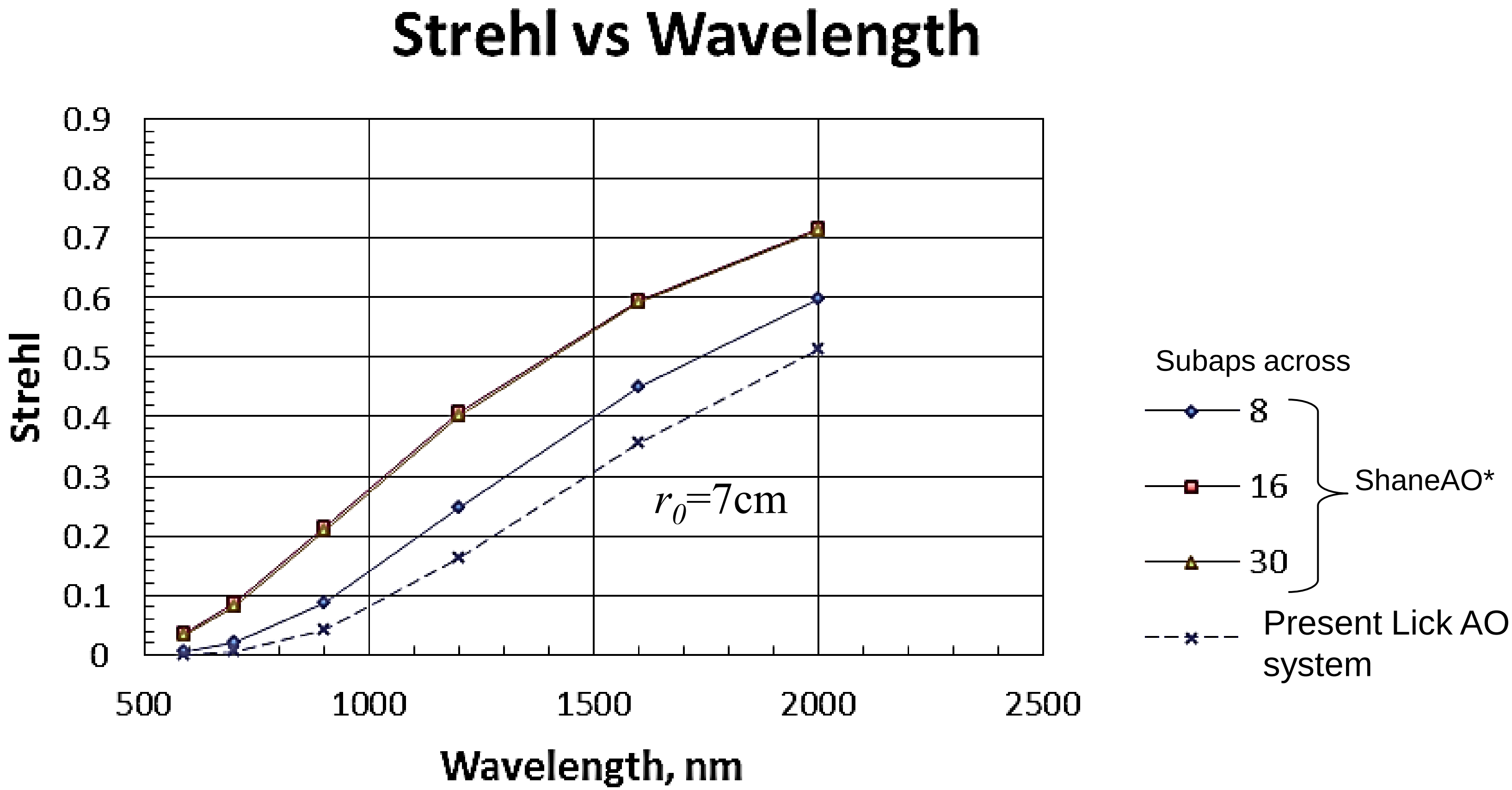
ShaneAO science pixels



Expanded Science
chip area for more spectral resolution



Improved Performance



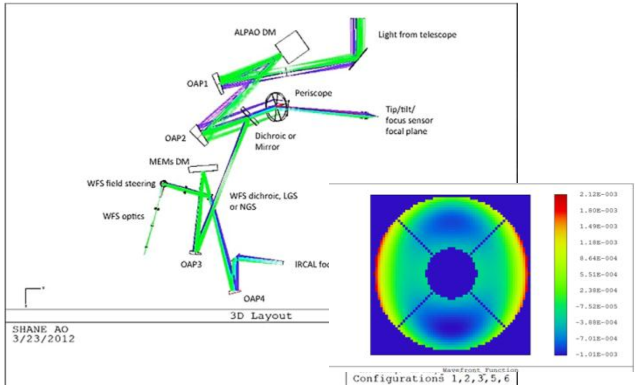
* Assumes the LLNL fiber laser

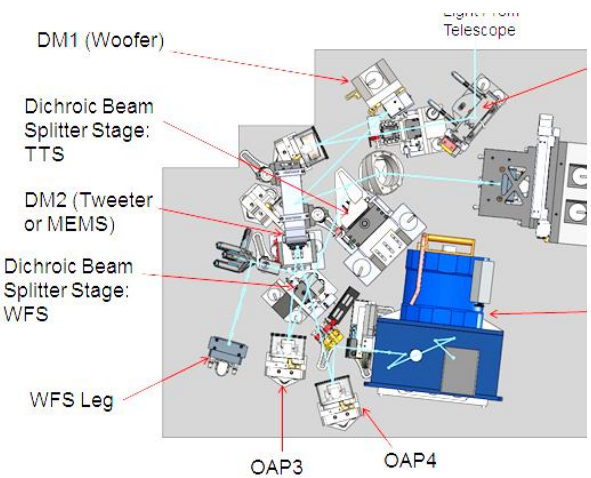
Purpose of the Review

- The review's objectives from our standpoint:
  - Overview the system objectives & requirements
  - Subject the design solution to critique
  - Achieve the milestone: design completion and transition to fabrication stage
- Charge to the reviewers:
  - Evaluate the design for effectiveness and completeness
  - Provide objective criticism and suggestions
  - Evaluate readiness to move to fabrication
  - Produce a summary report

Agenda

- 1:00 Intro
  - Charge to the reviewers
  - Top level requirements
  - Science and science camera
- 1:30 Optical design
- 2:15 Mechanical design
- 4:15 Reviewer closed session
- 4:40 Feedback





Key top-level Requirements

- Diffraction-limited imaging in J, H, K bands; science imaging in I
- 20” unvignetted science field of view
- Field rotation
- Wavefront correctors at pupil conjugates
- Selects tip/tilt stars on a 60 arcsec radius field
- Opto-mechanical stability to enable a 4-hour “blind” exposure (+/- 2 hours across zenith) ★

ShaneAO Science Camera (IRCAL) Upgrade

C. Rockosi, M. Peck,
R. McGurk, D. Cowley, M. Saylor
Shane AO Team

IRCAL

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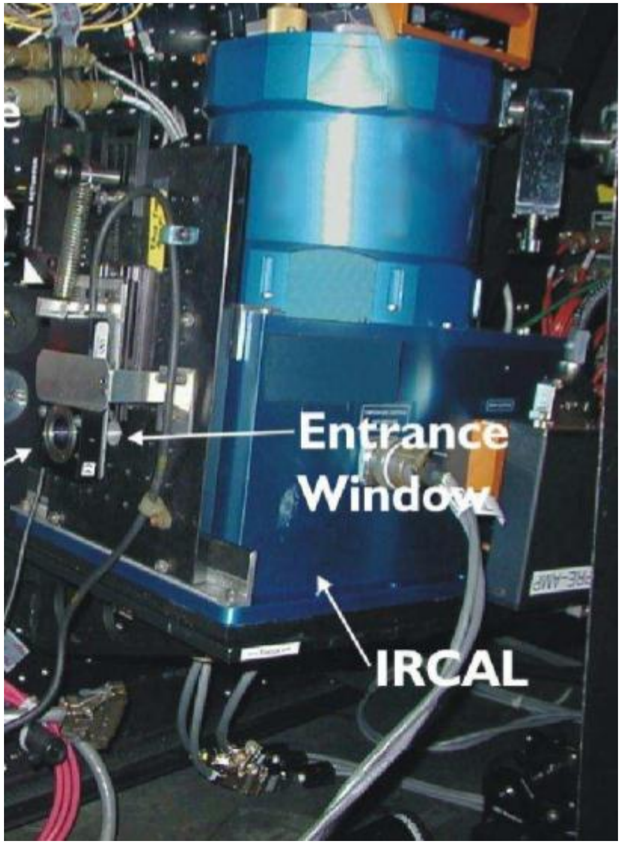
- Primary AO science instrument
  - guest instruments also possible
  - in operation since 1999, built by J. Graham, J. Lloyd, M. Perrin (pol)
- 20” FoV
- Aperture wheel at focal plane, two filter wheels near cold stop.
  - JHK, narrow-band filters, grisms, polarimeter
- Motors outside dewar, coupled w/ feed-thrus
- IR-Labs LN2-cooled dewar.
  - Good hold time, generally trouble-free.
- Aluminum optical bench to match CTE of OAPs. Designed to allow alignment at room temperature. Works well.

IRCAL

- Relevant features of the current IRCAL:
  - detector: PICNIC 256k, 76 mas/pix
    - compare 3m diffraction limit in H: 0.11” FWHM
  - cold stop after aperture wheels
  - stationary pupil mask at cold stop
- Successful workhorse instrument for imaging, polarimetry.
- Spectroscopy is a goal for upgrade



From Perrin et al. 2008

IRCAL: upgrade plans

- New detector: H2RG engineering device
  - 18 um pixels, 35 mas/pix
    - Compare J-band diffraction limit 0.086”
  - QE: goal > 80% for λ > 1 um vs. 62% in K for the PICNIC array
- Move cold stop before filter wheels for polarimetry
- Detents at each aperture wheel position for repeatable location
  - reliable spectroscopy
- Enable TUB rotation of entire AO bench, including IRCAL
  - slit rotation, occulting finger position, ...
- New cold mask on optical substrate, no mask for spider vanes
- Mechanical mods seem straightforward to implement. Reviewer comments on ?

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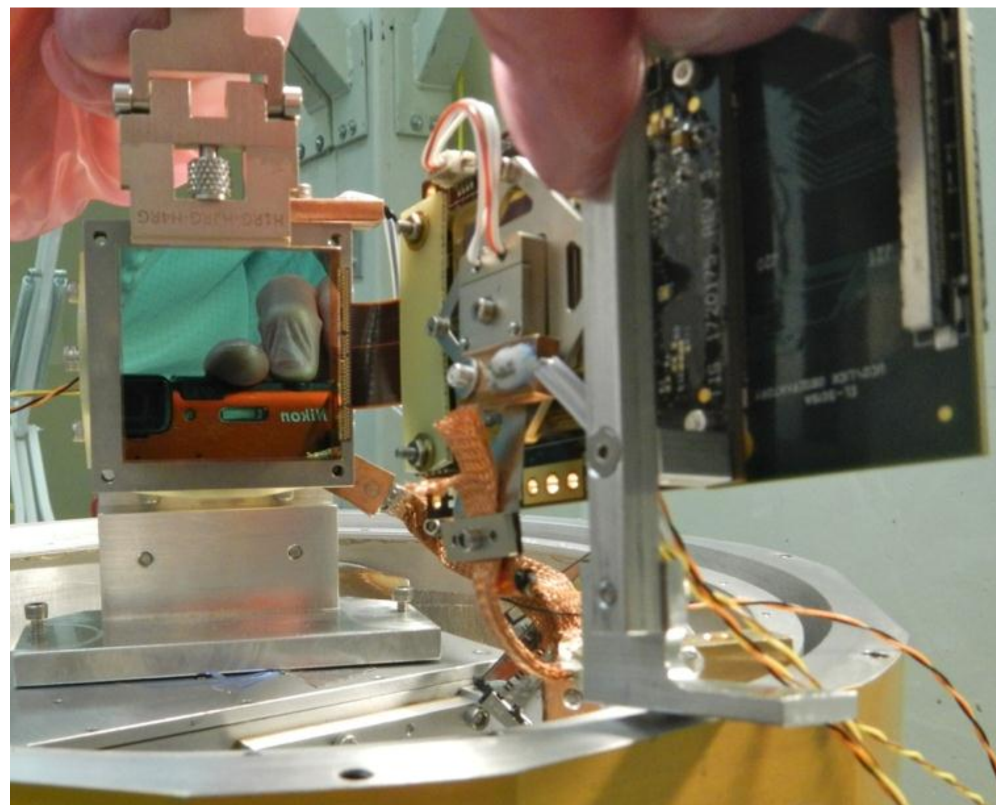
IRCAL: new detector plans

- New detector: H2RG engineering device
  - 18 um pixels
  - IRCAL 20” FoV ~ 600x600 pix
  - 34 mas/pix, compare J-band diffraction limit 0.086”
  - Engineering device is missing 800 rows, otherwise meets H2RG science specs
  - Cutoff wavelength 2.5 um



IRCAL: new detector plans

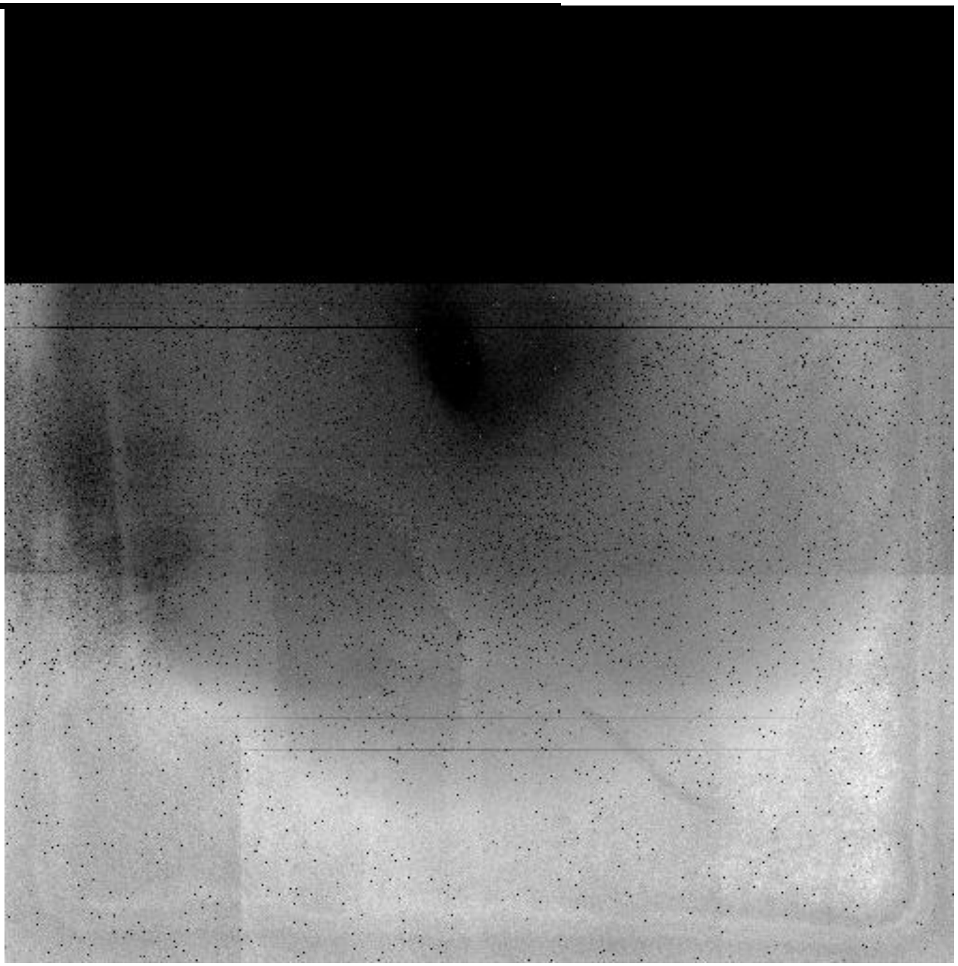
- Electronics: Teledyne's ASIC and JADE2 interface card
  - COTS cable + custom interface board between ASIC and JADE2 through dewar wall
- Software: Jason Weiss @ UCLA will help (0.5 FTE) modify the MOSFIRE detector software to work with the new IRCAL
  - disentangle IRCAL software from the AO Bench software

IRCAL: new detector

- H2RG, ROIC and ASIC in-hand
- Teledyne test data:
  - CDS noise: 14 e- (single read), 5.1 e- (Fowler 32)
  - QE:

800 nm	1 um	1.23 um	2 um
0.85	0.78	0.91	0.93

  - H2RG data cold in test dewar (4/24)
    - ASIC, JADE2 and custom interface cables, Teledyne software



Background and Sensitivity

- Mt. Hamiltion NIR sky brightness, mag arcsec^{-2}
  - J = 16 H = 14 K' = 13
- IRCAL Ks total background: 10.3 mag arcsec^{-2}
- Model sky, telescope and AO system emission and transmission
  - sky spectra from Gemini SciOps, measured or representative coating data, average observatory temperatures
  - model validated by reproducing* Mauna Kea and Mt. Hamilton sky brightness, Keck AO system background measurements. NGAO document KAON501
- Useful comparison: Mauna Kea NIR sky brightness, mag arcsec^{-2}
  - J = 16.1 H = 13.8 K = 14.9
  - NIRC2 background: K = 12.6 mag arcsec^{-2}
  - Mt. Hamilton K-band sky > 6x brighter than MK
  - Shane AO and Keck AO BG factor ~10 brighter than sky

Background and Sensitivity

- Useful comparison: Mauna Kea NIR sky brightness, mag arcsec^{-2}
  - Mt. Hamilton K-band sky > 6x brighter than MK
  - Shane AO and Keck AO BG factor ~10 brighter than sky
  - Keck AO system: 14 surfaces, $\langle T_{MK} \rangle$ 5 C
  - Shane AO system: 12 surfaces, $\langle T_{MH} \rangle$ 10 C
  - Shane AO system BG ~10x brighter than Keck w/ ~same # surfaces
  - Difficult to explain with any reasonable model for Shane AO
  - Consistent with optical model for IRCAL that shows cold pupil mask is 18% oversize
  - Predicted IRCAL BG in Ks including oversize pupil mask: 11.1 mag arcsec^{-2}
  - remaining ~0.8 mag plausibly dust, coating degradation, model uncertainty, ...

Backup

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H2RG Teledyne Test Data

Parameter	Unit	Specification [1]	Goal [1]	Measured [1]	Pass / Fail
Read-out integrated circuit (ROIC)		Hawaii-2RG	-	-	By Design
Number of Pixel [2]	#	2048 x 2048	-	-	By Design
Pixel Size	µm	18	-	-	By Design
Outputs [3]		Programmable 1, 4, 32	-	1, 4, 32	Pass
Power Dissipation [4]	mW	≤ 1.0	≤ 0.5	0.33	Achieves Goal
Detector Material		HgCdTe	-	-	By Process
Detector Substrate		CdZnTe - Removed	-	-	By Process
Cutoff wavelength @ 77 K (50% of peak QE) [5]	µm	2.45 - 2.65	2.50 - 2.55	2.51	Achieves Goal
Quantum Efficiency (QE) 0.6 - 1.0 µm [5, 6]	%	≥ 55	≥ 70	82	Achieves Goal
Quantum Efficiency (QE) 1.0 - 2.4 µm [5, 6]	%	≥ 70	≥ 80	85	Achieves Goal
Median Dark current @ 0.25 V bias and 77 K	e-/s	≤ 0.1	≤ 0.01	0.003	Achieves Goal
Median Read Noise (single CDS) [7]	e-	≤ 25	≤ 15	14	Achieves Goal
Well Capacity at 0.25 V bias	e-	≥ 65,000	≥ 100,000	113,000	Achieves Goal
Crosstalk [8]	%	≤ 5	≤ 2	0.8	Achieves Goal
Residual Image (Latency) [9]	%	≤ 0.1	≤ 0.01	0.02	Pass
Operability [10]	%	≥ 95	≥ 99	68.62	Fail *)
Cluster: 50 or more contiguous inoperable pixel	%	≤ 1% of array	≤ 0.5% of array	0.03	Achieves Goal
SCA Flatness [11]	µm	≤ 30	≤ 10	8	Achieves Goal
SCA Parallelism [12]	µm	≤ 50	≤ 25	23	Achieves Goal

Science & Requirements

Reviewer Q&A
and Discussion

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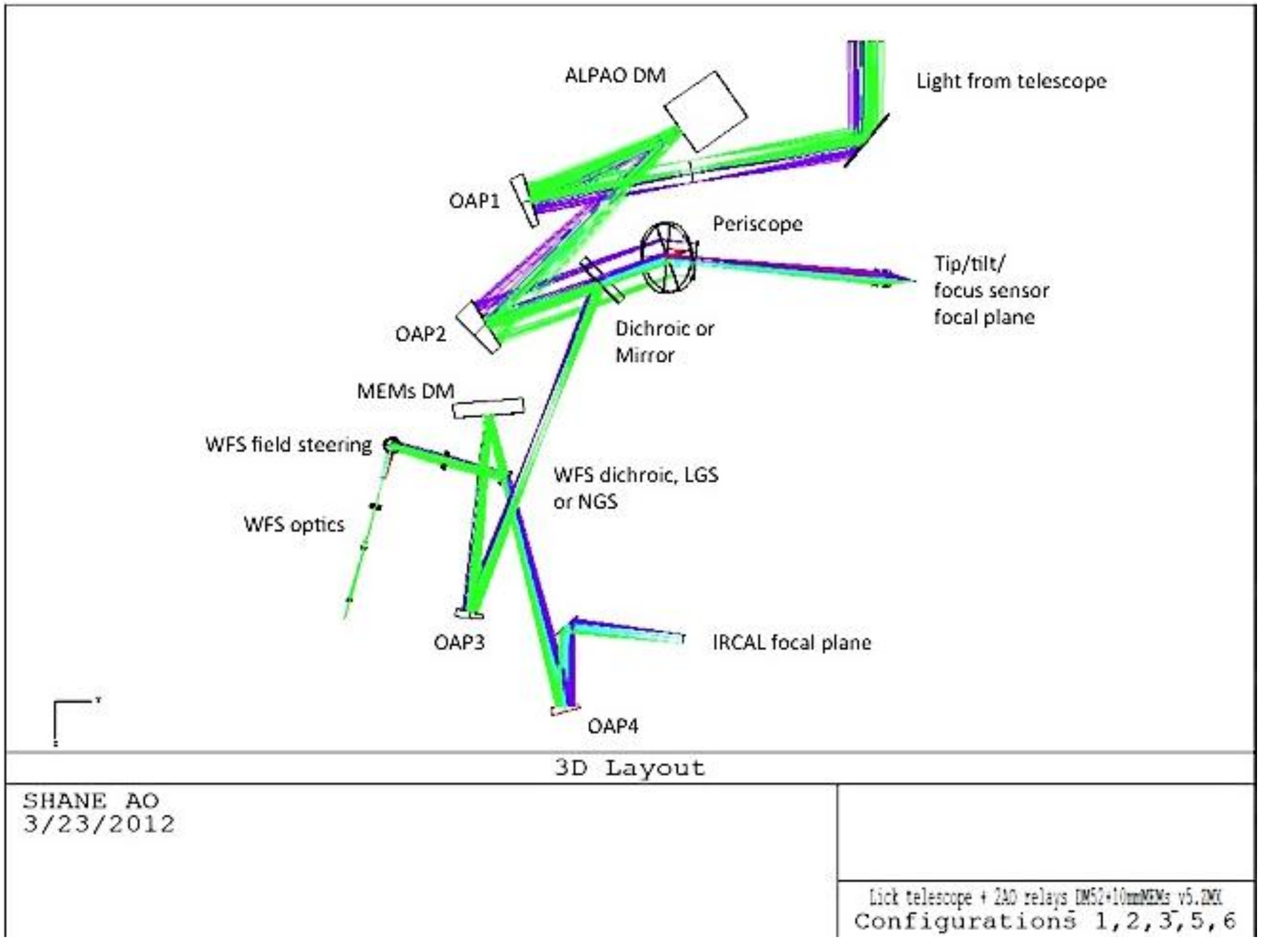
Shane AO Optical Design



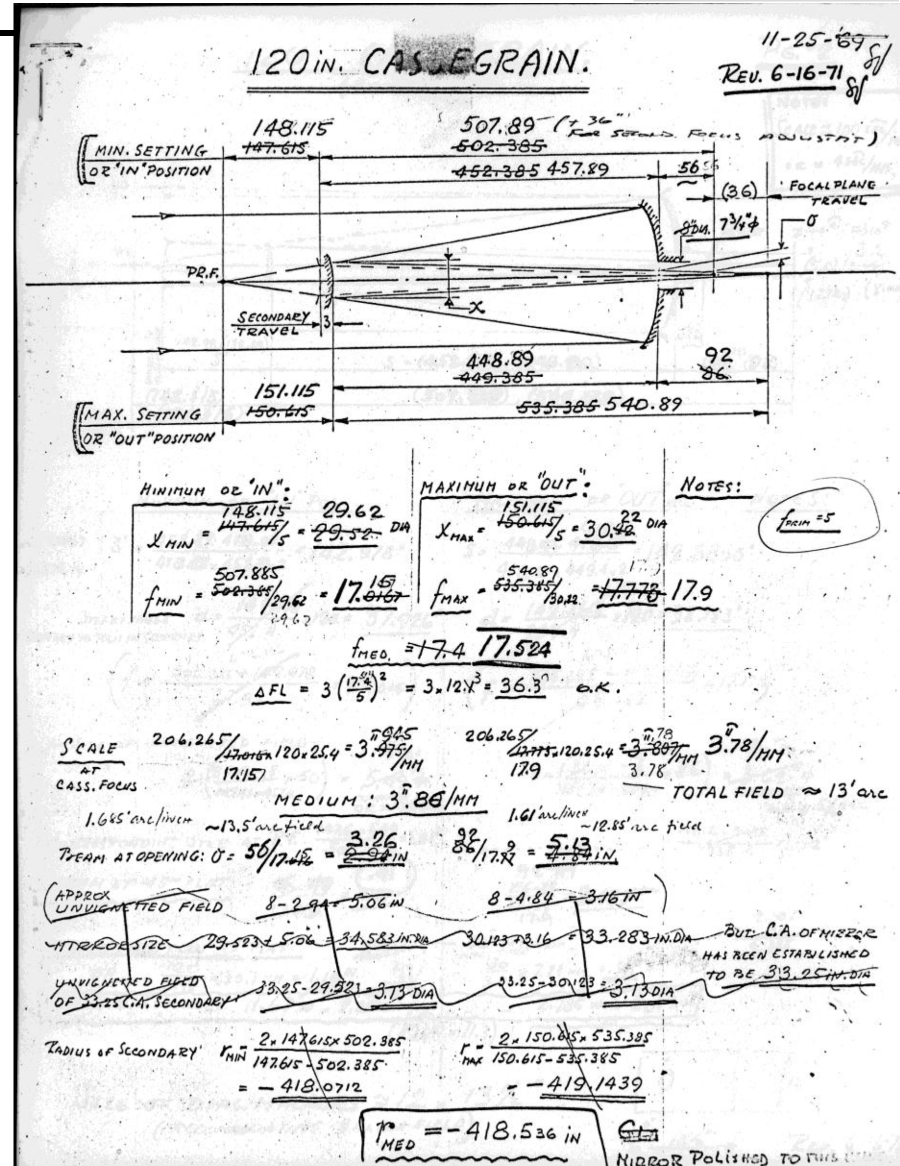
Lick 3-meter telescope

- 3-meter parabolic primary mirror
- ShaneAO will be mounted as a Cassegrain instrument
- Secondary provides f/17.1 – f/18 beam at Cassegrain focus depending on position (moved to focus telescope)
- Exit pupil is 16.8 m upstream of Cassegrain focus with a diameter of 0.9 m
- Plate scale of approximately 4”/mm at Cassegrain focus

Reviewer Question

Q: Why so much uncertainty in the delivered telescope f#? It's a +/-3% variation, which is +/- 1 subap, which means you need to keep updating the partial subap thinking, or at least you don't know what your partial subap situation is going to be?

A: The delivered telescope f/# varies from f/17.1-f/18 depending on the location of the secondary mirror. Those numbers are based on a hand-made drawing and calculations from 1971. We have measured the position of the Cassegrain focus relative to the telescope tub at mid-travel of the secondary, but don't have any additional information about the f/# at that point.



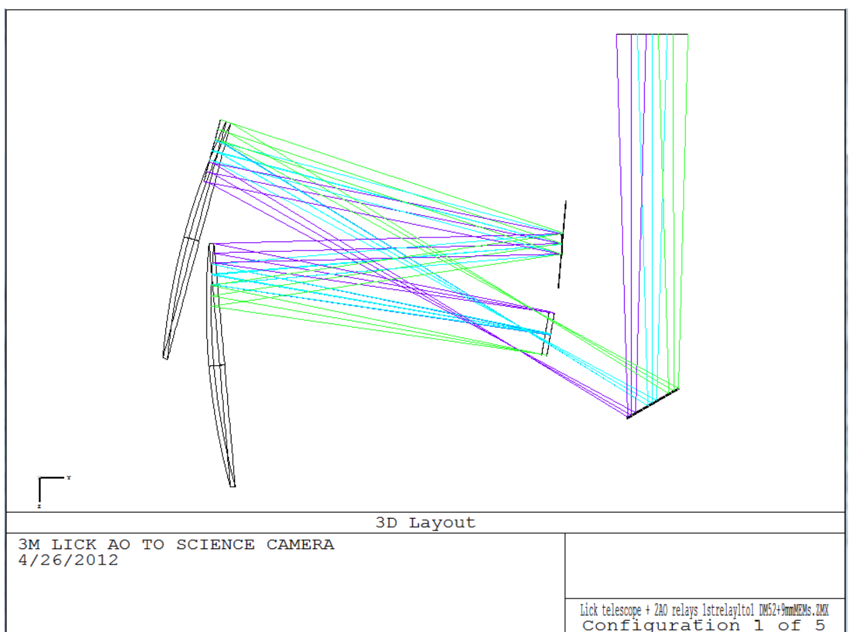
Wide field, 1st relay

- Unmatched OAP relay, f/17.5 input, f/28.5 output
- Low-order deformable mirror, 15 mm diameter, 52 actuators provides tip/tilt and low order, slow correction
- Reflects 0.589 μm (LGS) and NIR to second relay, transmits 0.6-0.9 μm to tip/tilt sensor
- Transmits 120” field of regard to tip/tilt sensor
- Calibration stage located at Cassegrain focus provides white light and red fiber source, and sky-pointing acquisition camera for bright stars

Reviewer Question

Q: Optical design: I’m curious (would like a bit more detail) as to why go to f/28.5 at the first relay? Wouldn’t it be more compact to do this at the second relay?

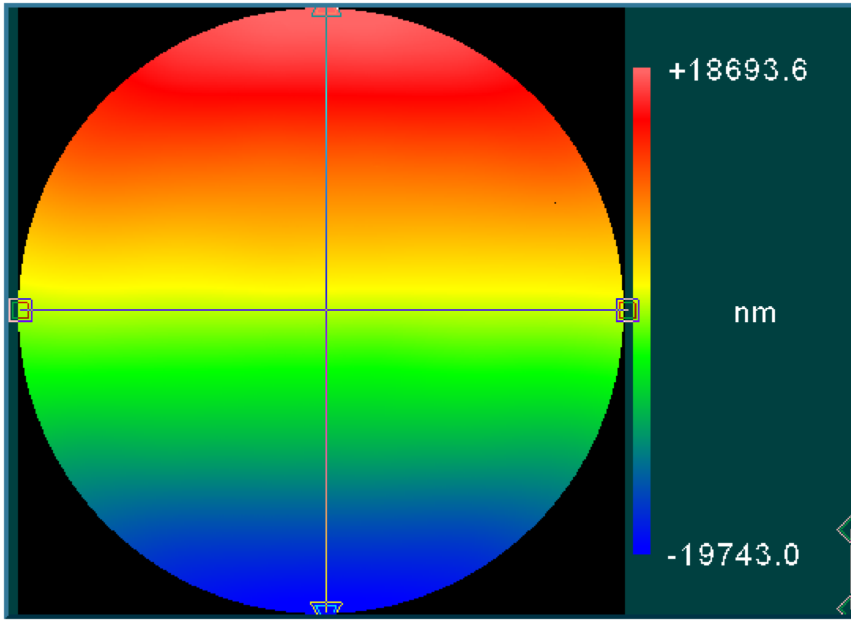
A: I would have preferred that, too. This is driven by layout considerations. The 15 mm diameter DM + 30 mm field of view made the packaging difficult with a matched relay. The focal lengths of the OAPs are relatively short compared to the size of the field.



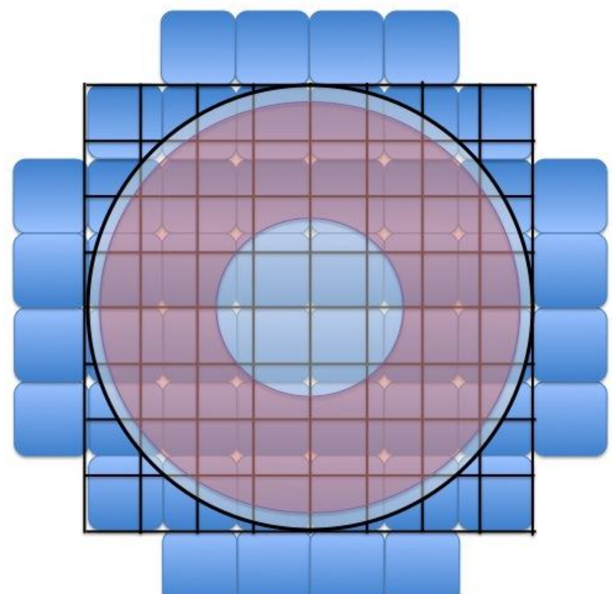
Woofer deformable mirror

- Voice-coil actuated
- 8 µm interactuator stroke (surface)
- 40 µm tip/tilt stroke (surface)
- 250 Hz bandwidth
- Clear aperture of 15 mm
- Protected silver coating

Woofer deformable mirror



- Measured woofer tilt stroke of 40 μm P-V, surface. Requirement: 32 μm P-V
- Departure from pure tilt increases with tilt, up to ~150 nm RMS at full stroke. This can be removed by tweeter



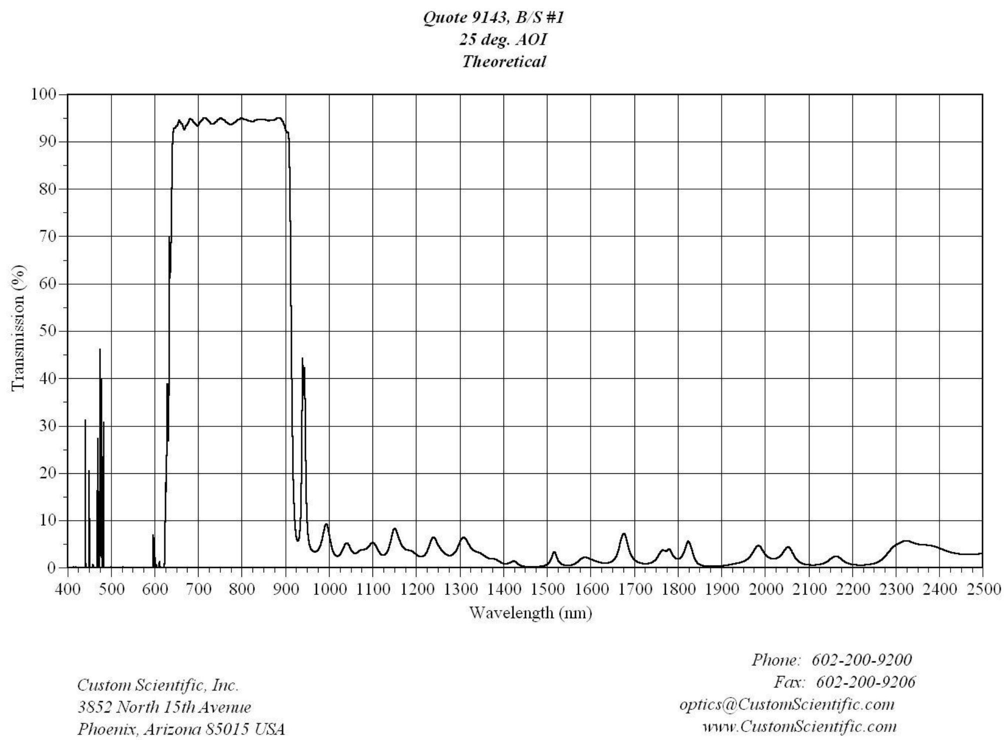
- Subaperture mapping on left, blue pads are mirror actuators, square grid is 8x8 WFS subapertures, the blue circle is the woofer mirror clear aperture, the pink annulus is the pupil image.
- Pupil undersized to account for uncertainty in f/# and beam wander over 120” patrol field.
- Pupil image elongated by 2% due to 10° AOI.

Reviewer Question

Q: The pupil size on the woofer seems like it doesn't match the text. I see 13.2x13.4 mm on the footprint diagram (elliptical probably due to 10 degree elongation), but in the text you say 15mm? I think the same mismatch applies on the MEMS sizing too.

A:In my first order calculations I assumed a pupil diameter of 15 mm on the woofer (similar with the MEMs - I considered the entire aperture in my first order calculations). I later refined that to account for various factors to get the final diameter. Clear aperture of the woofer DM is 15 mm.

TTFS Switchyard

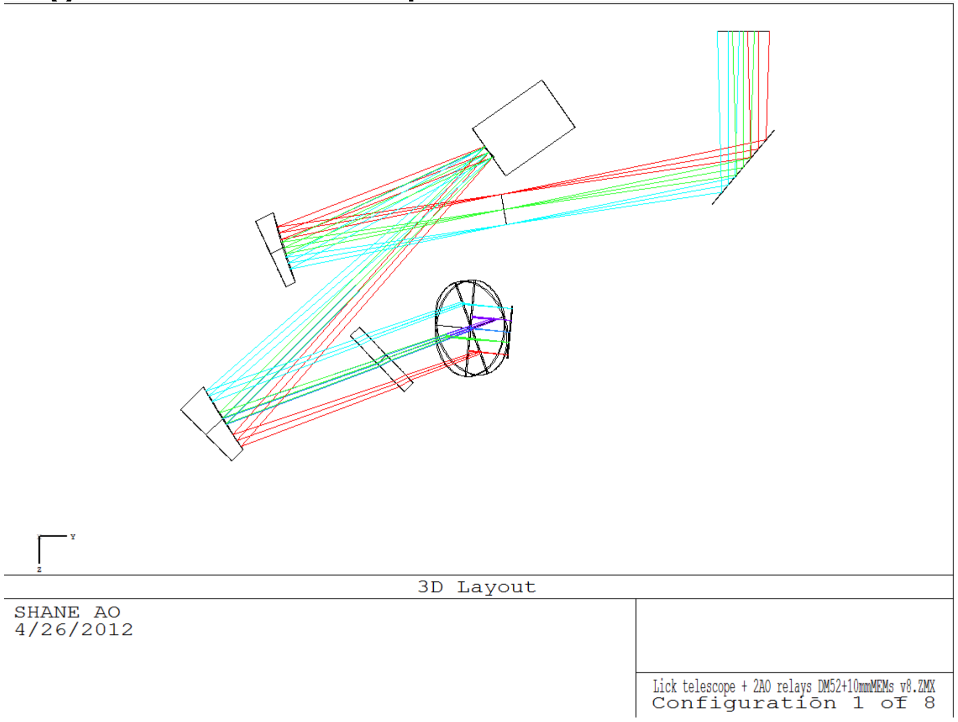


- During LGS operations, visible light will be transmitted to the tip/tilt/focus sensor by a dichroic beamsplitter, transmission curve shown to left.
- During NGS operations, the dichroic beamsplitter will be replaced by a mirror, allowing all wavelengths to enter the second relay.

Reviewer Question

Q: Reasons for choosing to put dichroic after OAP2 rather than before? Or after OAP3?

A:'m assuming you mean TT dichroic? I have tried placing it before OAP2 but the TTFS interfered with the woofer, FM1, and or the calibration stage. Also a little tight with OAP1 for the dichroic changer After OAP3 would mean sizing OAP3 to accept the entire 120" TT patrol field. For the WFS dichroic we preferred the MEMs operating with closed-loop control.



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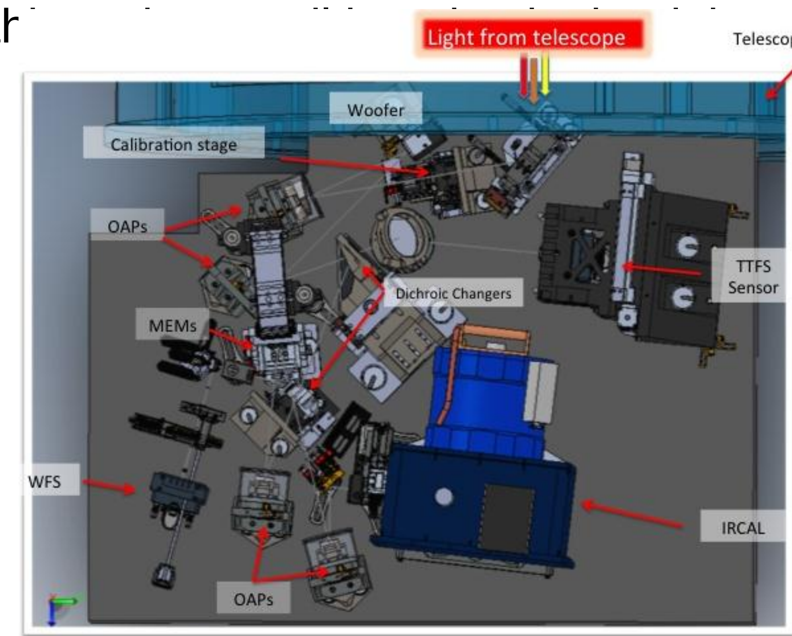
Narrow field, 2nd relay

- Matched OAP relay maintains f/28.5
- High-order deformable mirror, MEMs, 32x32 actuators on 0.340 mm pitch, 10.88 mm square
- Reflects 0.589 – 0.9 μm light to natural and laser guide star wavefront sensor, transmits NIR (1.0-2.4 μm) to science instrument
- Passes an unvignetted 28” circular field of view
- A deployable waveplate is used during polarimetry
- Provides diffraction-limited imaging at 1.0 μm over the entire field of view.

Reviewer Question

Q: Would it have made sense to have changed the f# into IRCAL? (p. 5)

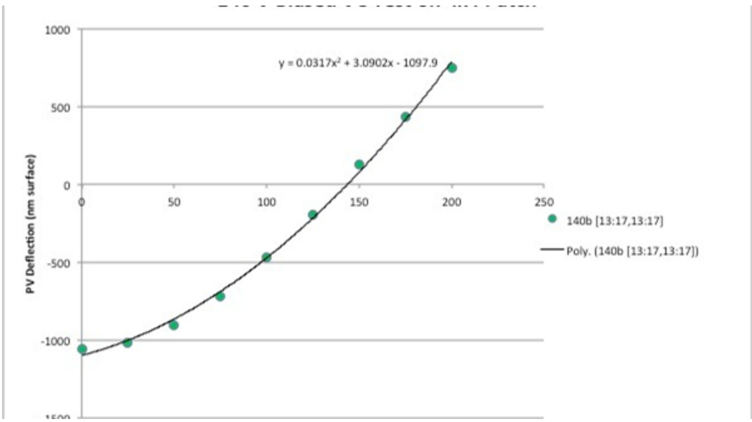
A: I did consider this when we decided to move the pupil in IRCAL. It would have been nice to have a larger pupil, as well. Mechanically it was not feasible to shorten the focal length of OAP4. Also considered lengthening focal length of OAP4 to give us more mechanical leading into IRCAL, but th ... ace of IRCAL difficult.

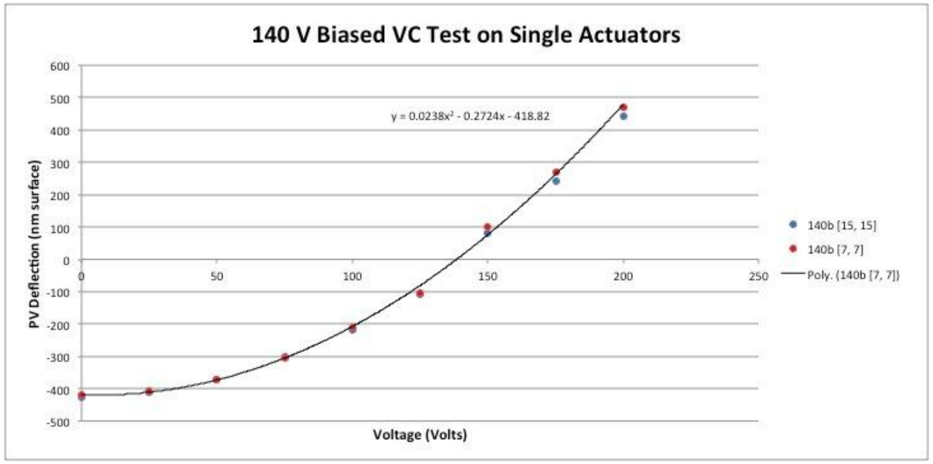


Tweeter Deformable Mirror

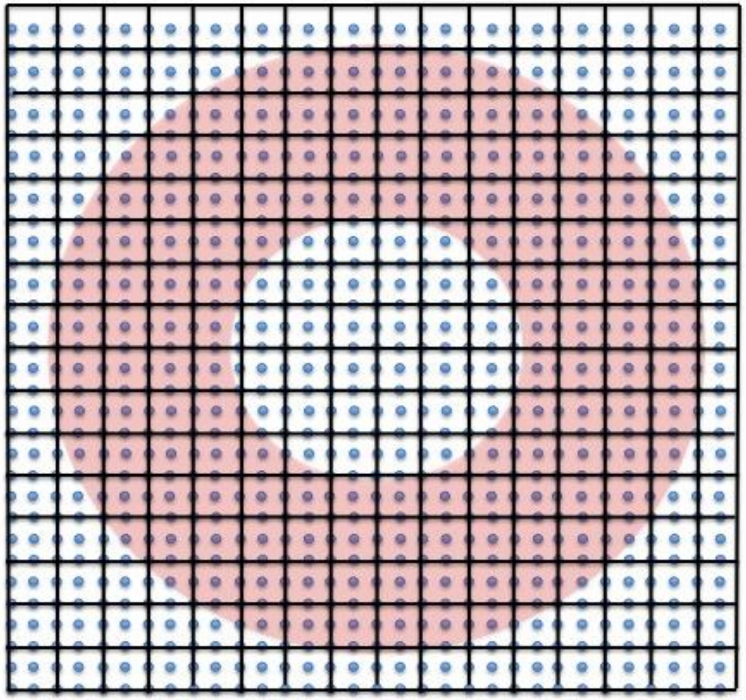
- Boston micromachines MEMs device
- 32x32 actuator with 0.340 mm pitch
- Bandwidth > 1KHz
- Tilted window protects device from environment (primarily high humidity)
- Gold coated

Tweeter Deformable mirror





- Measure single and 4x4 actuator stroke to left
- Pupil mapping on MEMs, below, blue dots are actuators, grid is wavefront sensor subapertures in 16x16, pink annulus is pupil image



WFS switchyard

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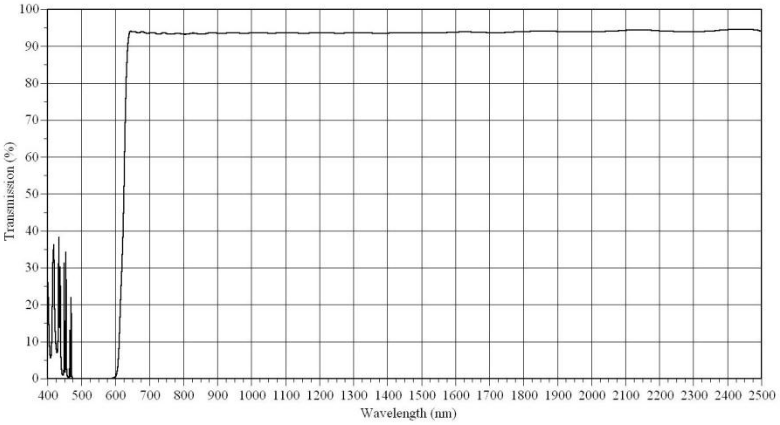

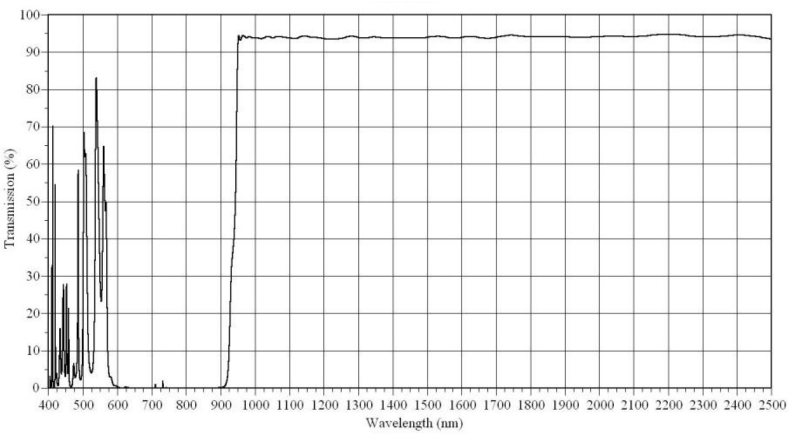

- A choice of two dichroic beamsplitters at pick-off to wavefront sensor allow for switching between LGS guide star, with some visible light science enabled, and NGS guide star with NIR science.

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Science Instrument

- Unmatched OAP relay with f/35 Output
- Pupil conjugate to coldstop located upstream of filter wheel (grism and Wollaston prism)
- Passes unvignetted, circular 28” field of view
- Equipped with a Wollaston prism, used in conjunction with half wave plate, for polarimetry.
- Equipped with narrow band filters for observations in J, H, and K bands
- Equipped with a grism for spectroscopy.
- An aperture wheel provides a selection of slits, pinholes, and an occulting finger
- H2RG has 18 μm pixels, and a plate scale of 0.035”/pixel for Nysquist sampling in J-band

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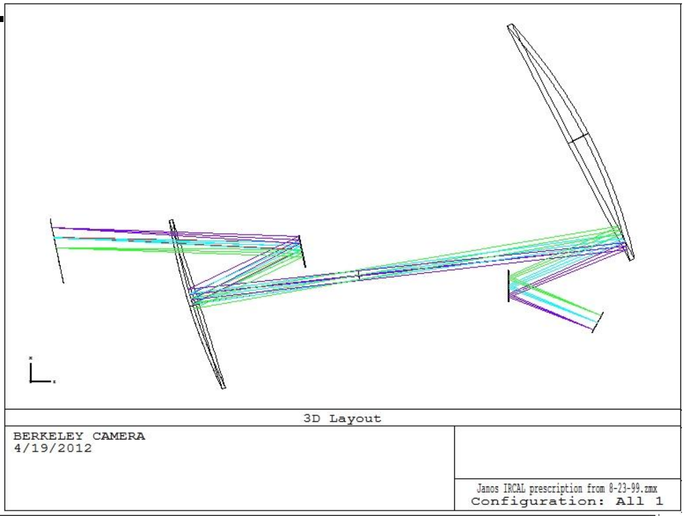
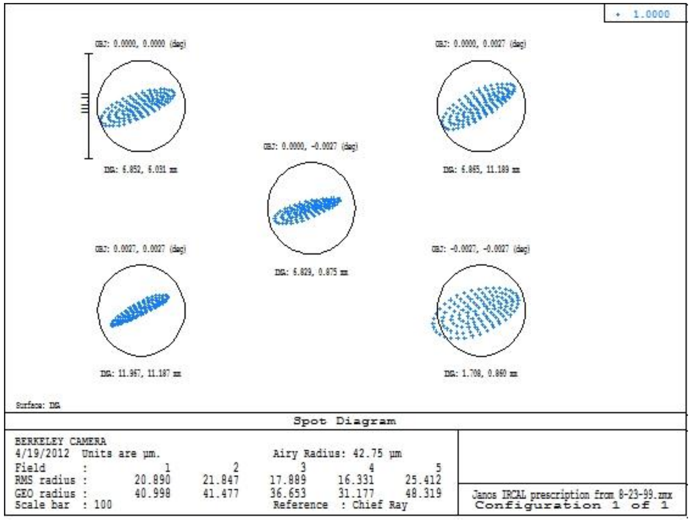
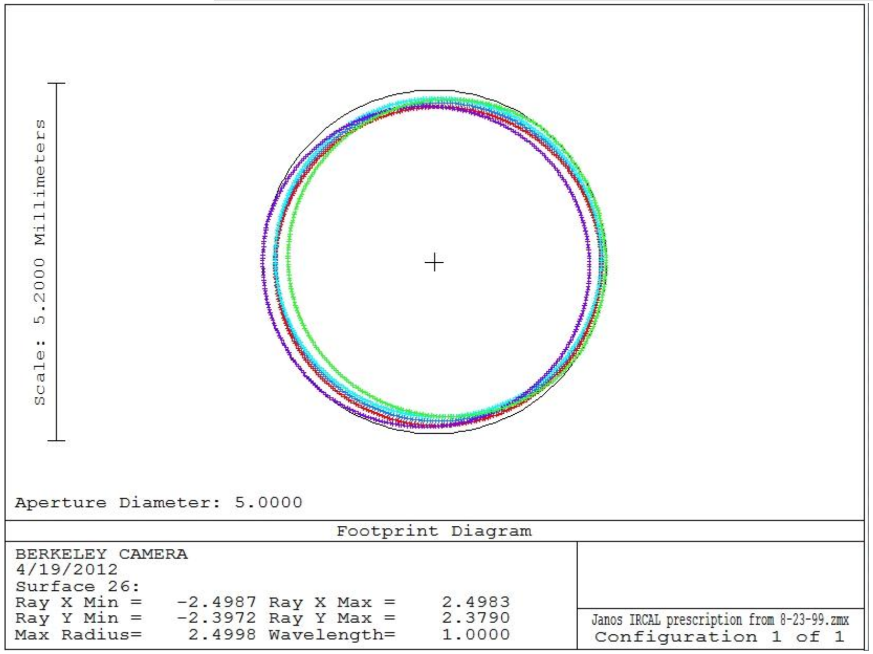
Existing IRCAL Science Instrument

- Optical prescription uncertain
- Cold stop after grism and Wollaston gives inconsistent pupil (PSF) depending on polarization, wavelength
- IRCAL observers report extremely high K-band background that does not meet predictions







Updated Science Camera, optical design

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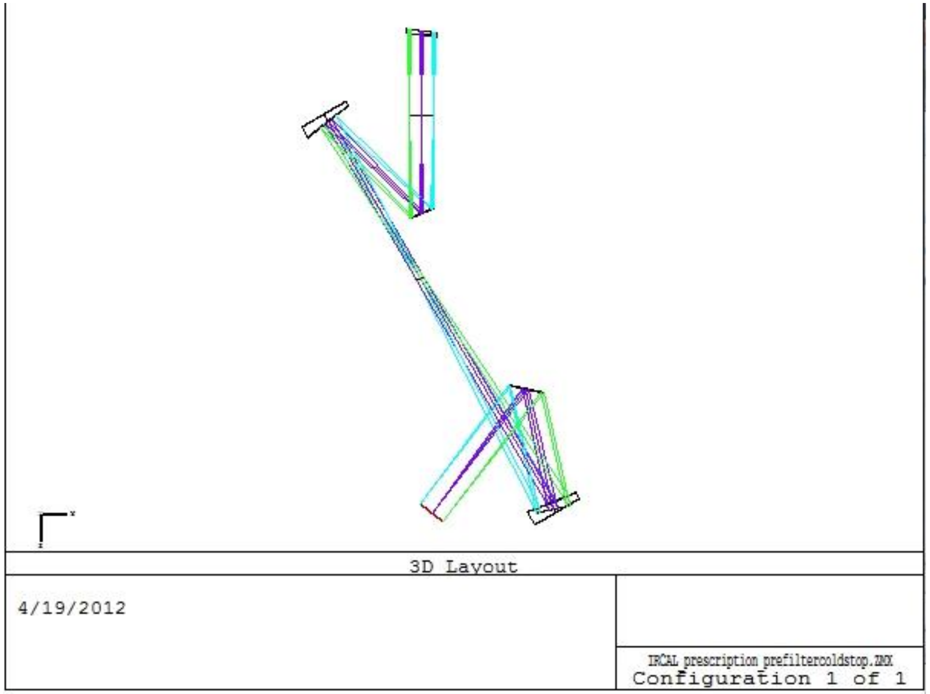
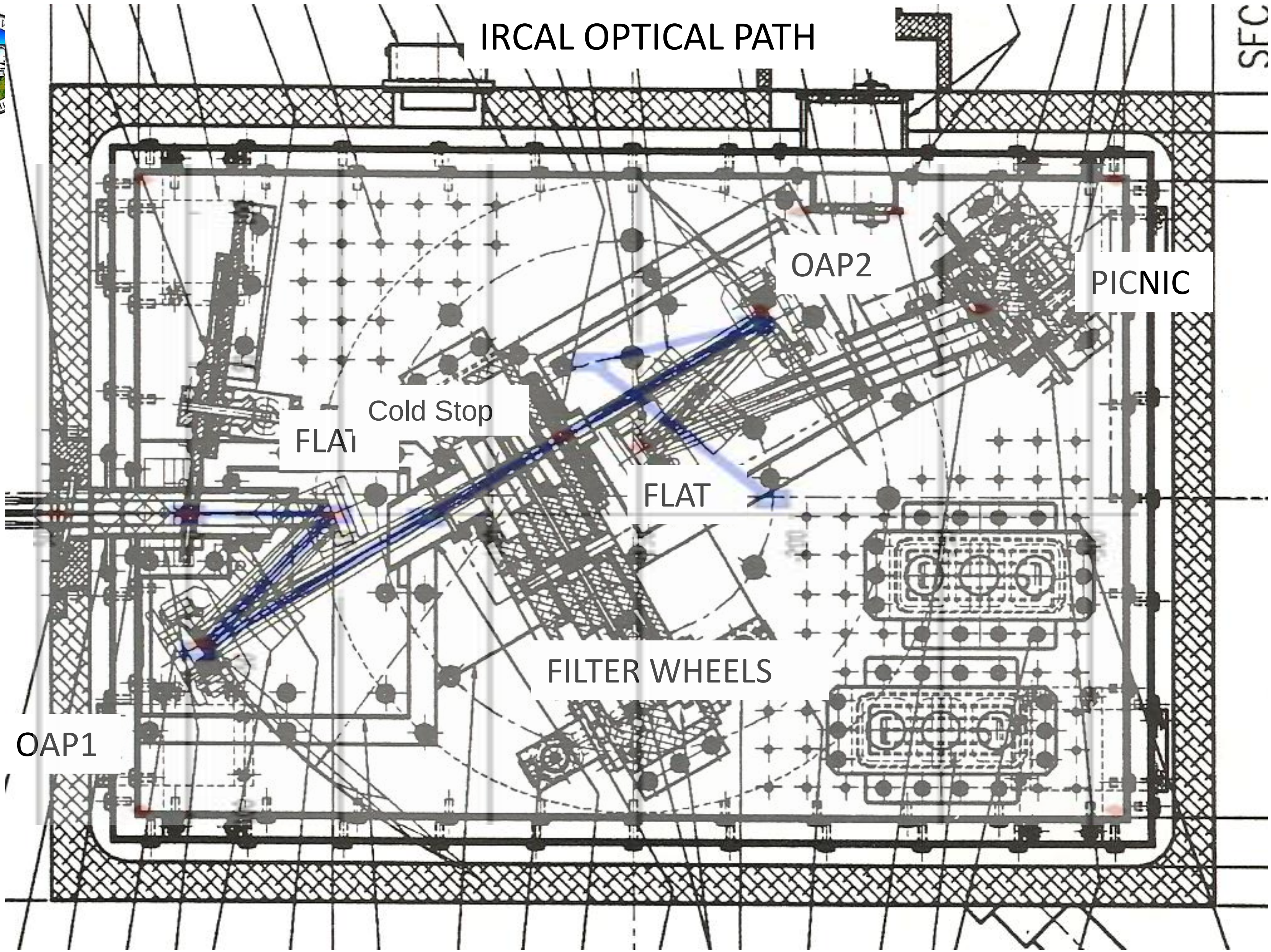
- Off-axis parabolas used in their optimum configuration for imaging
- Beam folded to area of dewar with space for H2RG and ASIC
- Cold stop repositioned (by moving entrance pupil into IRCAL) before filter wheels, Wollaston, and grism



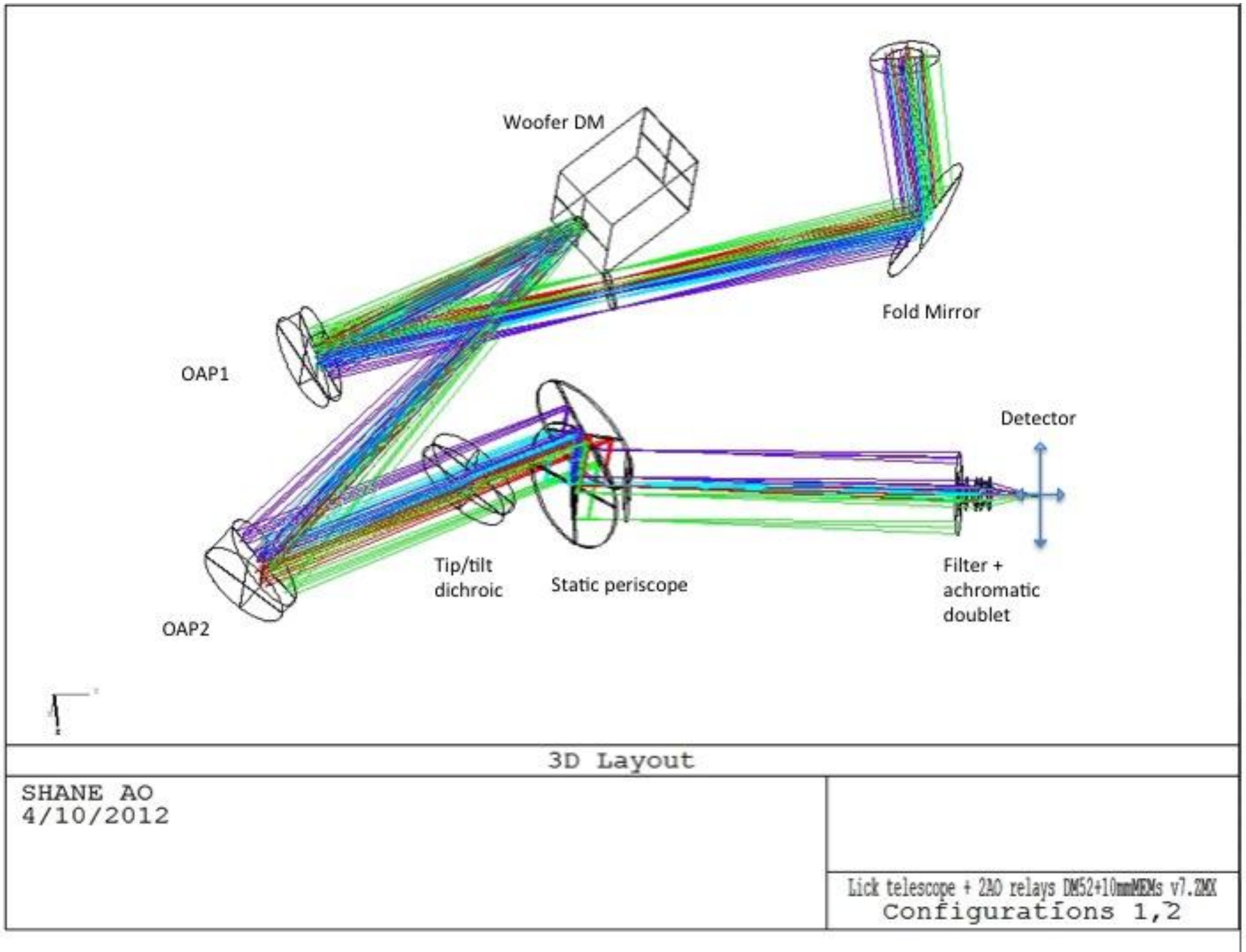
IRCAL OPTICAL PATH



Tip/tilt/focus sensor (TTFS)

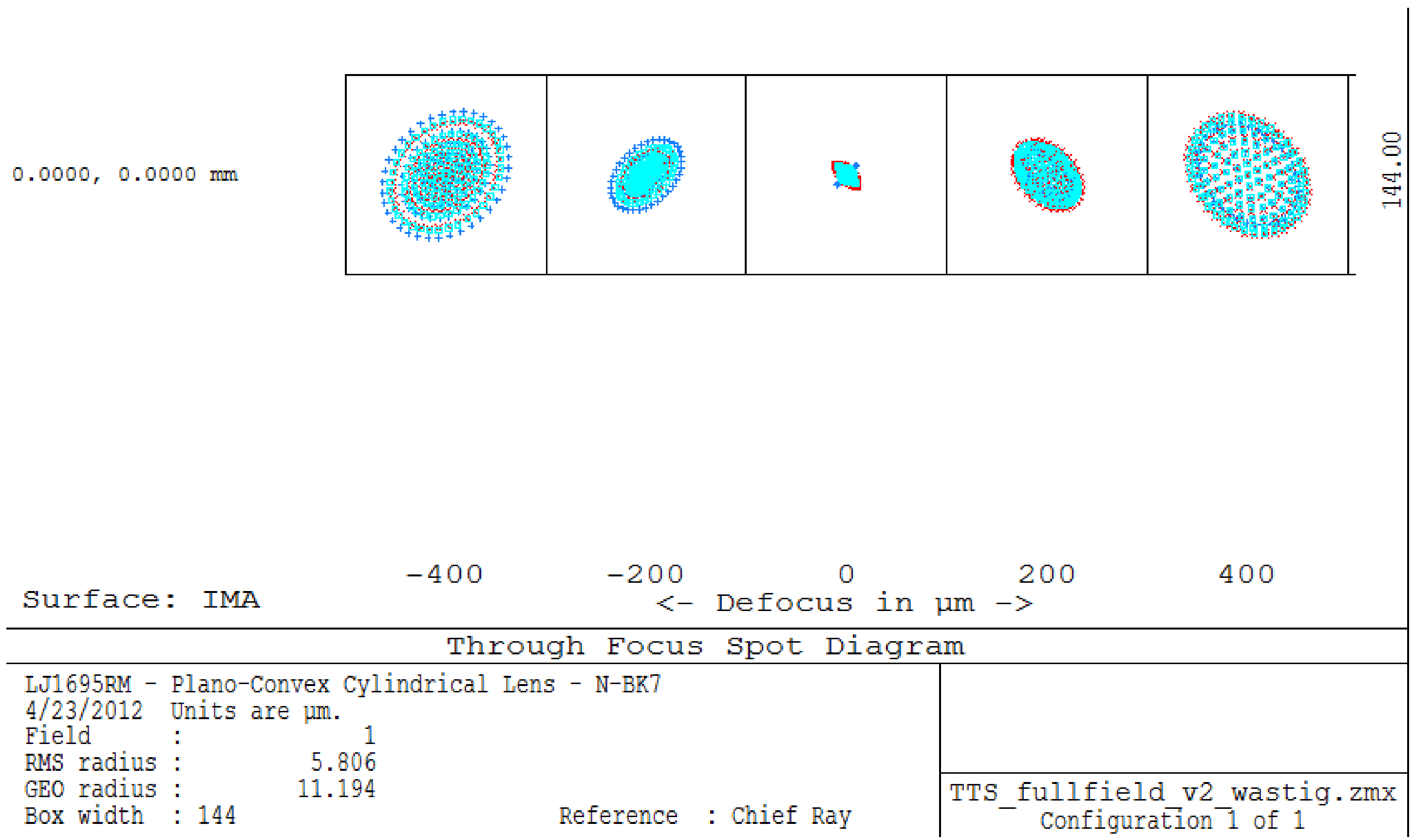
- Used only during LGS observations. During NGS observations, all wavelengths are reflected to WFS and science path
- Receives transmitted 0.6-0.9 μm light through tip/tilt dichroic beamsplitter
- Patrols 120” field of regard
- Offers slow focus sensing through use of astigmatic focus sensor
- TTFS utilizes the 80x80 Scimeasure Little Joe with 24 μm pixels.
- Plate scale at TTFS focal plane of 0.072 mm/”, or three (binned) pixels per arcsecond

TTFS Optical Layout



Focus sensing with astigmatic lens

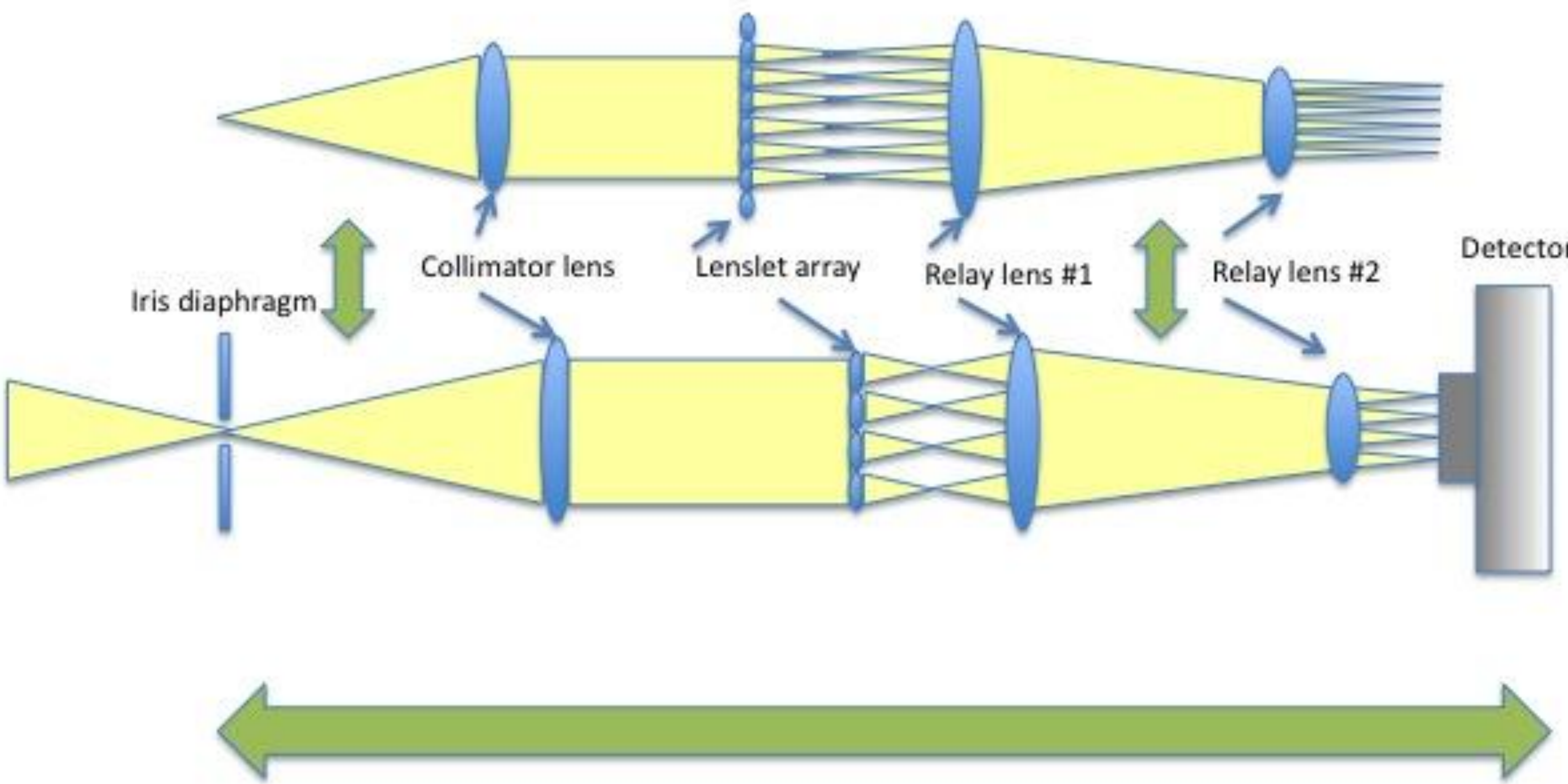
With an astigmatic lens (about 3 waves of astigmatism) with axis tilted at 45° with respect to sensor pixels, defocus can be detected as a signal in a quadrant sensor.



Wavefront Sensor (WFS)

- Can be configured for natural or laser guide star observations through a change in the WFS beamsplitter and refocus
- Two modes of operation: 8x8 or 16x16 subapertures with a possible addition of 30x30
- Active refocusing for change in distance to sodium layer during operation
- A pointing and centering pair allow positioning of an off-axis reference source within the science field of view.
- Each configuration has 4x4 pixel subapertures with a guard band
- WFS detector is Scimeasure CCID66 with 21 µm pixels
- Pixel scales are 2”/pixel and 1.6”/pixel for the 8x8 and 16x16 subaperture modes, respectively

Wavefront Sensor Optical Path



Reviewer Questions

Q: Hmmmm…..more non-common path optics than previously. How do you calibrate?
A: We assume the non-common path aberrations are low-order and perform image sharpening with the calibration source.

Q: The WFS path focusing lens (before the field stop) is not producing a pupil at infinity, so if you adjust the WFS stage focus (especially for LGS), the pupil will change size. Is the change enough to matter? It might. I think we had this issue for the last Lick AO system, but it wasn't enough to hurt us because we only had 8 subaps and longer focal lengths. I'll have to think about this one. In general, did you look at what happens when you put in finite object distances (LGS)?
A: It is telecentric output (175 mm focal length lens about 175 mm from MEMs. I checked the telecentricity at that point a couple of ways. Did I make an error in the design?

Reviewer Questions

Q: Explain the dot relay design. It's clearly far from a 4-f type concept, and I'm not sure why it would be better, especially if there are tightish tolerances on focal length and requires custom optics.
A: You're right, it's not a 4-f design, and it's not necessarily better. I wanted each of the WFS paths from field stop to detector to be exactly the same length to facilitate changing between modes. I costed custom lenslet arrays (in order to use stock relay lenses), and decided, because of cost, to go with stock lenslet arrays and custom relay lenses. It was one or the other to get the 105 micron subapertures on the WFS detector. I started out with 4-f designs for the custom relay optics, but wasn't happy with the lengths (mechanical) I needed to achieve the magnifications. Using one lens for the relay did not give satisfactory results (I think field curvature or distortion was large). At Keck they had used a field lens+lens approach for the relays instead of a 4f to shorten them, and that seemed to work in this case, too. I'd be happy to discuss design alternatives with you given the constraints.

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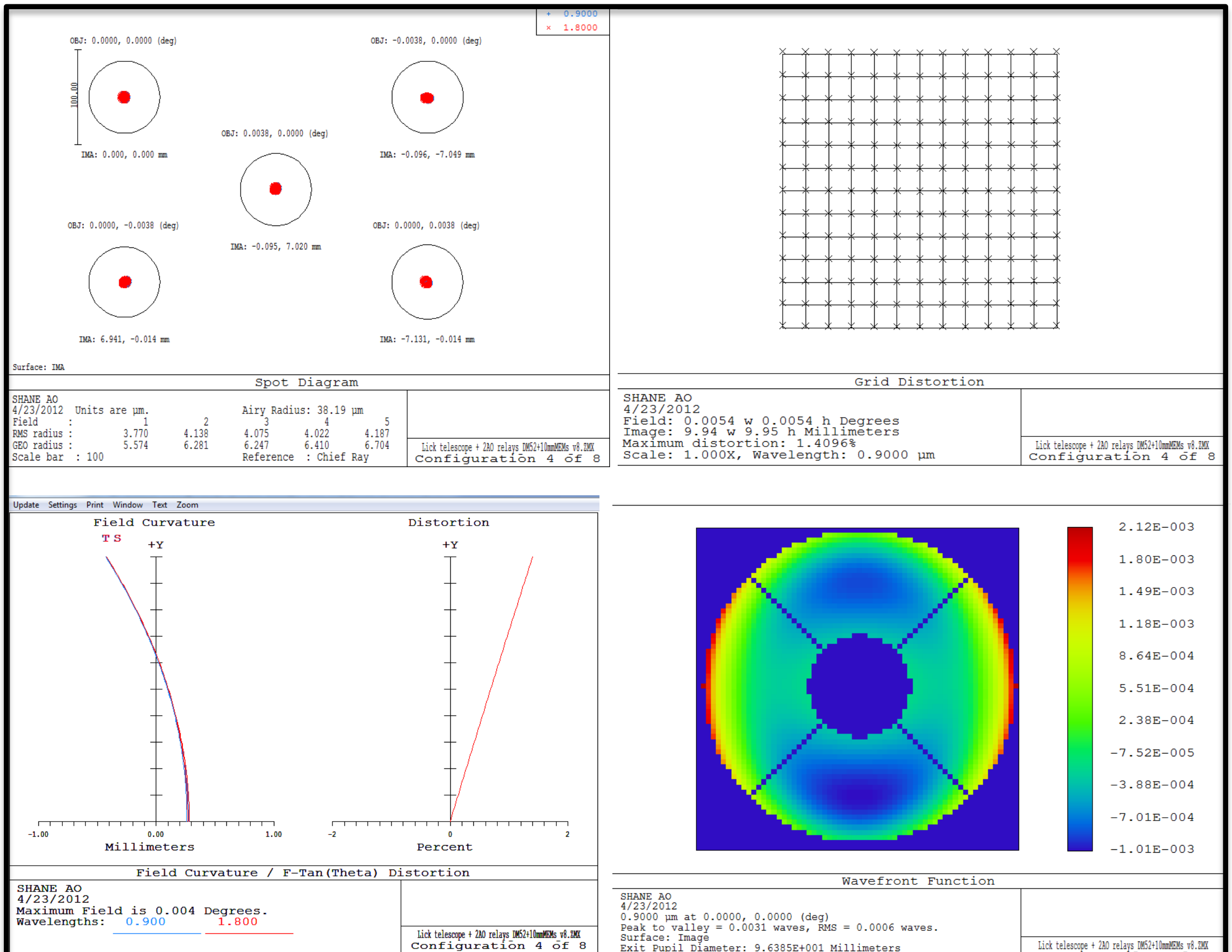
Science Detector Image Plane



TTFS Analysis

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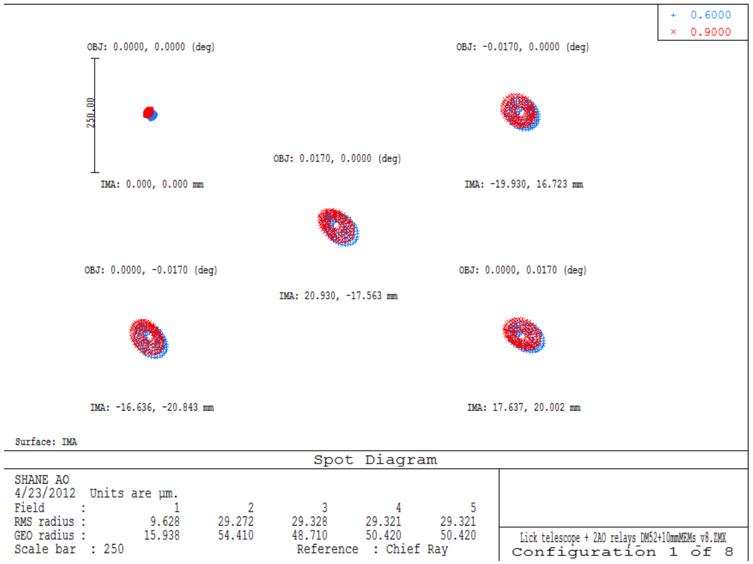
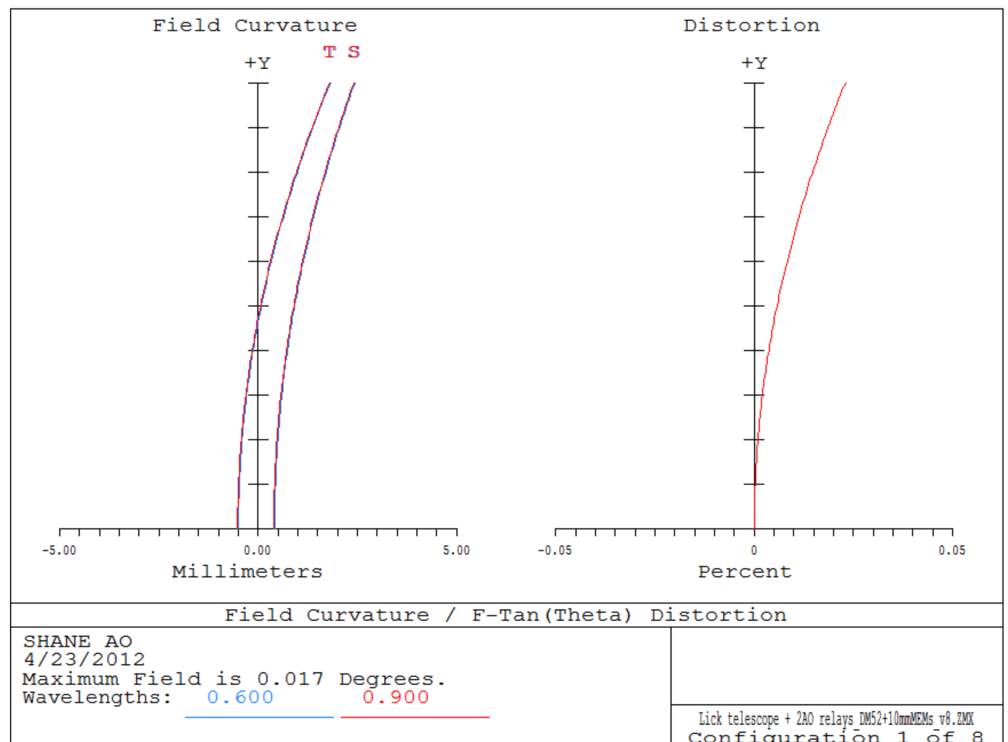


- 1st relay produces a focal plane with field curvature and astigmatism at extreme field points

If focus signal from TTFS is linear over a large enough range of defocus, instead of using the astigmatic focus sensor to null the signal, we can calibrate the zero focus position for different field points.



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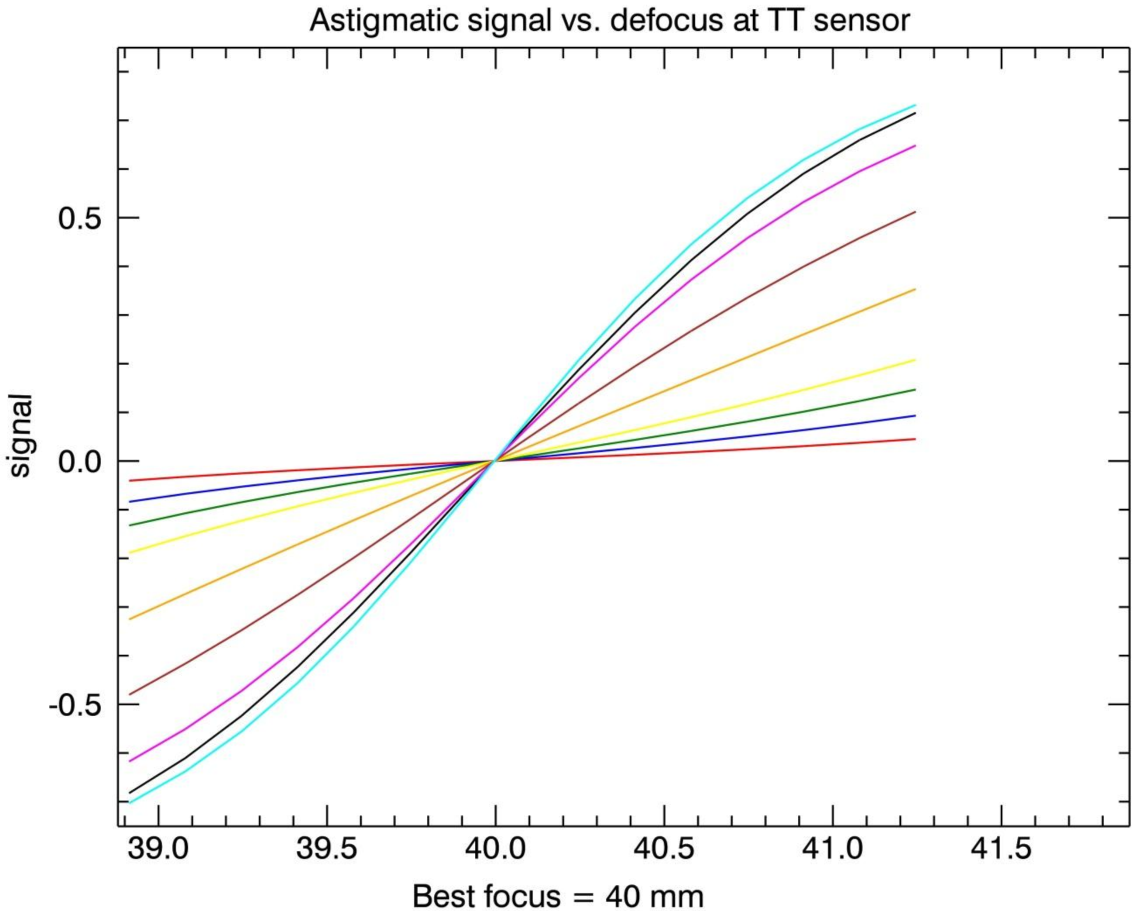
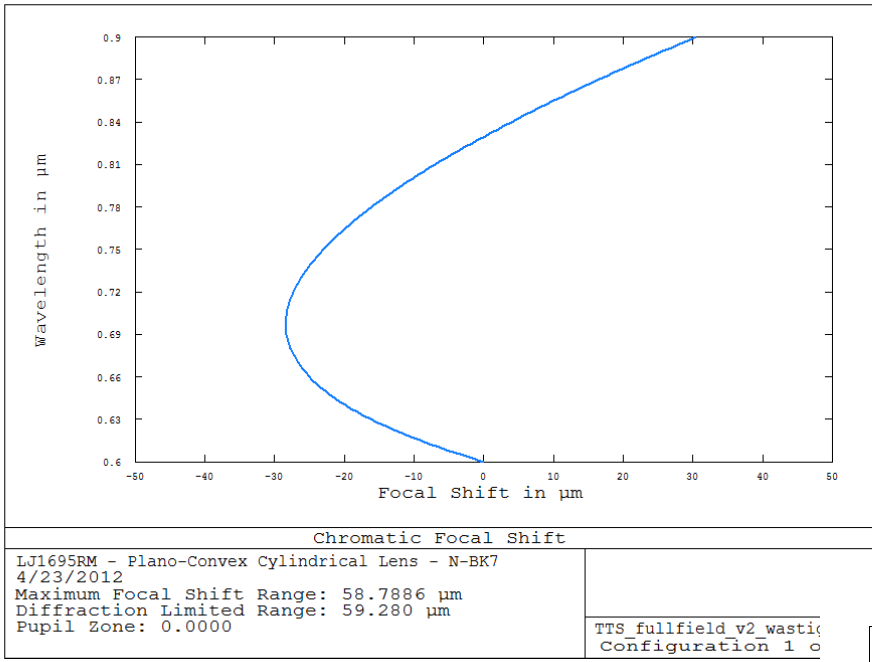
Focus sensor is linear



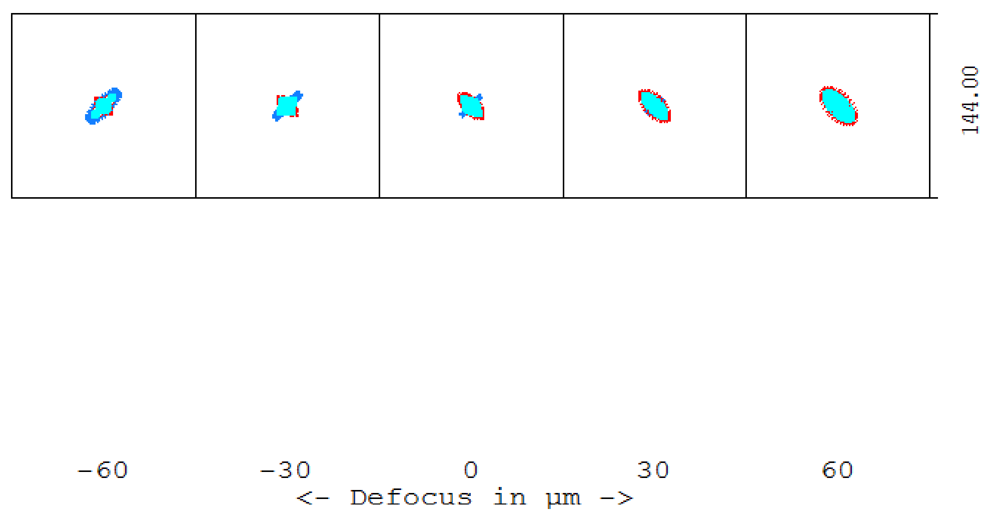
colors represent different amounts of astigmatism from 0.25 (red) to 4.0 waves (black)

Results from Fresnel propagation simulation suggest that signal is linear over required defocus distance.

Astigmatic lens must be achromat



To detect focus shifts on order of a depth of focus, the astigmatic lens must be achromatic over the TTFS wavelength range of 0.6-0.9 µm.



WFS Optical Design Analysis, 8x8

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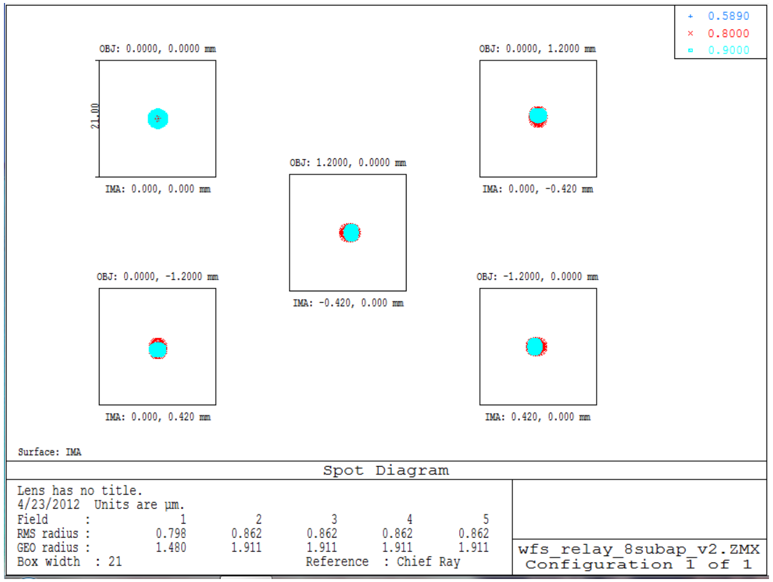

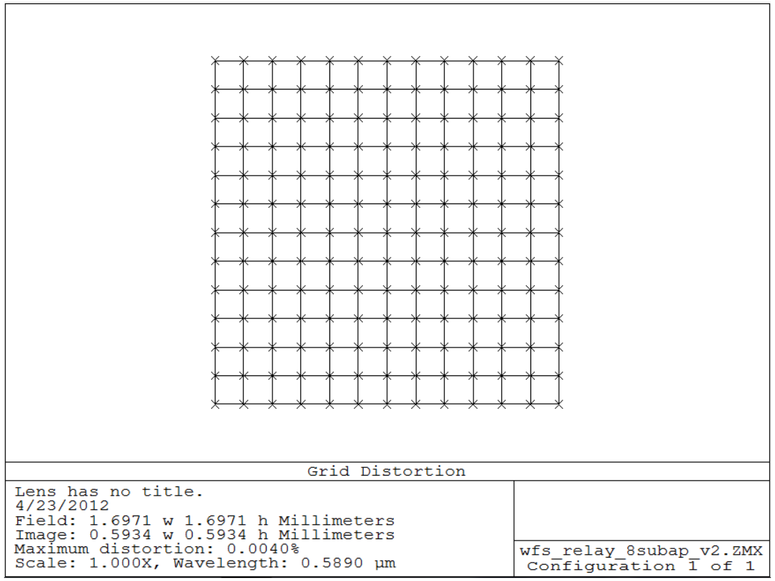

Hartmann spots are relayed from lenslet array focal plane to WFS detector. Geometric spot analysis above show spots in center and edge subapertures, in 0.589-0.9 µm wavelength range, compared to the size of a WFS pixel.

Distortion of the Hartmann spot grid produced by the lenslet array is small, as seen above (0.004%)

WFS Optical Design Analysis, 16x16

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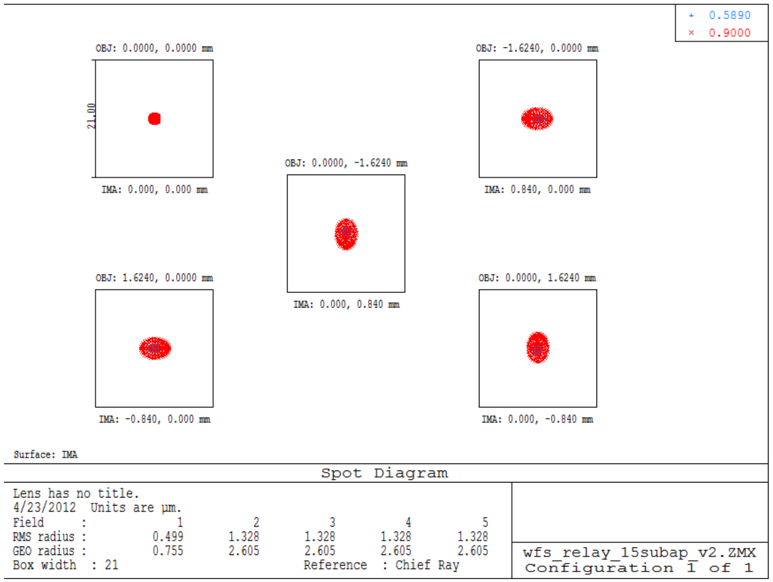

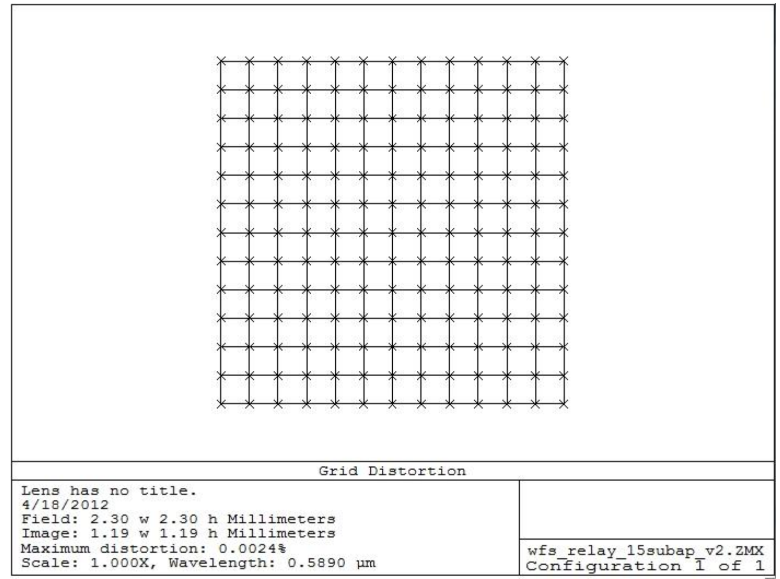

Hartmann spots are relayed from lenslet array focal plane to WFS detector. Geometric spot analysis above show spots in center and edge subapertures, in 0.589-0.9 µm wavelength range, compared to the size of a WFS pixel.

Distortion of the Hartmann spot grid produced by the lenslet array is small, as seen above (0.002%)

Pupil Analysis

There are four planes conjugate to the pupil in the ShaneAO system (woofer, tweeter, lenslet array and coldstop). Each of these were analyzed for the following pupil imaging effects:

- “Pupil wander” for off-axis field points
- Pupil distortion
- Pupil tilt and curvature
- Pupil edge blur (related to pupil wander – field dependent).

Each of these were evaluated compared to the relevant parameters of the pupil plane (actuator or lenslet pitch).

Woofer has some pupil tilt, corresponding to 136 m at primary

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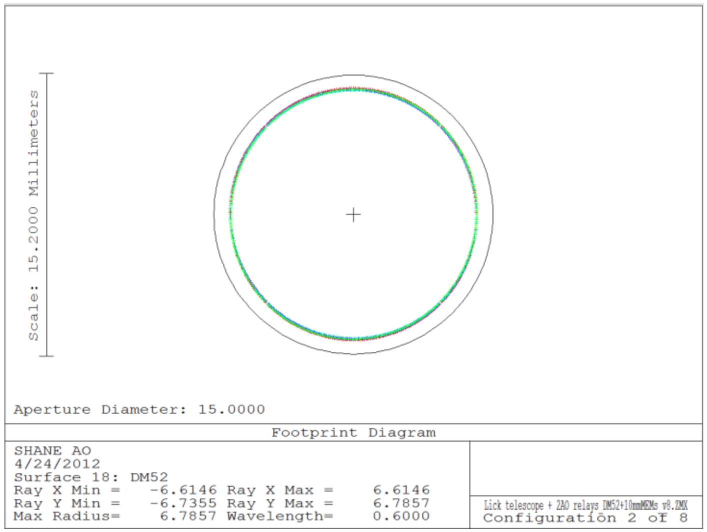
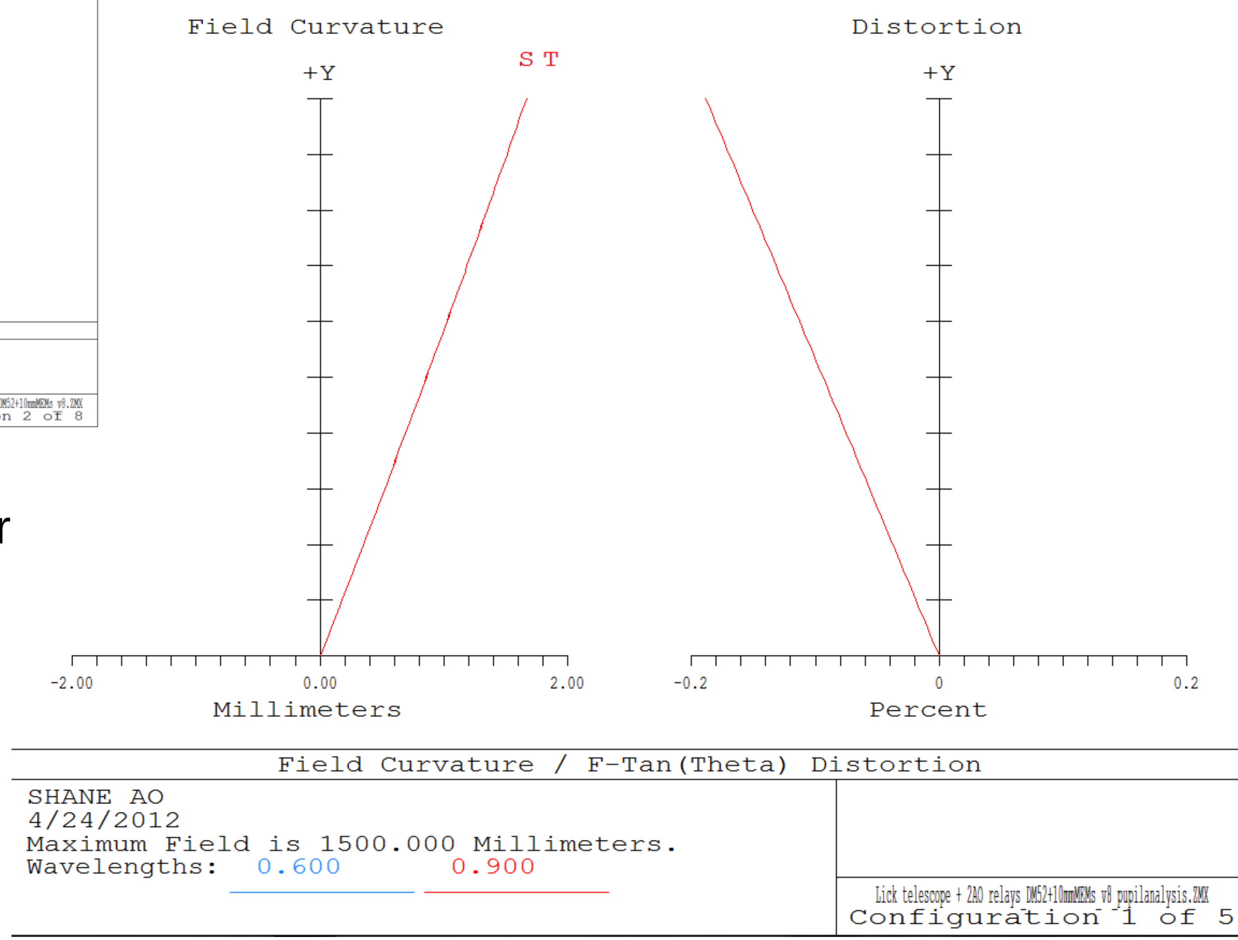
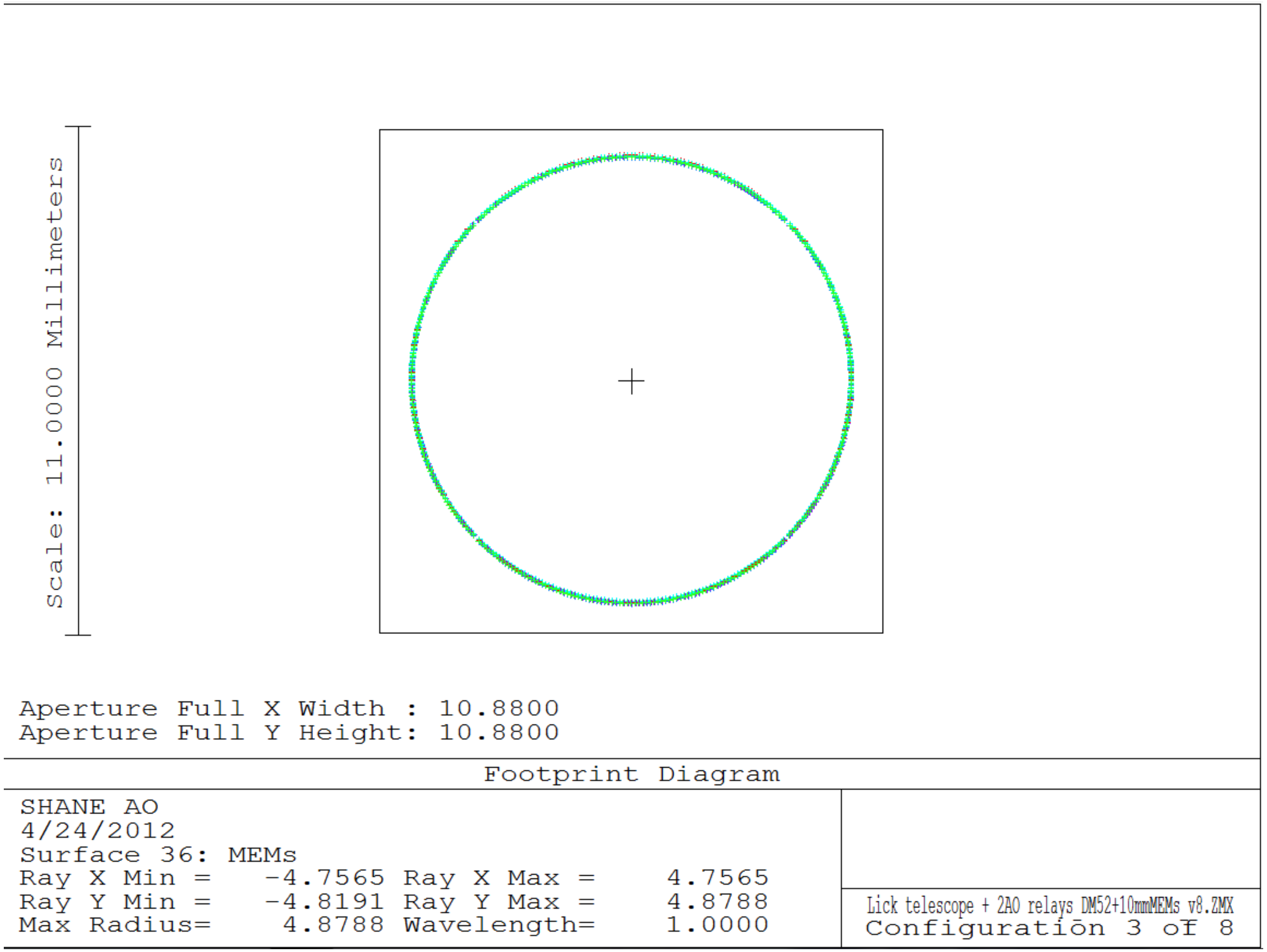




- Minimal beam wander and distortion.

MEMs pupil has minimal beam wander, tilt or distortion



Lenslet array pupil quality is acceptable

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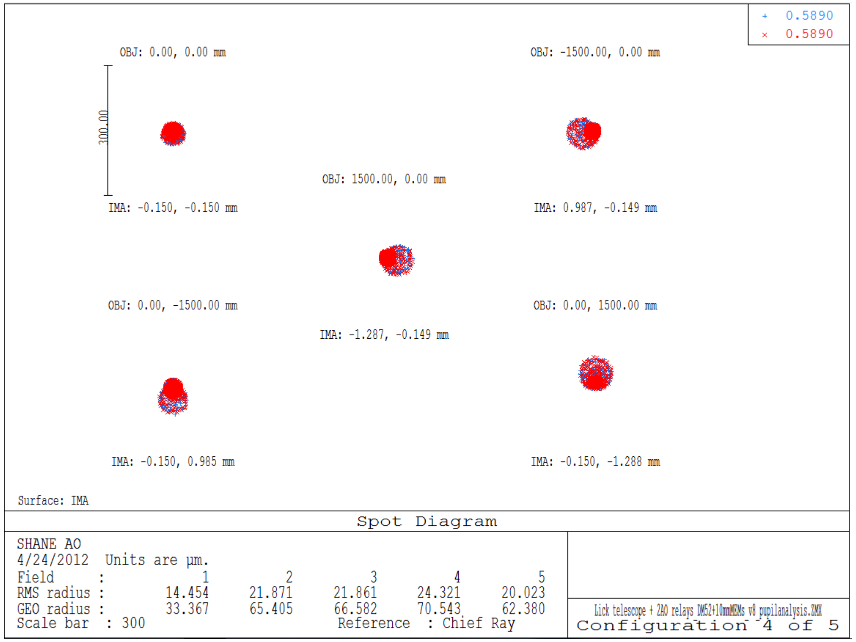
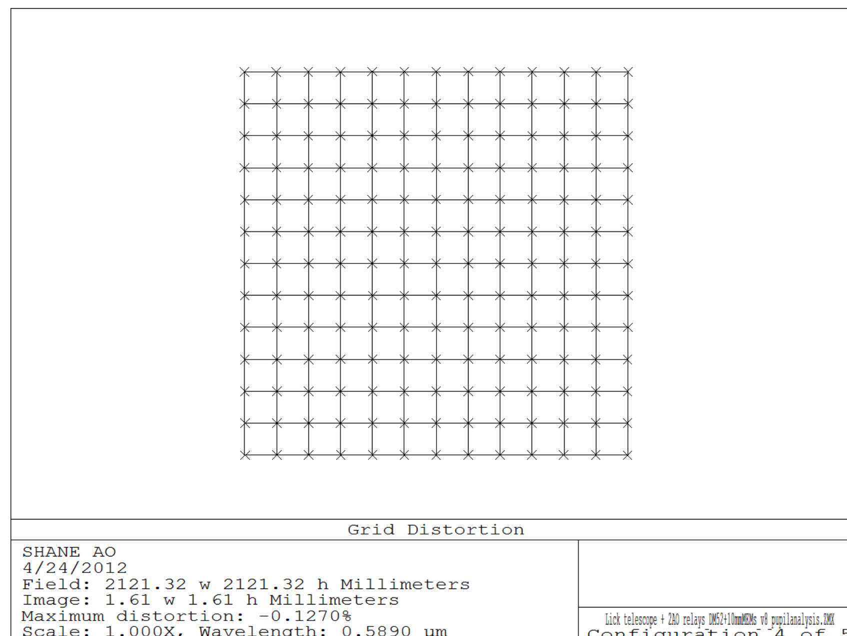


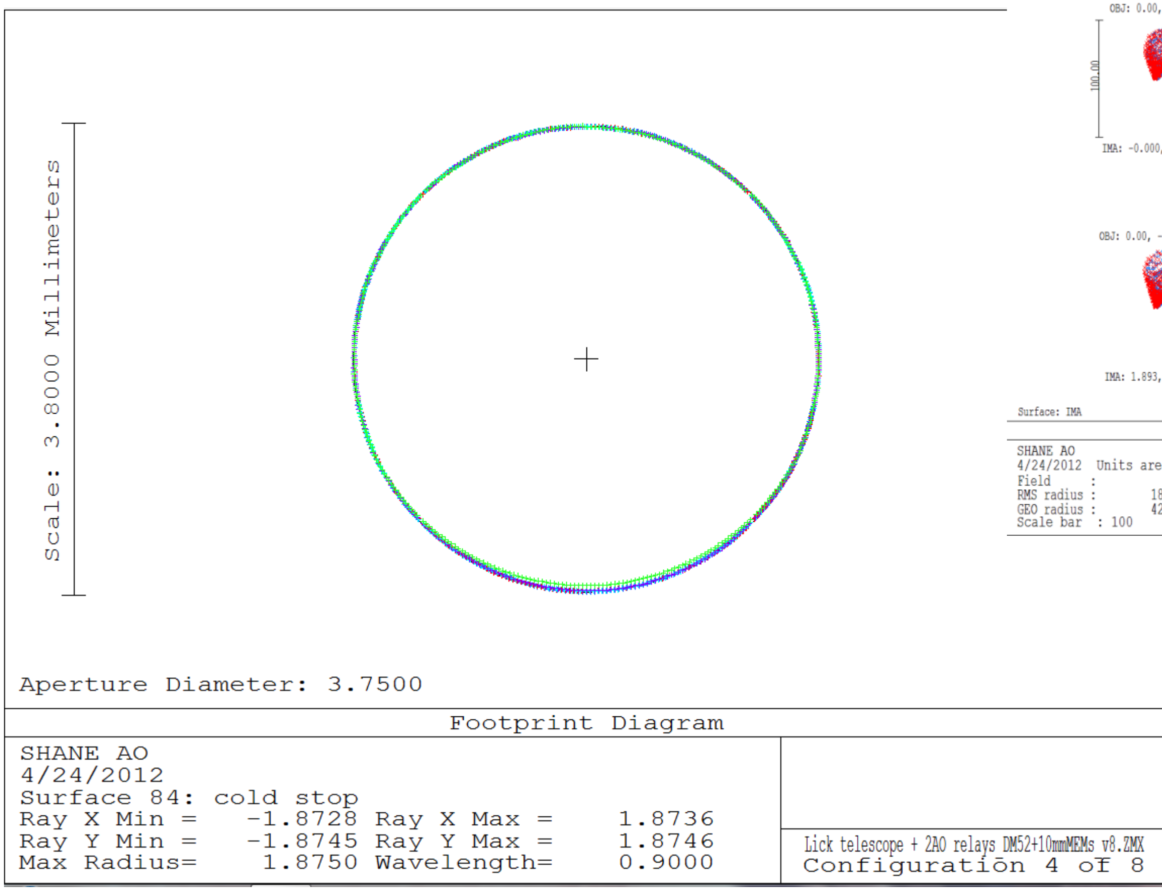
The spot diagram at left shows geometric spots from the center and edges of the primary mirror, as imaged on the lenslet array. The lenslet array pitch is shown on the scale bar. Similar results for 8x8 and 26x16 subapertures.

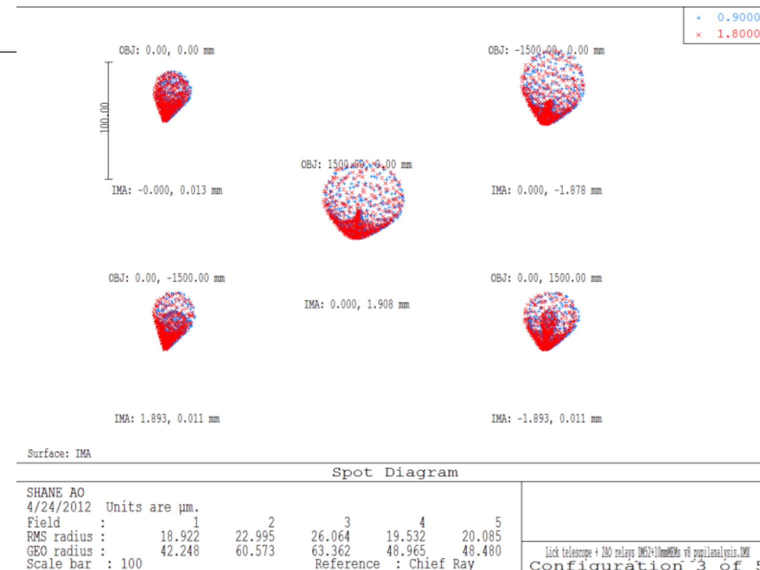


Distortion of the primary mirror at the lenslet array is 0.12%.

Cold stop must be undersized

To block unwanted thermal background, the cold stop must be undersized to allow for pupil wander. The undersizing results in loss of throughput, so there is a desire to maximize the pupil size.





Pupil must be undersized by approximately 200 µm.

Throughput

	AO relay throughput (average over bandpass), not including sky and telescope
Tip/tilt/focus sensor, 0.6-0.9 μm	87%
Wavefront Sensor, 0.589 μm	71%
Science, J-band	70%
Science, H-band	73%
Science, K-band	77%

Alignment

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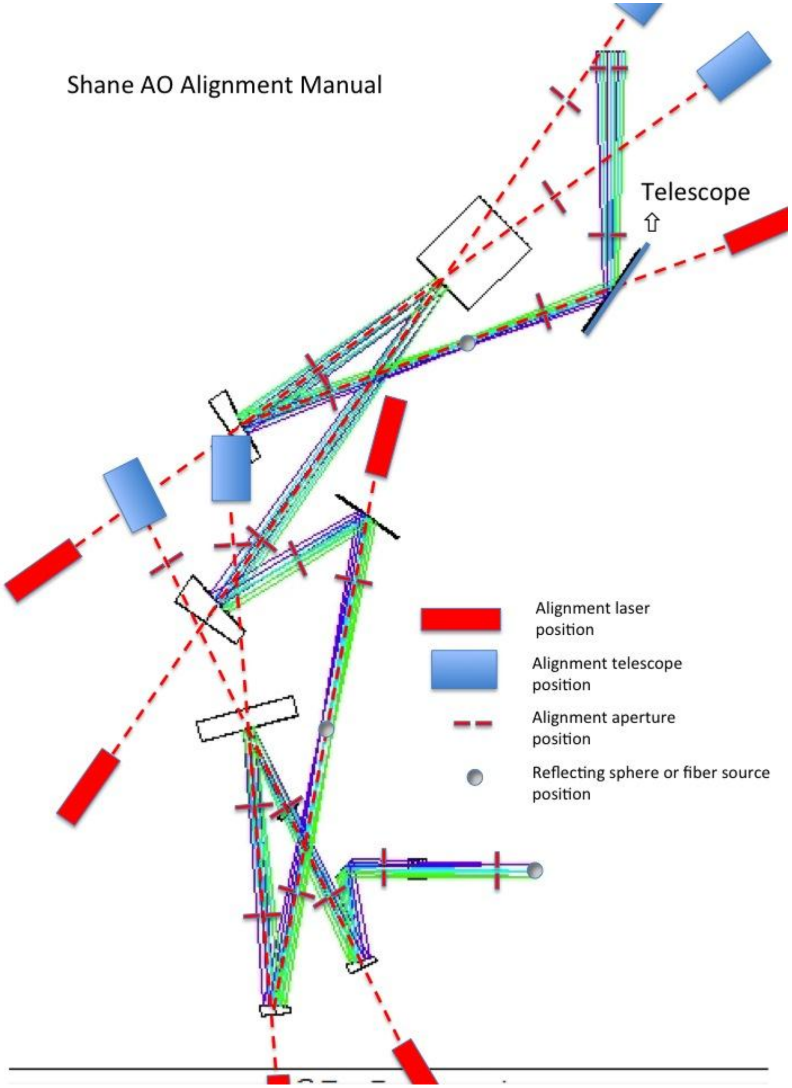
- We have an alignment plan that includes the alignment hardware indicated in the figure at right:
  - Alignment lasers
  - Alignment telescope
  - Reference spheres
  - Cross hairs or pinheads
- Coordinate measuring machine will be utilized to define reference points (foci, beamlines)
- Alignment begins from the science focus, 2^{nd} relay first working backward towards FM1



Alignment (continued)

- Alignment to science camera uses the tweeter and last fold mirror as a pointing and centering pair
- Alignment to telescope uses the telescope pointing and the first fold mirror as the pointing and centering pair.
- The TTFS lens will be aligned to the TTFS detector off-bench
- The WFS configuration optics will be aligned off-bench
- To adjust alignment of WFS optics after changing modes:
    - If adjustable iris can close down to pinhole size, then this part can be done with calibration lamp. Iris provides point source for WFS optics
    - WFS detector has x-y motion with picomotors, align wfs detector to lenslet array
    - With calibration source on and iris open, adjust field steering mirrors until MEMs is aligned with lenslet/detector grid.
    - On-sky, with starlight. adjust FM1 until pupil is centered in WFS.

Optical Design

Reviewer Q&A
and Discussion

ShaneAO Opto-Mechanical Subassemblies

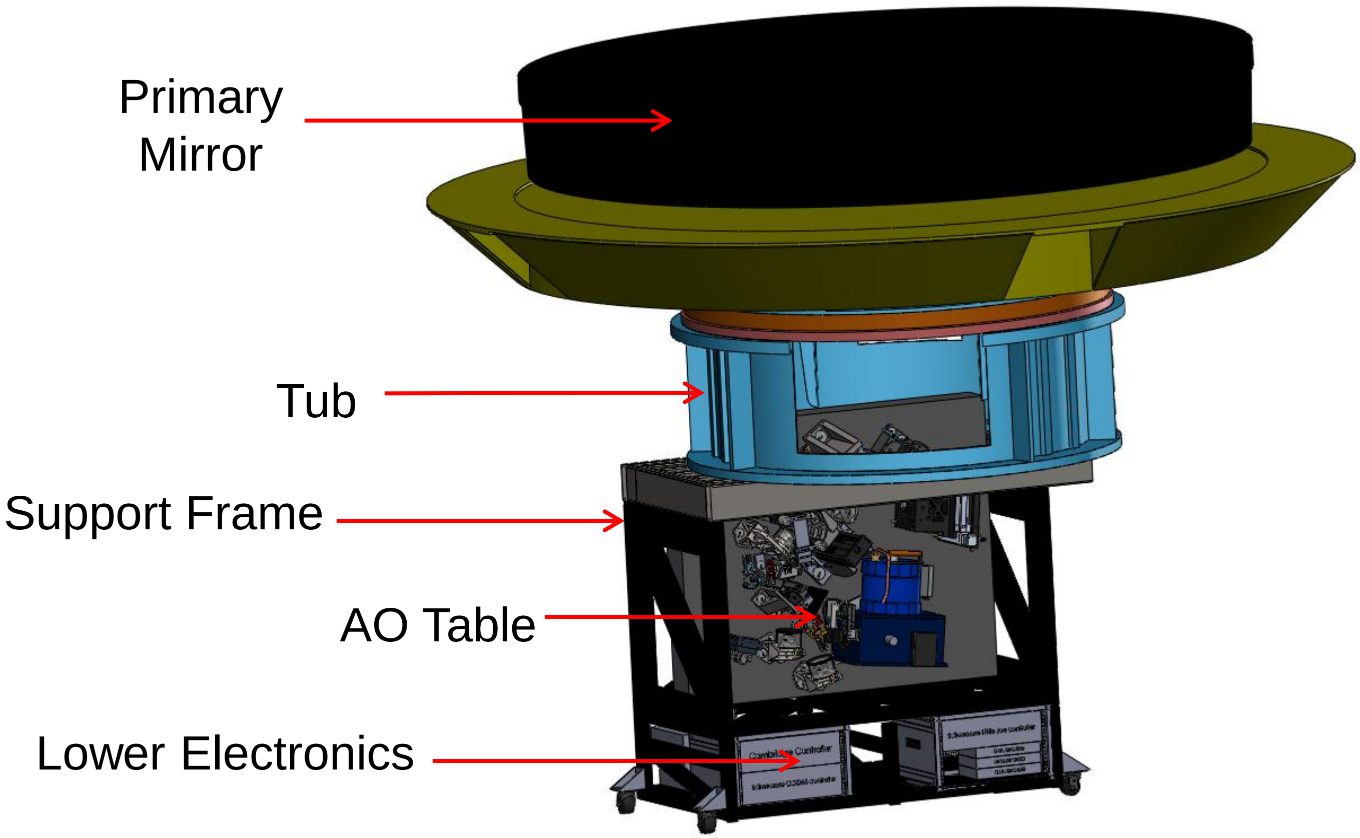
Presentation Schedule:

1. **Overview, Assembly Description (<10 minutes)**

2. **Optomechanical subsystems (90 minutes)**

3. **WFS (15 minutes)**

ShaneAO System



Main Mechanical Subassemblies

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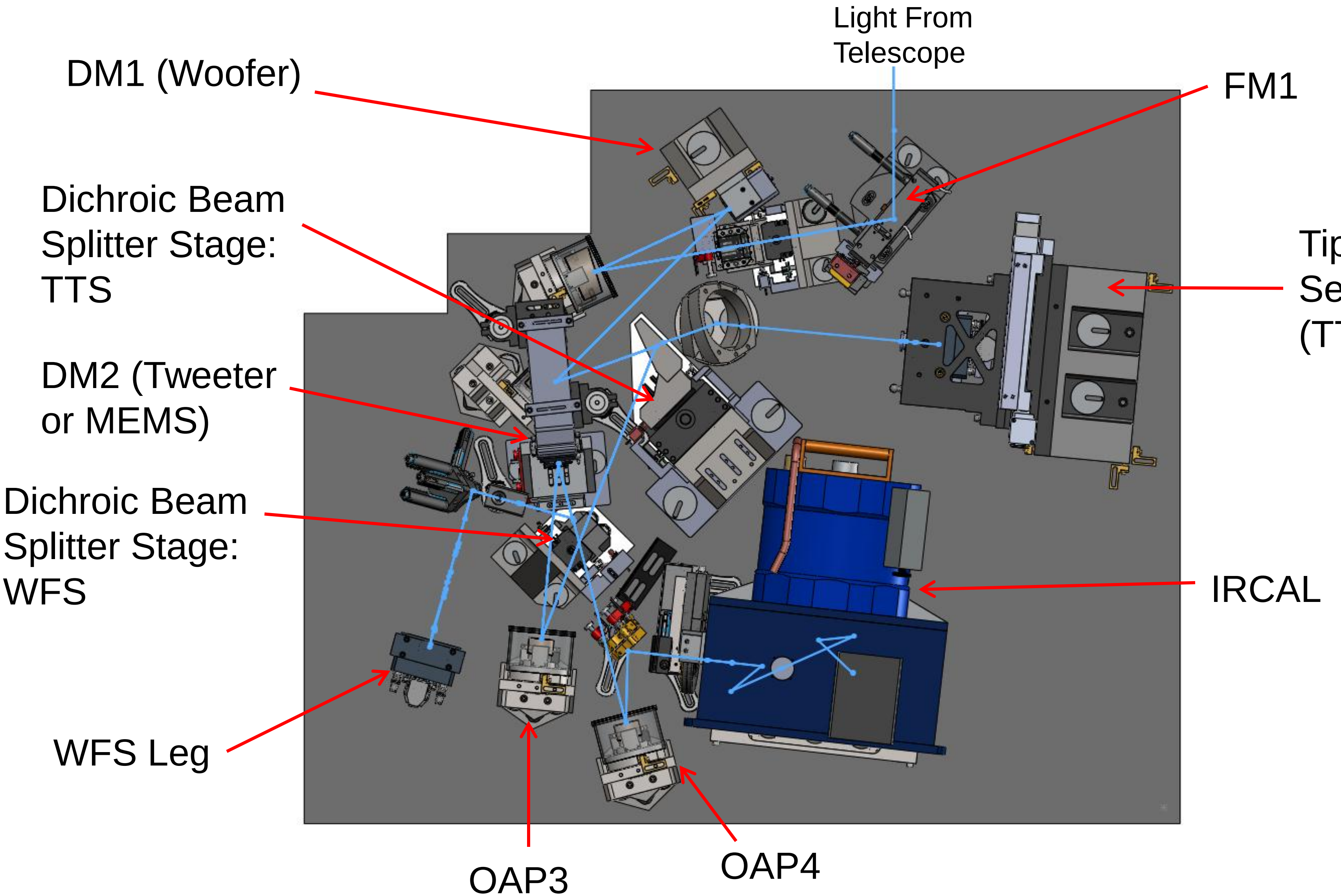

ShaneAO

Subassembly Review Topics:

1. MEMS DM mount
2. Tip/Tilt Sensor Stage
3. Tip Tilt Dichroic Stage
4. WFS steering mirrors
5. OAP mounts
6. Periscope
7. IRCAL Mount
8. FM1
9. Low Order DM
10. Calibration Stage
11. Optical Bench Design
12. Optical Bench to Telescope Mounting

MEMs DM Assembly Design

Agenda:

- **Overview and Requirements**
- **Deflection analysis: FEA**
- **Summary**
- **Deflection Testing**

MEMs DM Assembly

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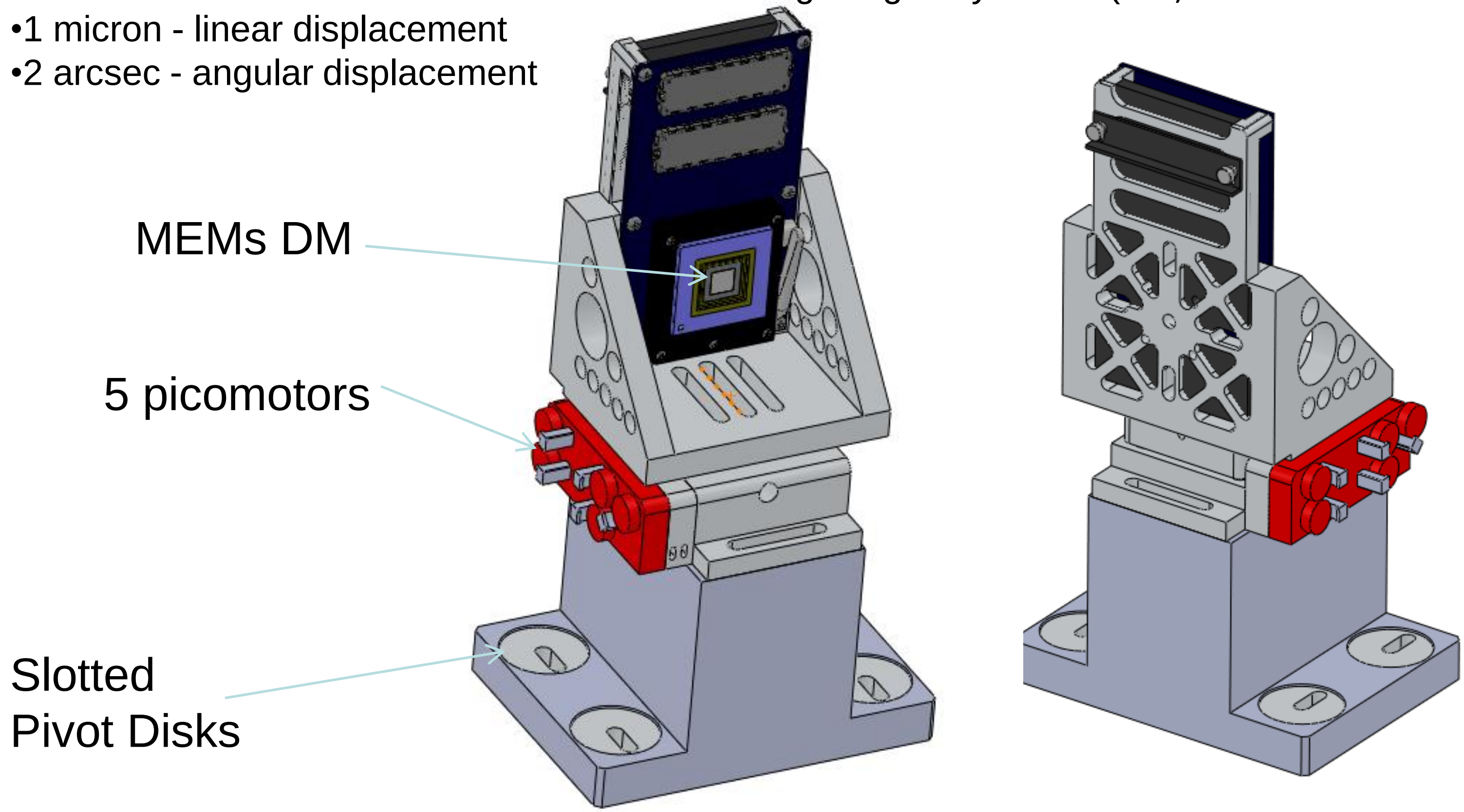
Overview/Requirements:

- Positioning stage for MEMs DM (Boston Micromachines Kilo)

- **Specifications:**
  - **X-Y positioning range/precision**: 3mm/1 micron
  - **Maximum Deflection Allowance** for worst case change in gravity vector (45°)
    - 1 micron - linear displacement
    - 2 arcsec - angular displacement



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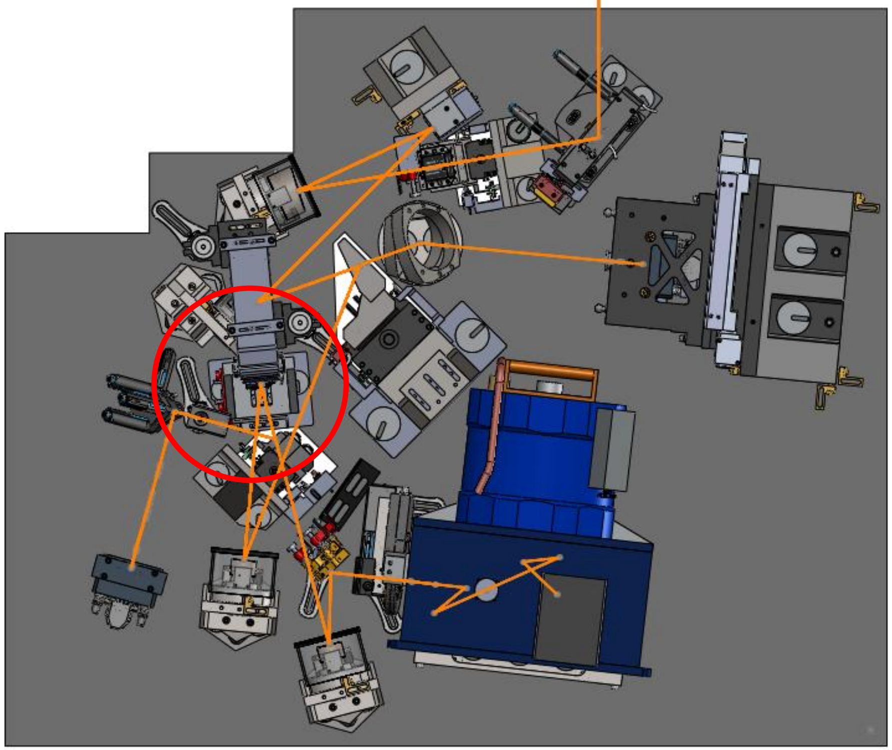
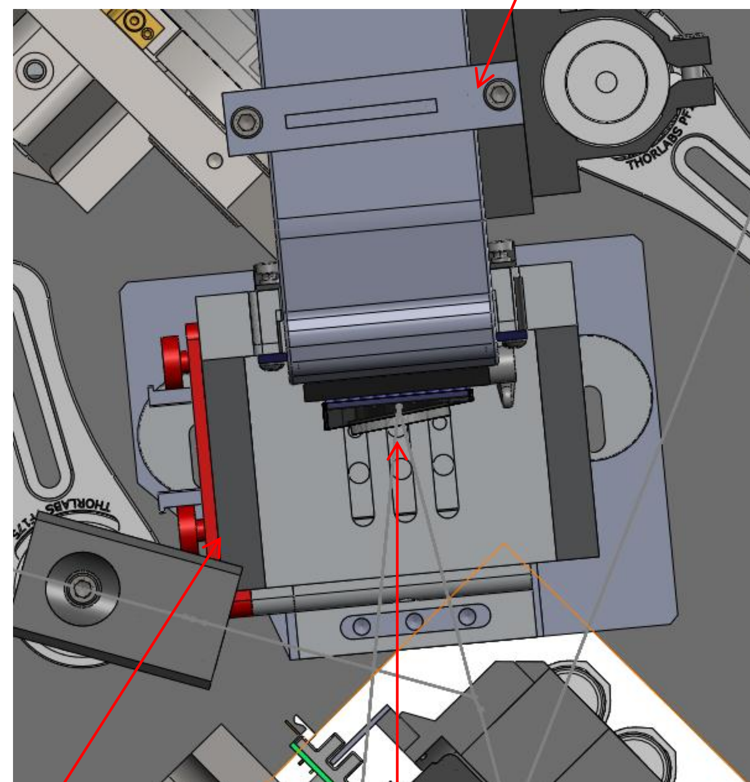
MEMs DM Assembly

MEMS DM Integrated in AO assembly:



Stress Relief Bracket



DM Window

5 DOF Stage, Modified New Focus Focus 8082

MEMs DM Stage

MEMS DM Stage:

- Meets resolution and range specs.
- <u>Stock design not rigid enough</u>
- Modification:
  - -Harder Kinematic Surfaces
  - -More preload force
  - -Analysis and experiments show it is close to allowed deflection limits
  - -<u>Repeatable deflection with new materials</u>

Motorized
Travel, 1/

Model: **8082**

$3390.00

Additional Series

Zoom Enlarge

Details & Specs **Drawings** **Literature & Downloads**

The 8082 XYZΘxΘy Motorized Wide Five-Axis Tilt Aligner increases the utility
kinematic stages by motorizing each of the axes. The addition of Picomotor™
stage allows remote high-resolution (<30 nm) adjustment of various combina
Θx, and Θy. Model 8082 five-axis aligners are ideal for positioning modulators
coupling light into waveguide devices. 8-32 and 1/4-20 tapped holes.

Model	**8082**

MEMs DM Kinematic Stage FEA

Objective:

1. Assess maximum angular and linear deflection of MEMs due to 90 degree change in gravity vector

Assumptions and Conditions:

1. Load of 20 N and 30 N normal force against each set of spherical supports (Different load for each orientation)
2. Gravity vector changes from telescope at zenith orientation to horizon orientation
3. No base support deflection
4. Optical table does not deflect
5. Spheres are made of stainless steel
6. Stock kinematic base plate is made of 6061 T6 Aluminum
7. MEMs PCB is made of acrylic (properties readily available)
8. MEMs housing is made of 6061 T6
9. All parts are rigidly connected/bonded

MEMs Kinematic Stage FEA

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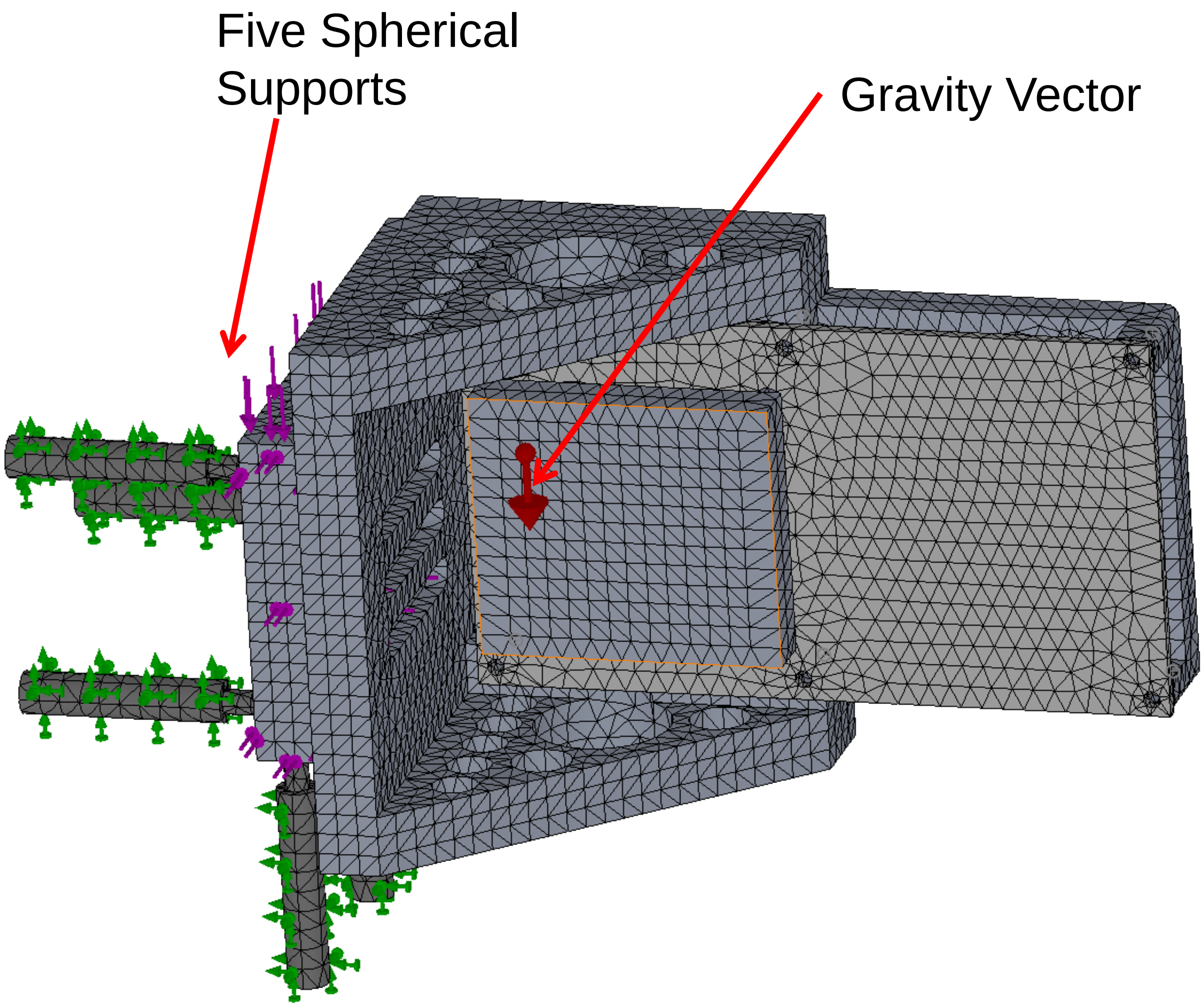
Meshed FEA Model:



MEMs Kinematic Stage FEA

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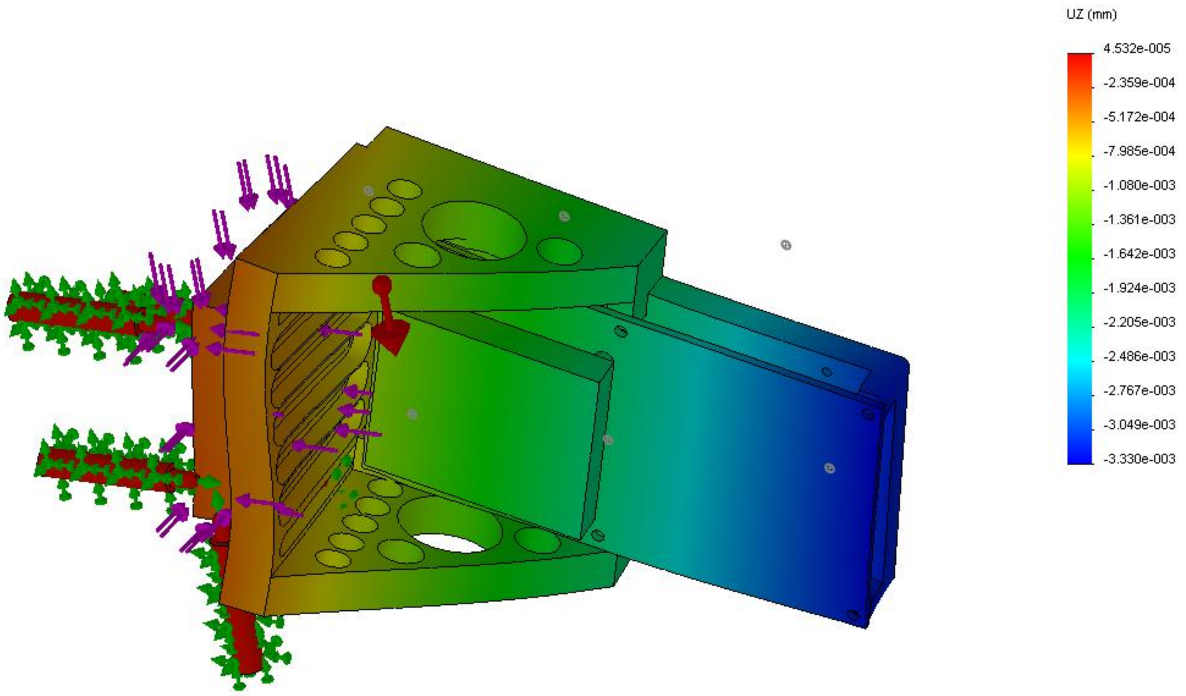
Worst case gravitation induced flex (exaggerated by 40,000x): Iteration 1
Linear deflection: 1.8 microns
Angular deflection: Greater than 5 arcsec



MEMs Kinematic Stage FEA

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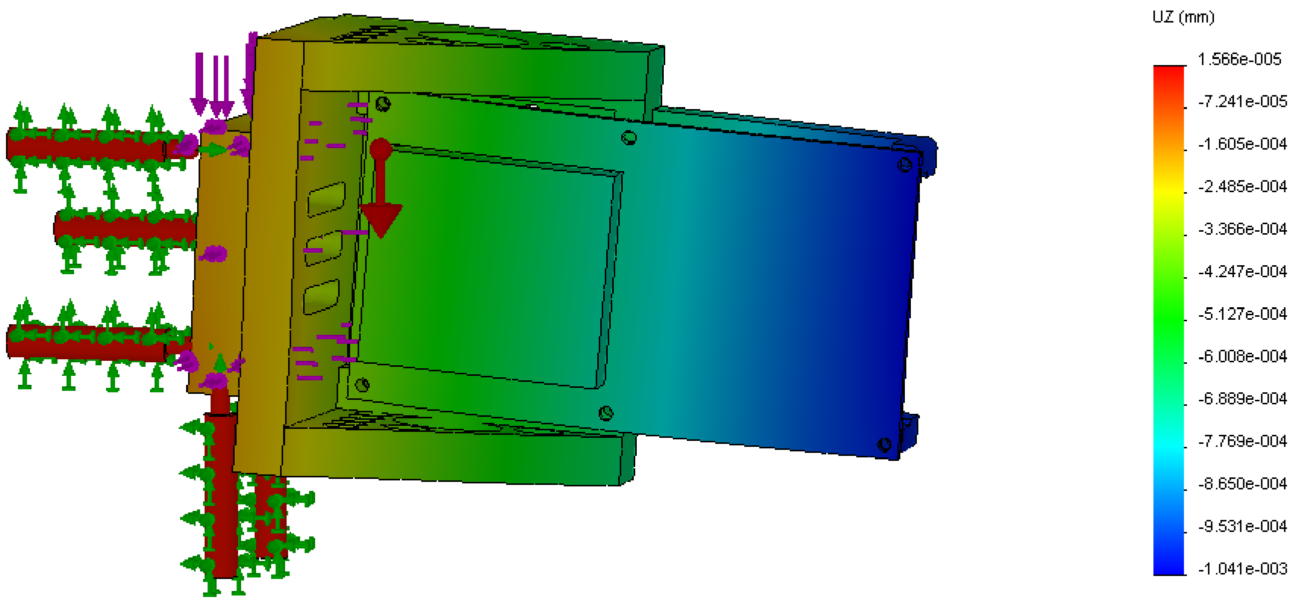
Worst case gravitation induced flex (exaggerated by 20,000x): Iteration 2, <u>Stiffer support bracket</u>
Deflection of MEMs in Z: 0.6 microns -OK
Angular deflection: 3.3 arcsec -Not OK



ANSYS FEA Contact Model

Description:

1. 2D axisymmetric model
2. Kinematic stage contact modeled with nonlinear contact interface surfaces
3. Nonlinear Stainless and Aluminum material properties
4. Stainless (SST 440C) 3/8” diameter ball
5. Kinematic 6061-T6 Aluminum base
6. Applied 20 and 30 Newton forces in sequence
7. Base later modified with sapphire

FEA Model Shows Brinelling

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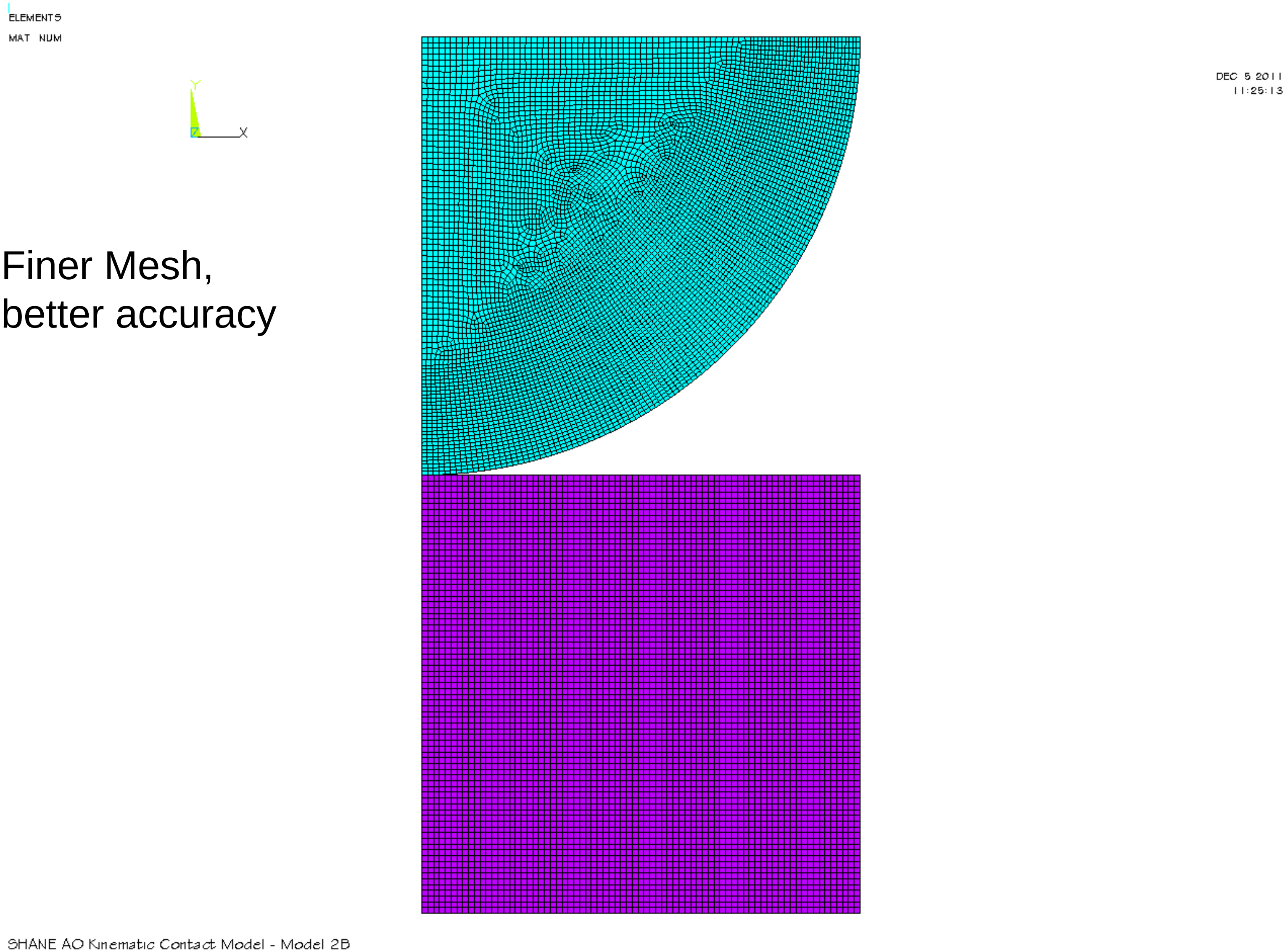
Finer Mesh,
better accuracy



Deflection Results Summary

Deflection of 3/8” SST Ball (Detent) in Microns

	Base Material	
Applied Load	**Aluminum**	**Sapphire**
20 N	2.50	1.34
30 N	3.38	1.93

MEMs Kinematic Stage

<u>Conclusion Remarks:</u>

- **Commercial Stage Did not Meet Deflection Requirements**
  - **Net change in deflection for 90 degree change in gravity vector**
    - **Less than 1 micron linear displacement**
    - **Approximately 3.3 arcseconds angular displacement**

- **Our Design Solution**
  - **Stronger springs (may be too much for picomotors)**
  - **Refabricate base from harder material: M2 Tool Steel**

- **Solution was tested in lab**

- **Stronger springs can get deflection to less than 2 arcsec, this is the recommended solution, <u>picomotors will work with preload up to 20 lbs, but no warranty for these high axial forces (per New Focus)</u>**

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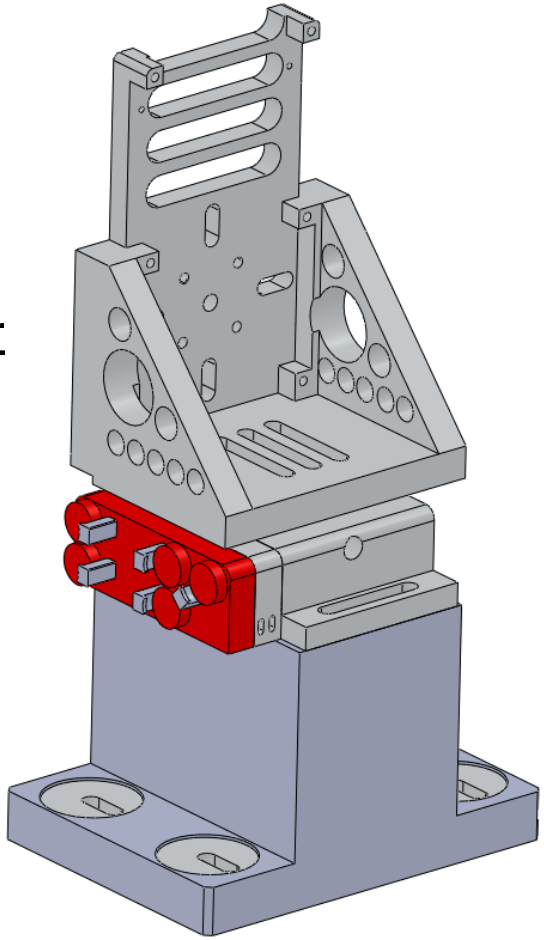
MEMs Kinematic Stage

Addendum: Deflection Testing

•Deflection Testing performed to measure actual deflection to back up analysis and determine if there are other contributors to deflection/instability

<u>Goal: Create a test setup where we mimic the deflection we would expect for different telescope pointing directions both with and without New Focus 9082 and for other test configurations such as stiffer springs and harder kinematic materials</u>



MEMs Kinematic Stage

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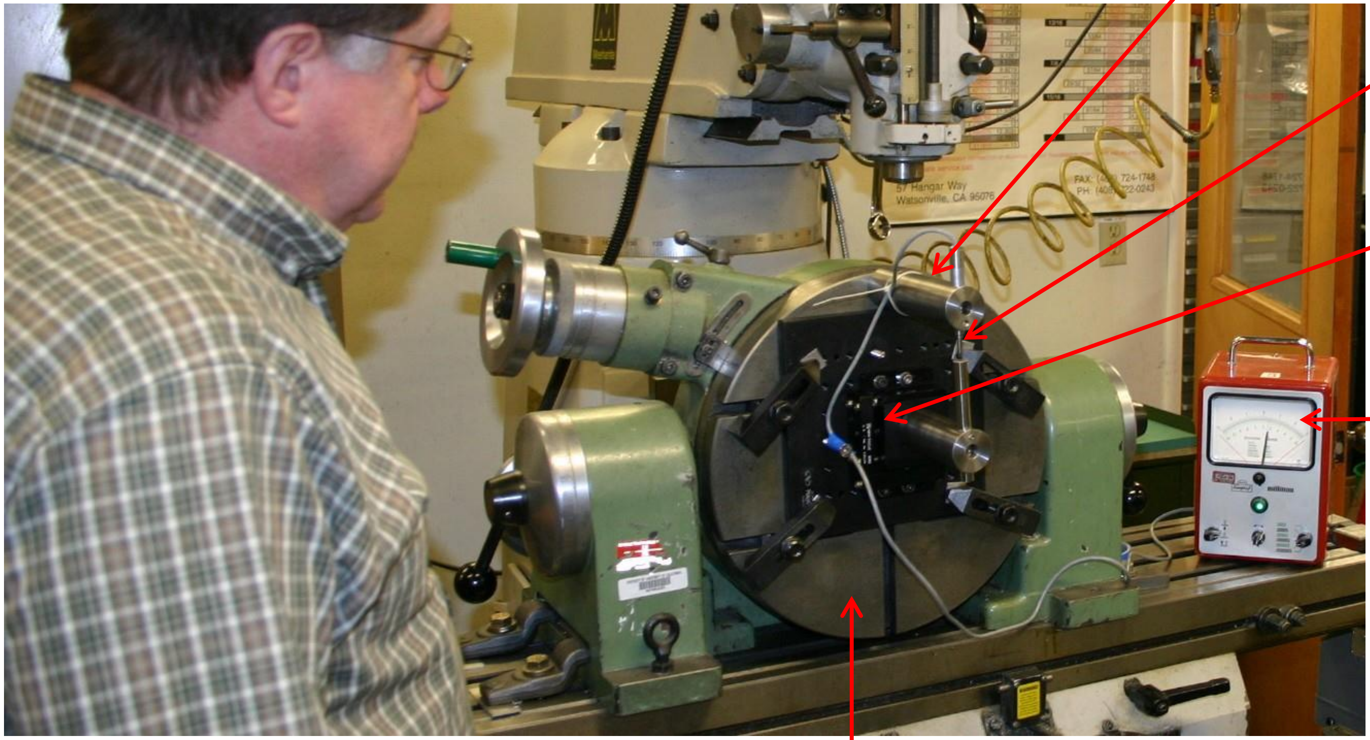
Addendum: Deflection Testing

•**Test Set Up: Zenith Orientation**

1.5” O.D. LVDT support rod

LVDT

New Focus 9082



Mahr Millitron Amplifier
(0.000005” resolution
=127nm)

2 axis rotation table

MEMs Kinematic Stage

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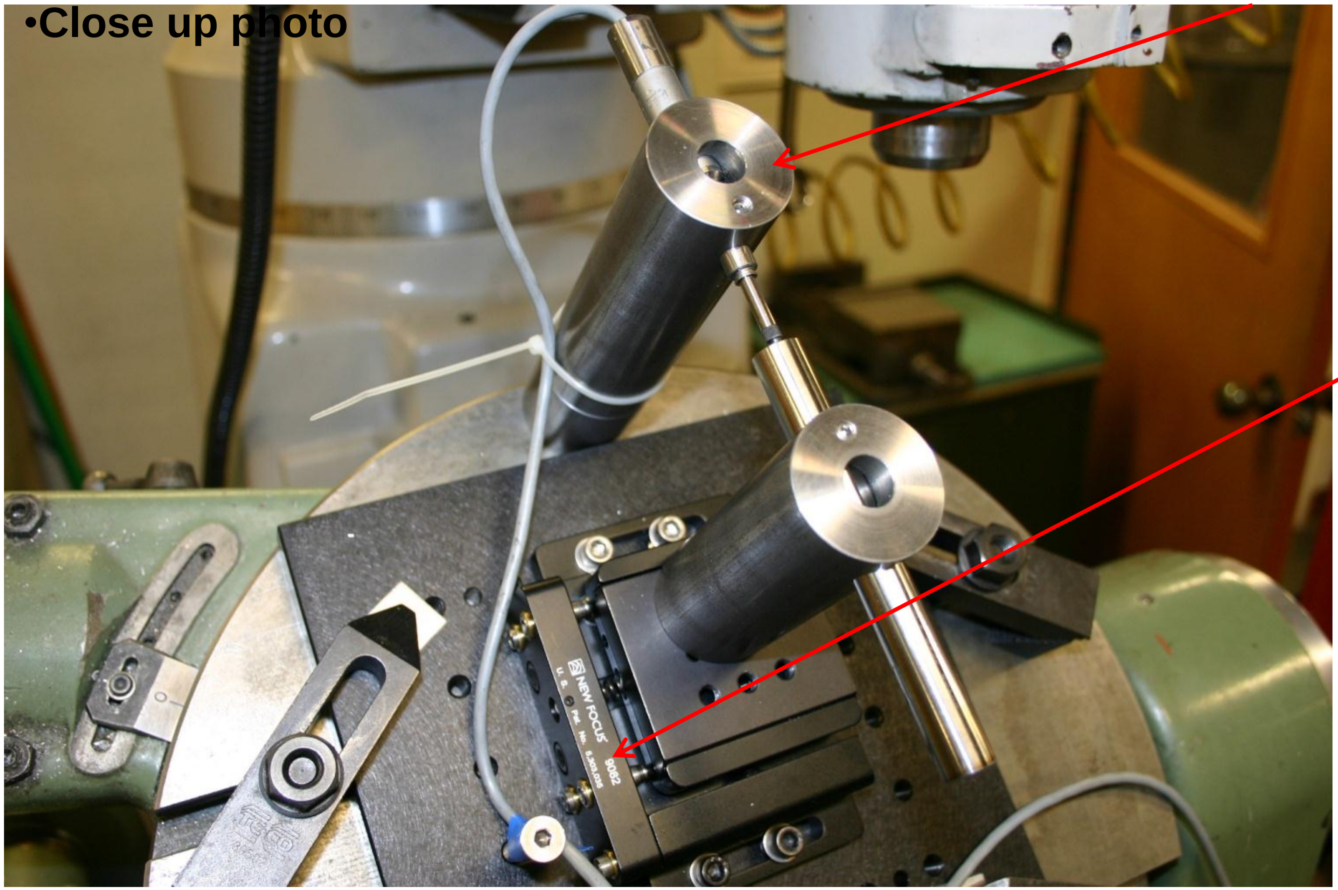
Case1 : stock kinematic stage configuration

1.5” O.D. LVDT support rod

•Close up photo



New Focus 9082

MEMs Kinematic Stage

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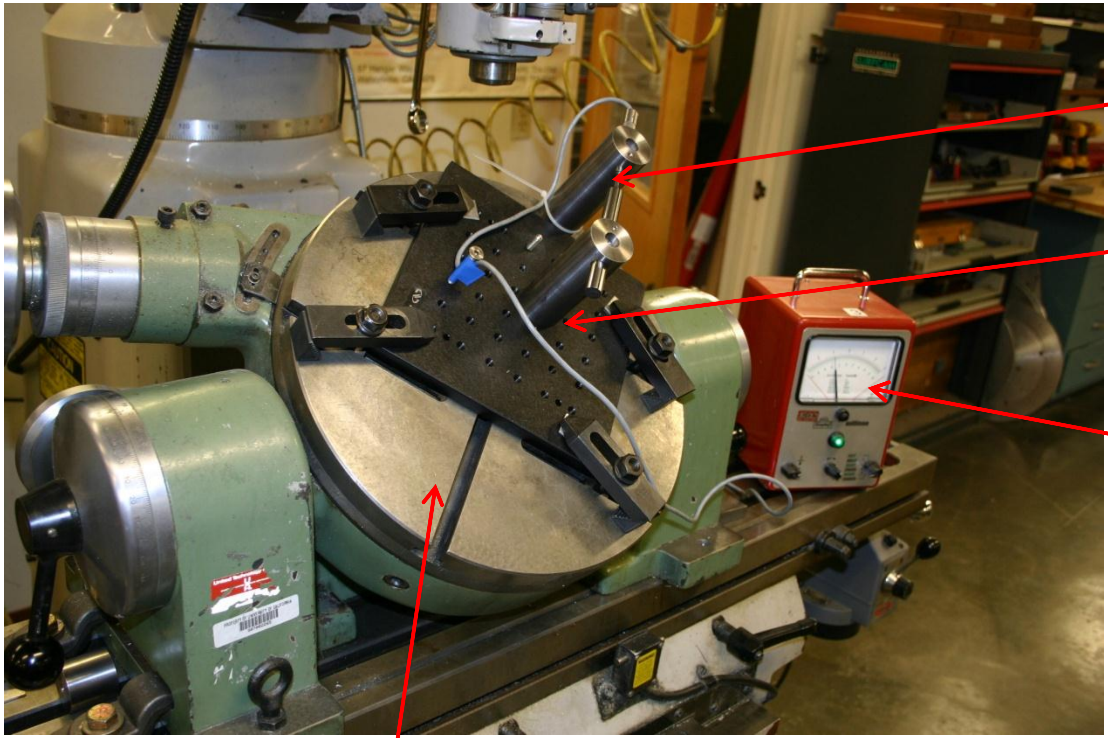
Case 2 : No Kinematic Stage, Baseline

•Test Set Up: Orientation (45° , -45°)



LVDT

New Focus 9082: removed

Mahr Millitron Amplifier (0.000005” resolution =127nm)

2 axis rotation table

MEMs Kinematic Stage

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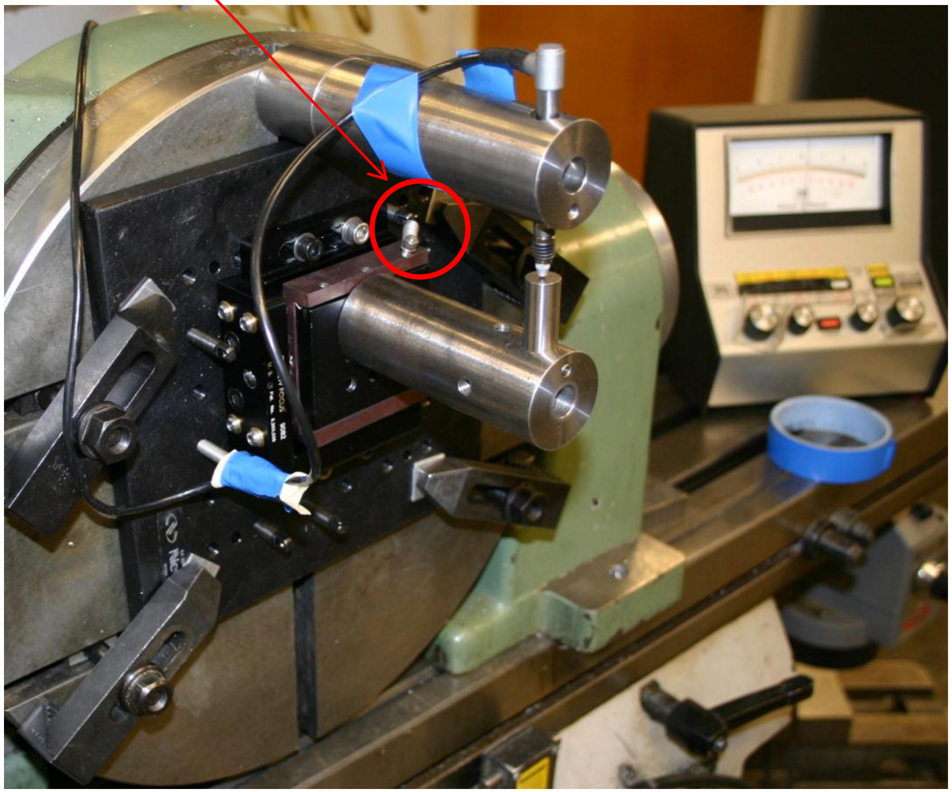
Case 5: M2 Tool steel and additional preload spring on weak corner



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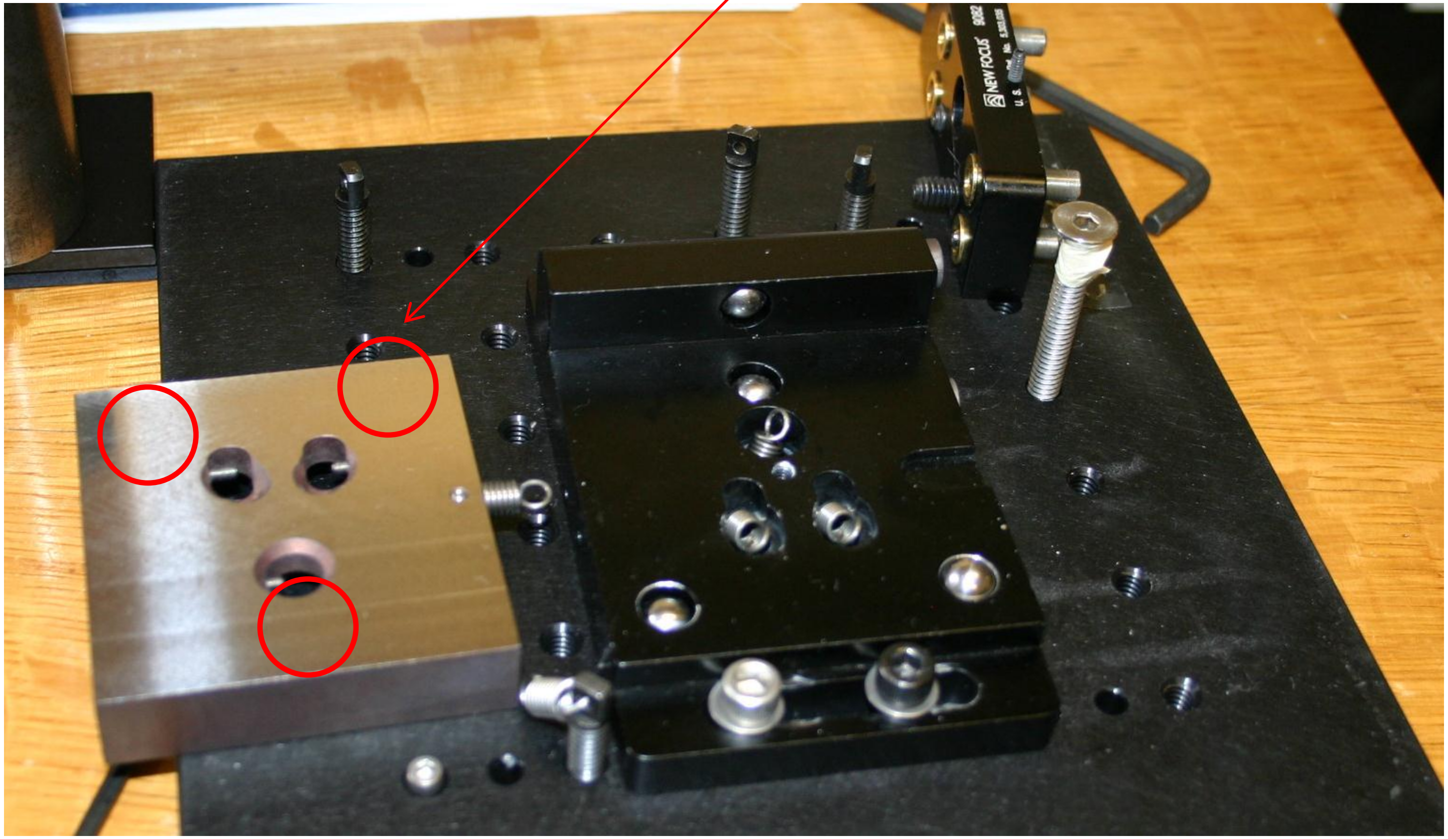
MEMs Kinematic Stage

Post Experiment Photo: No plastic deformation, repeatable



MEMs DM Kinematic Stage Summary

	Case1: Stock Kinematic Stage	Case 2: No Kinematic Stage, Fixed Rods*	Case 3: Heavily Preloaded Stock Stage (approx 15 lbs typical)**	Case4: M2 Tool Steel and 6 to 11 lb preload	Case5: M2 Tool Steel and 9 to 11 lb preload***	Case6: M2 Tool Steel and 15 to 20 lb preload
Maximum Deflection within 22.5° of Zenith	3.7 µm	0.5 µm	0.5 µm	1.4 µm	1.2 µm	0.8µm
Maximum Angular Deflection within 22.5° of Zenith	7.3 arcsec	1.0 arcsec	1.0 arcsec	2.8 arcsec	2.4 arcsec	1.6 arcsec
Maximum Deflection within 45° of Zenith	4.6 µm	0.5 µm	1.7 µm	2.2 µm	2.1 µm	1.5 µm
Maximum Angular Deflection within 45° of Zenith	9.0 arcsec	1.0 arcsec	3.3 arcsec	4.3 arcsec	4.1 arcsec	2.9 arcsec
Hysteresis (at Zenith)	3.0µm	0.5µm	0.9µm	1.1µm	0.6µm	0.25µm
Angular Hysteresis	5.9 arcsec	1.0 arcsec	1.8 arcsec	2.2 arcsec	1.2 arcsec	0.5 arcsec

*May be due primarily to thermal expansion, temperatures not monitored, calculated gravity deflection estimate: 0.1 microns
**Kinematic surfaces brinnelled after this test, could lead to difficult position control
***No Brinelling observed with M2 (Rockwell 65 C scale hardness) kinematic surfaces

Tip/Tilt Sensor

- **Functional Requirements for Tip/Tilt Sensor**
- **Design description**
- **Deformation analyses**
  - **FEA**
  - **Moment Rigidity (IKO)**
  - **Kinematic Doublet Mount Deformation: Sphere on Cylinder Hertzian Deformation**
- **Alignment**

Tip/Tilt Sensor

Functional Requirements:

- Position Specifications (stringent ones in **Bold**):
  - Doublet lens axis must be within +/-0.1mm of CCD center
  - +/- 30mm travel in x and y (must be able to position anywhere in full field of view)
  - x/y tilt of lens axis must be within 0.05 degrees of CCD normal
  - Range of Z adjustment for doublet lens or CCD +/- 25 microns (now relaxed)
  - **<u>Perpendicularity of x-y trajectory relative to beam axis: +/-25 microns</u>**
    - Straightness of stage: <6 microns
- Gravitational deflection allowance (for 3 hour exposure time):
  - Change in position of CCD relative to Optical Bench:
    - **<u>Linear displacement< 2.5 micron</u>**
    - Angular displacement<1 arcmin
  - **Change in position of CCD relative to lens: <u><0.5 microns</u>**
  - Change in position of filter wheel relative to CCD and lens: <0.1 degree angular displacement -FEA complete

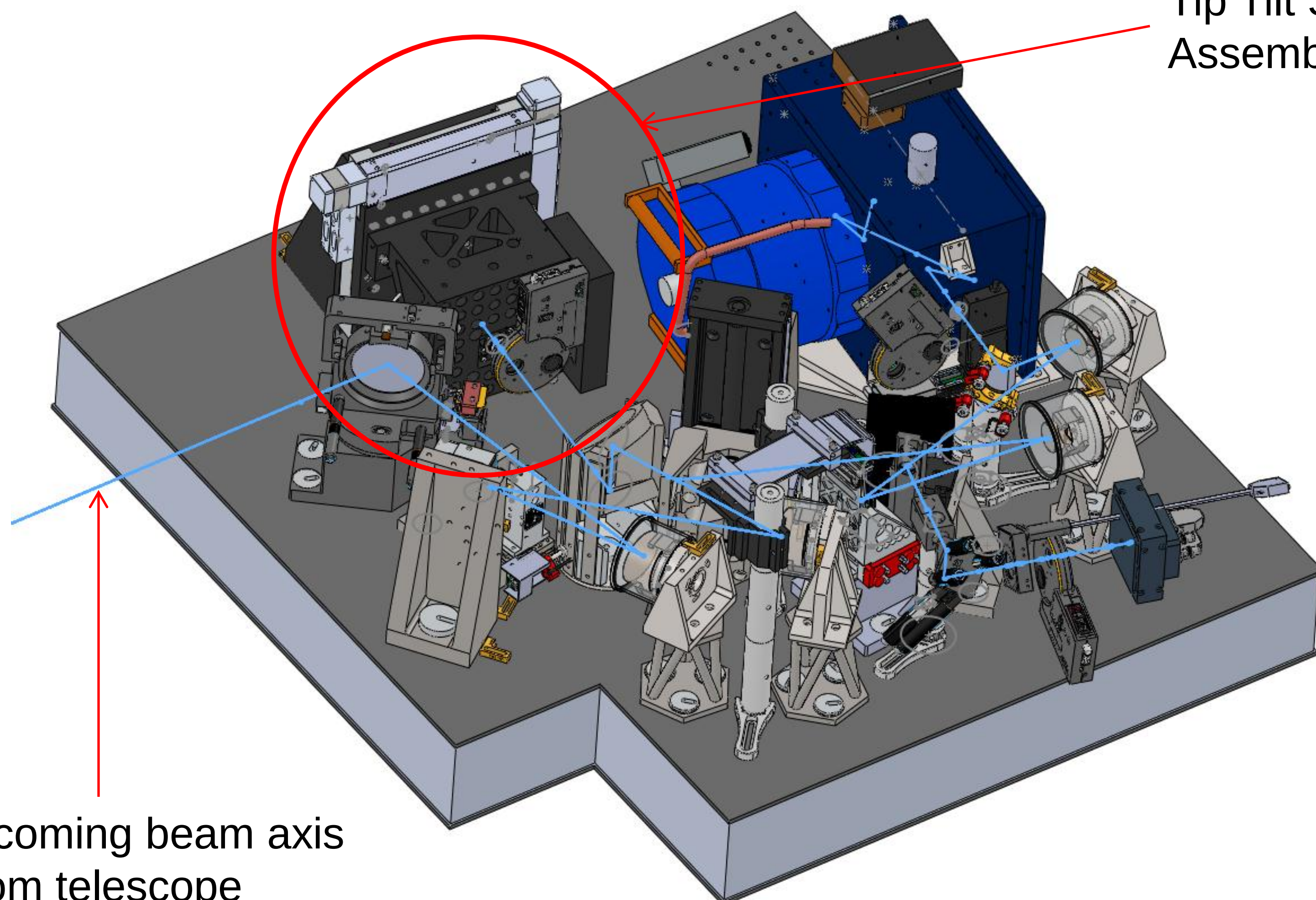
- Sequence of Events for TTS while on sky

  Our target acquisition sequence is as follows:

  1. Center TTS in middle of range
  2. Center tip/tilt (TT) star in science camera.
  3. Based on offset between science object and tip tilt star, drive telescope to center science object on science camera.
  4. Drive TTS to center TT star on TTS. Once the TT star is centered on TTS, no movement of the TTS will be required (unless the flexure is bad enough that we need to offload to the TTS, but I can't see that happening more than a few times an hour, and it would be a very small movement (~50 microns)).

Tip/Tilt Sensor Design

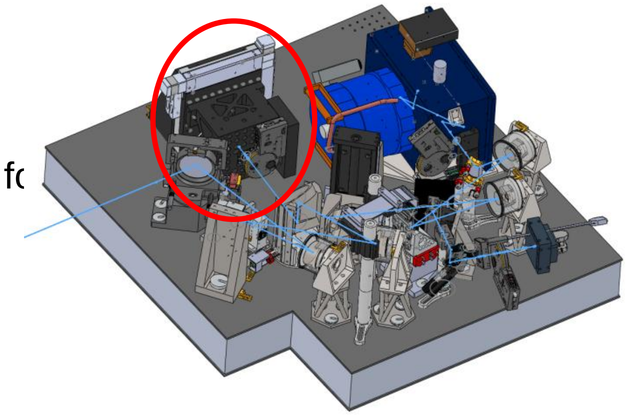
Layout in Main Assembly:

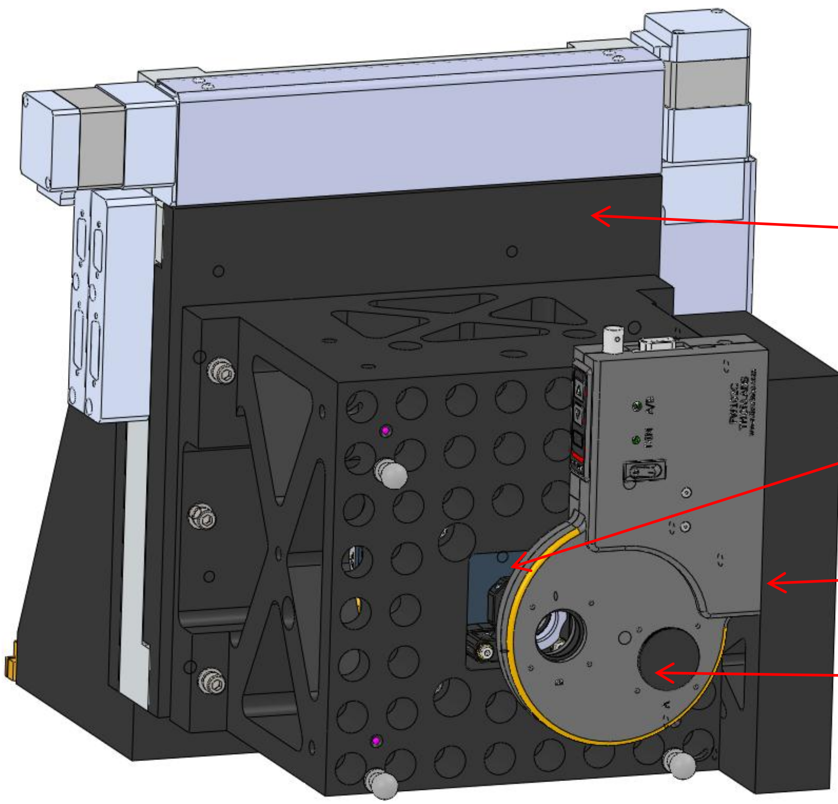


Tip/Tilt Sensor

Tip/Tilt Sensor Description:

-Main Element: SciMeasure C39 80x80 CCD camera (aka “Lil Joe”)
-Needs to move anywhere in x-y field of view (60mm x 60mm)
-Currently design utilizes Griffin Motion x-y stage along with mechanisms fo
camera, TTS doublet, and filter wheel

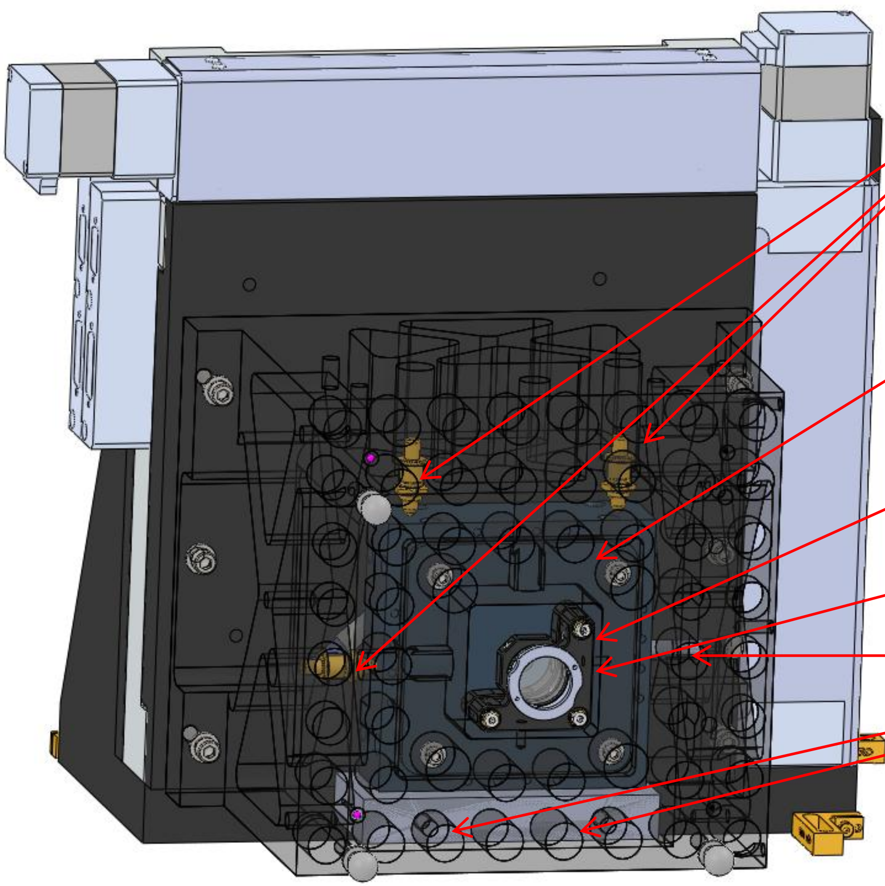




Tip/Tilt Sensor

Tip/Tilt Sensor Description:

-Some items removed for clear view



3 XY precision adjustment screws
(CCD to doublet alignment)

SciMeasure C39 CCD
Camera 80x80

Tip/Tilt Z Thorlabs KS1R,
detachable kinematic face

Doublet Clocking Grip
(Glued in place)

3 Spring loaded
plungers: opposing
adjustment screws

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Tip/Tilt Sensor

Tip/Tilt Sensor: Top View

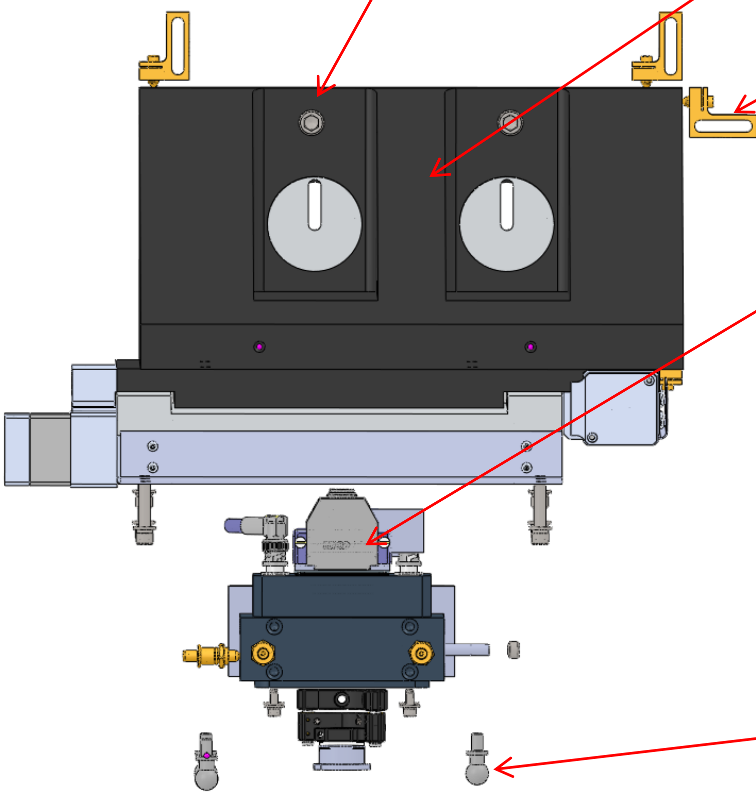
-Components removed for clarity

Jacking Screws: For adding shims

Stage Mount: 6061

Nudgers

New side exit DB connectors replace existing (both shown)



Tooling Balls for initial placement

Tip/Tilt Sensor

Tip/Tilt Sensor: Stage Positions

-Components removed for clarity

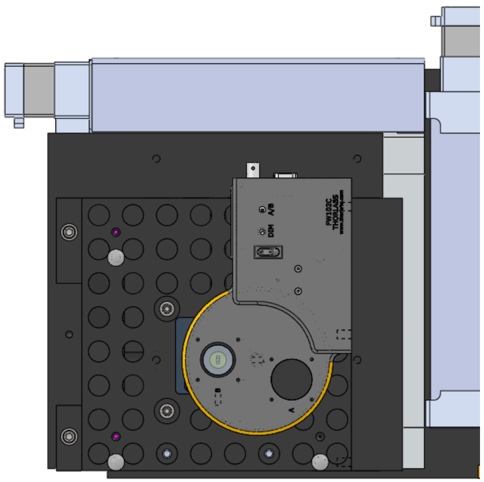


Table Position:
-30mm, -30mm

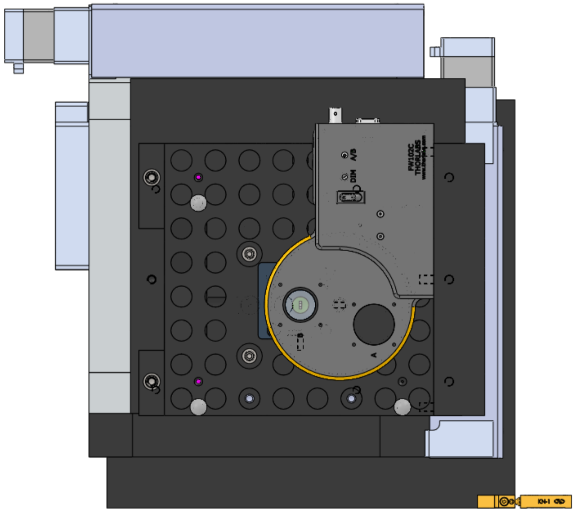


Table Position:
+30mm, +30mm

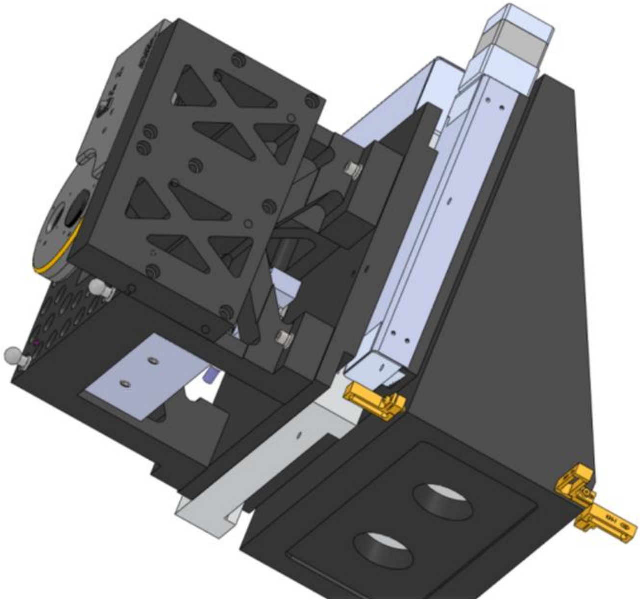


Table Position:
+30mm, -30mm

Tip/Tilt Sensor Deformation Analysis

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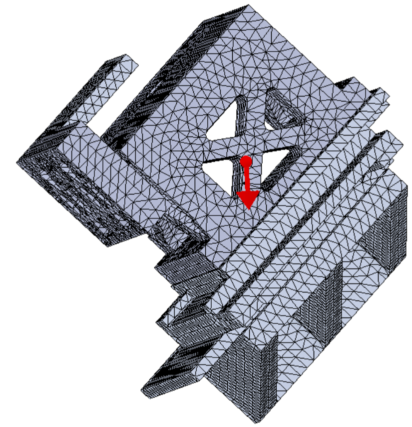


Objective:

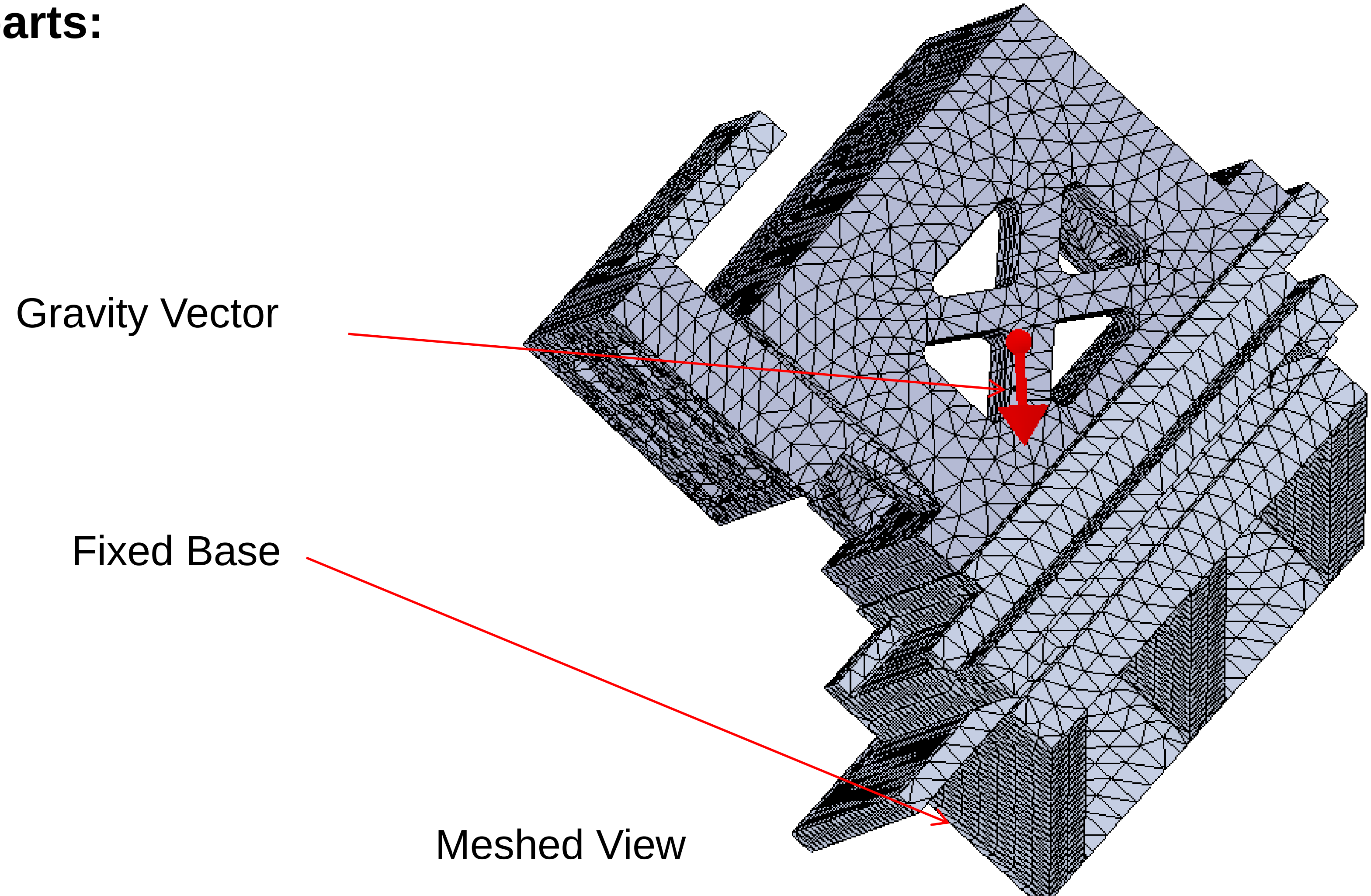
1. Determine maximum linear deflection of TTS CCD camera and doublet for worst case condition -<u>should be less than 2.5 microns</u>
    - 3 items to assess deflection
        - Major structural parts
        - Cross roller bearings (hertzian deformation)
        - KS1R kinematic lens mount

Tip/Tilt Sensor FEA Assumptions and Conditions:

1. Rigid bracket base is fixed, no deformation of optical table surface (need to assess separately with table FEA)
2. Linear carriage assembly is preloaded, treated as plane faces bonded to rail (no Hertzian contact)
3. Assembly is initially aligned with telescope at zenith, aligned with gravity vector
4. Filter wheel is approximated as block of 6061 Aluminum with similar dimensions
5. All materials are 6061 T6 Aluminum unless otherwise noted
6. Linear deflection value is critical, goal is to be under <u>2.5 microns</u>
7. Worst case change in gravity vector: 45 degrees. This is equivalent to a 3 hour exposure of a celestial body

Tip/Tilt Sensor Deformation Analysis

Simplified Meshed FEA Model for major structural parts:



Meshed View

TTS Deformation Analysis

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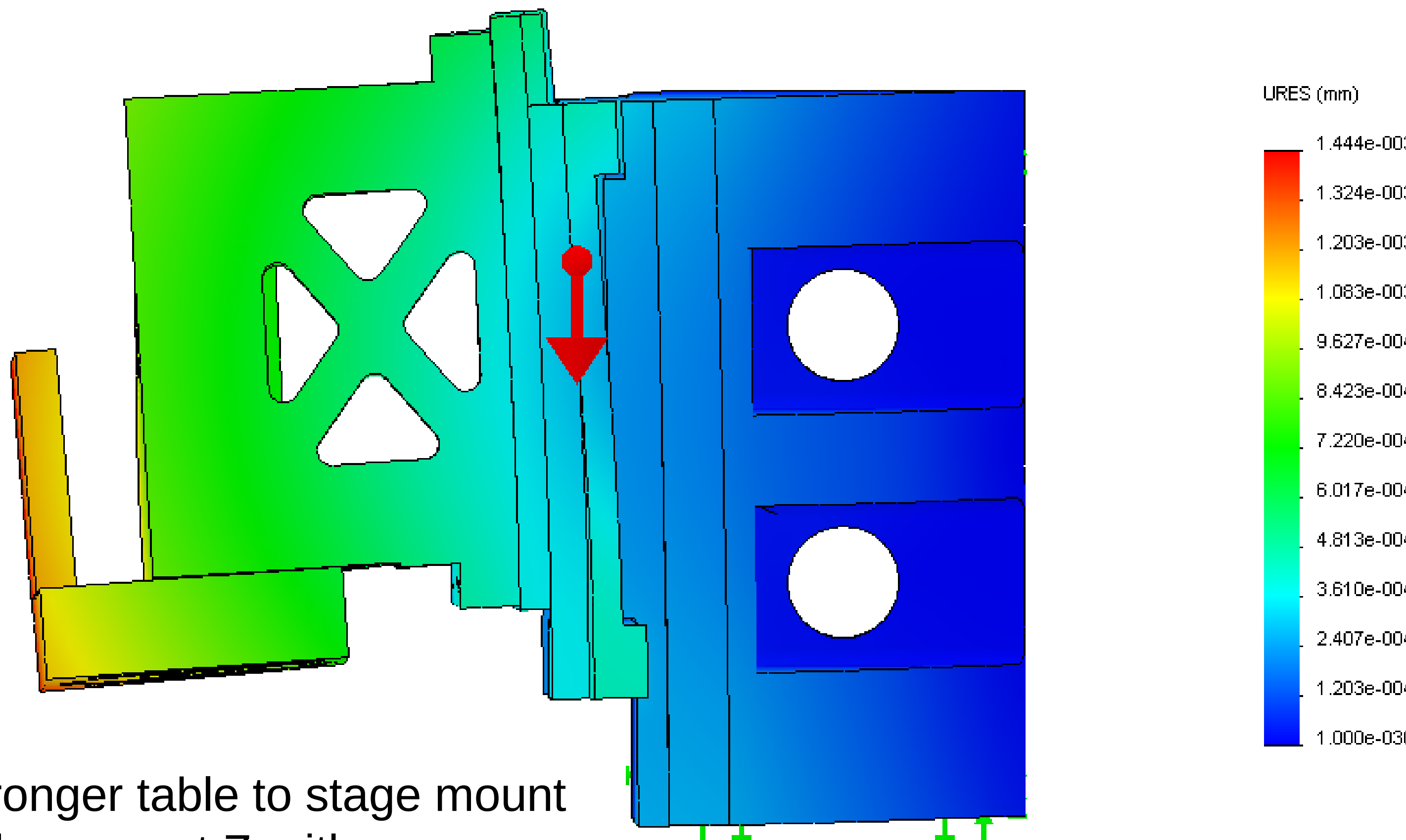
Gravitation induced flex with change in telescope position (exaggerated by 20,000x):



Latest Design: stronger table to stage mount
Baseline load: Telescope at Zenith
Net Deflection for Camera/Lens relative to bench: 1 micron

TTS Deformation Analysis

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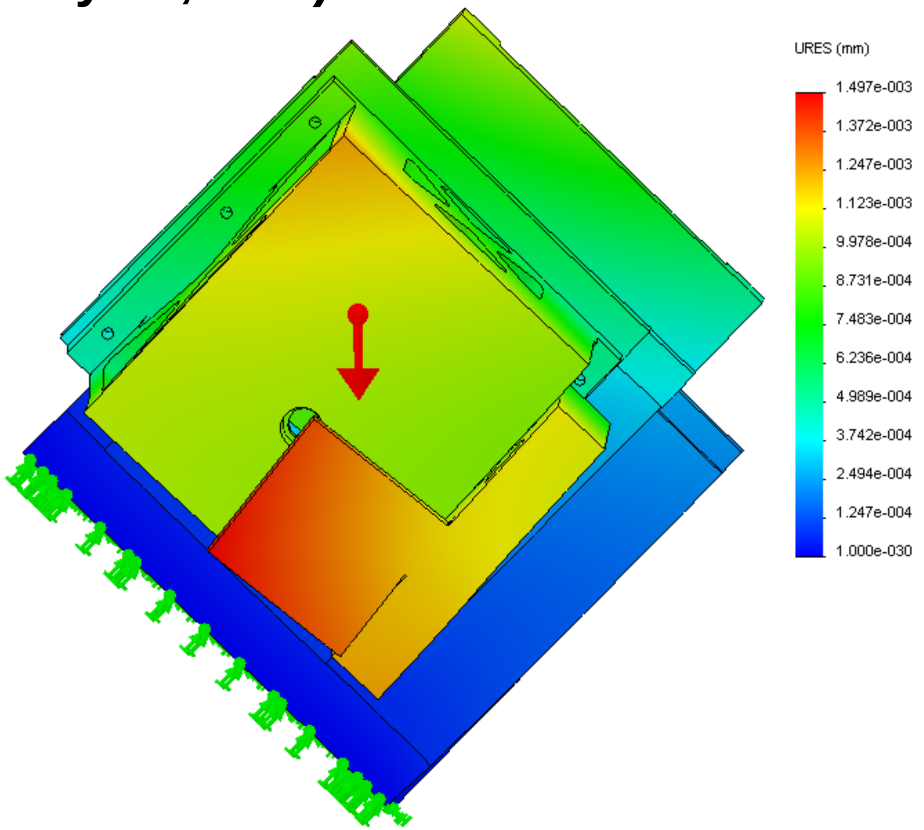
Gravitation induced flex with change in telescope position (exaggerated by 20,000x):



Load: Telescope at 45 Degrees from Zenith (about Z axis)
Net Deflection for Camera/Lens relative to bench: 1 micron

TTS Deformation Analysis

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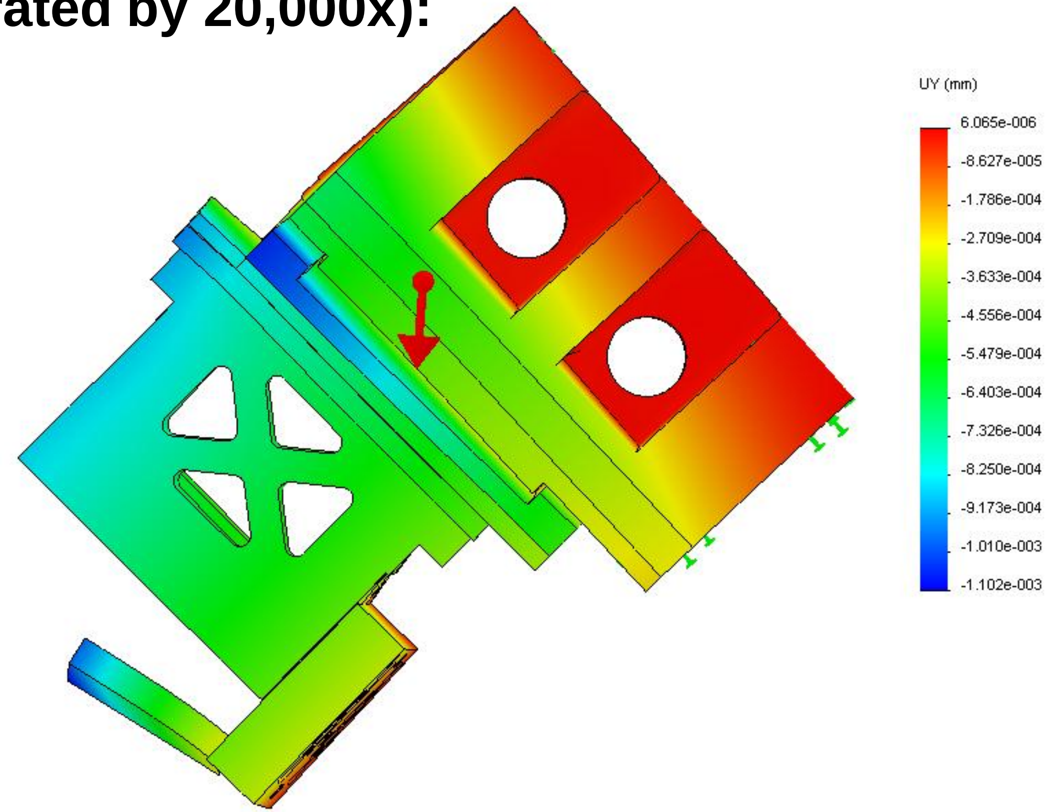
Gravitation induced flex with change in telescope position (exaggerated by 20,000x):



Load: Telescope at +45 Degrees from Zenith (about X axis)
Net Deflection for Camera/Lens relative to bench: 1 micron

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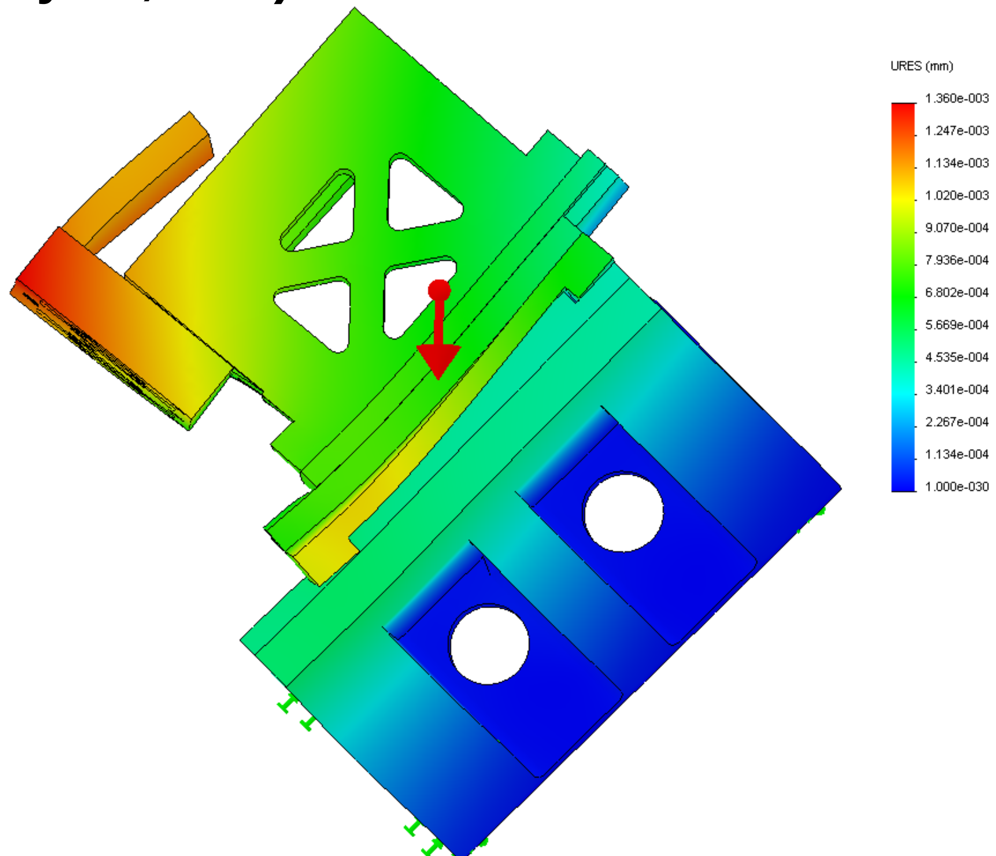
Gravitation induced flex with change in telescope position (exaggerated by 20,000x):



Load: Telescope at -45 Degrees from Zenith (about X axis)
Net Deflection for Camera/Lens relative to bench: 1 micron

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Results Table: Linear displacement at center of lens in different orientations with x and y stage fully extended: does not account for lens mount (KS1R) deflection, linear bearing Hertzian deflection or table deformation

Conditions	Linear X Displacement (microns)	Linear Y Displacement (microns)	Linear Z Displacement (microns)
Zenith	+.03	-.08	-0.95
45 degrees about Z	-0.73	-0.16	-0.67
+45 degrees about Z	-0.47	-0.39	-0.71
-45 degrees about Z	+0.53	+0.3	-0.64
Max Linear Displacement Change from Zenith	+0.5	+0.38	+0.31

TTS Deformation Analysis

Cross Roller Bearing Hertzian Deflection:

- **30 lb load**
- **Preloaded Roller Bearing (IKO CRW3-250)**
- **Result from Yugi at IKO (310)-609-3988 x207**

Material	Net Change in Angular Deflection
Lateral Deflection	0.4 microns
Normal Deflection	0.4 microns

Net worst case linear deflection when load shifts from +90 to -90: 0.8 microns

TTS Doublet Kinematic Mount

Detachable Kinematic Mirror Mount for Ø1" Optics

Combining the functionality of our popular kinematic base plates (see pages 97 - 99) with our versatile kinematic mirror mounts, the KS1R offers a unique solution for multi-path beam steering. The detachable front plate houses three 1/4"-80 lockable fine adjustment screws, allowing multiple plates to be individually adjusted from a common base plate. Rare earth magnets supply ample coupling force between the front and rear plates.

The KS1RF front plate allows you to mount and align more than one optic in a system and easily swap them in and out without needing to realign the system.

KS1R
Optic, Post, and Post Holder Not Included

- Detachable Kinematic Front Plate
- Rare Earth Magnets Provide Repeatability Better than 10 µrad
- Front Plate of KS1RF can be Individually Adjusted for Specific Positioning Requirements
- Contains Three Lockable High-Precision Adjusters

KS1R with Front Panel Removed

TTS Kinematic Doublet Mount Deformation Analysis

Conditions and Assumptions for Linear displacement at center of doublet lens:

1. **Lens is Glass (weight 0.07 lbs)**
2. **Lens is rigidly fixed to KS1R**
3. **KS1R is 6061 T6 Aluminum**
4. **KS1R is rigidly connected to support structure (tight screws)**
5. **Front Plate of KS1R weight: 0.17 lbs**
6. **Contact diameter between spheres and flats of 0.010" diameter (calculated actual: 0.003")**
    - **Mesh issues prevented smaller than 0.)10"**
7. **Preload on 3 spheres: 10.6 N (Per New Focus Specs)**
    - **Analysis does account for this preload**

TTS Kinematic Lens Mount Deformation Analysis

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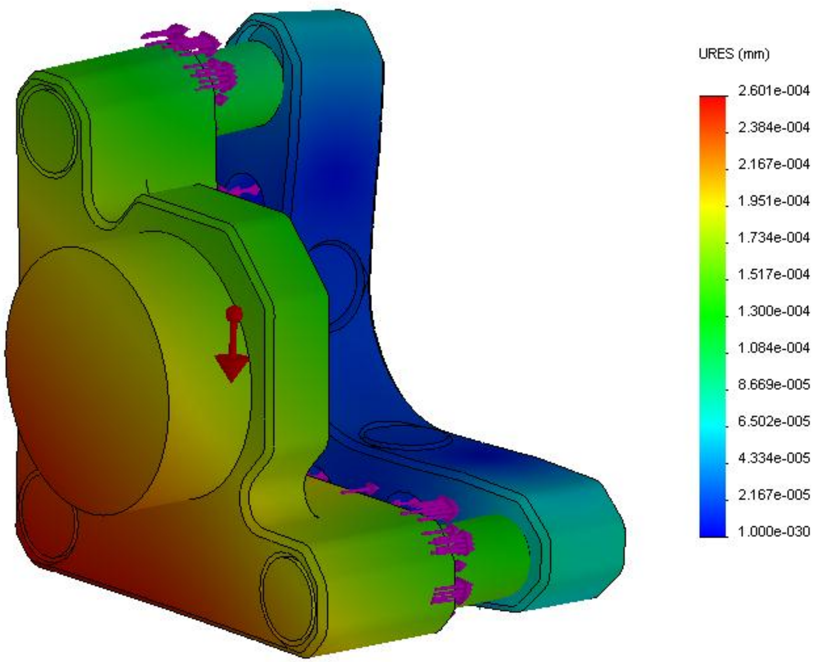
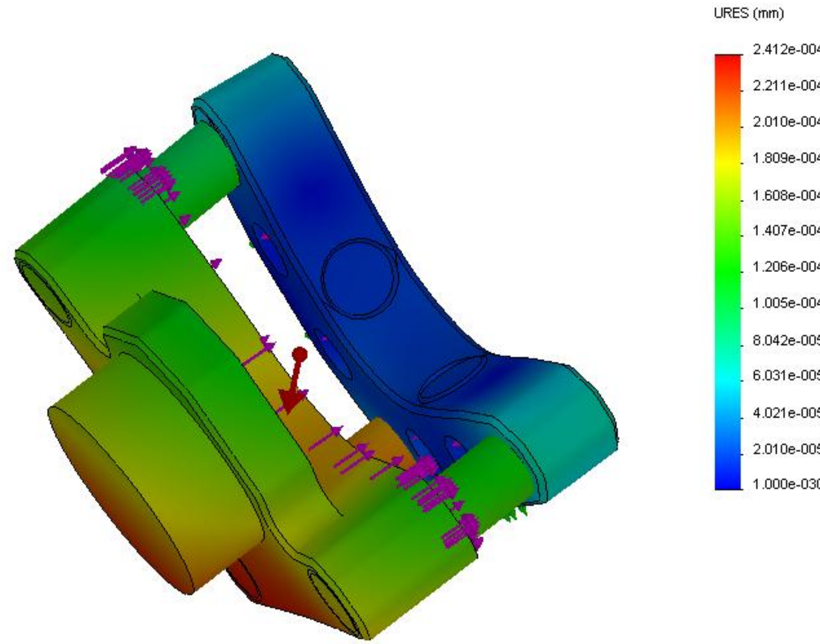
Gravitation induced flex with 45 degree change in telescope position:



<u>Baseline orientation</u>: Telescope at Zenith (0.26 micron max deflection)



<u>Telescope pointed 45 degrees South</u> (0.24 micron max deflection)

TTS Kinematic Lens Mount Deformation Analysis

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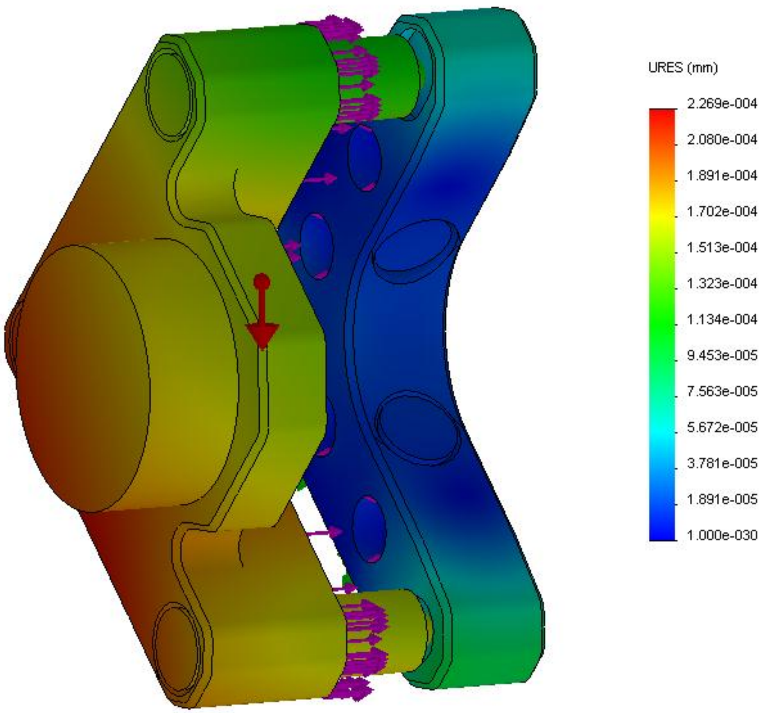
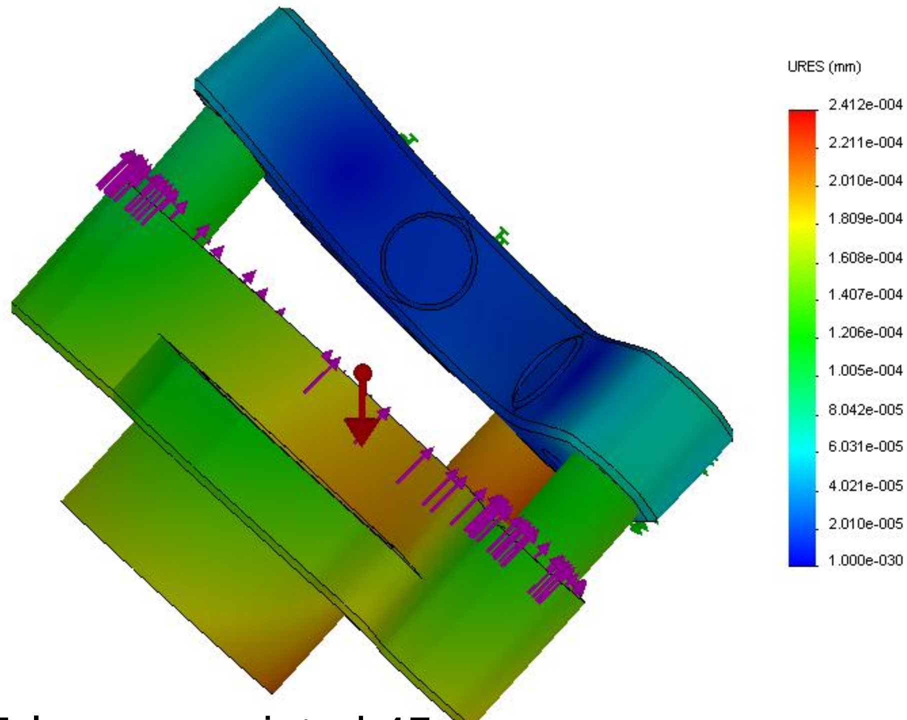
Gravitation induced flex with 45 degree change in telescope position:



Telescope pointed 45 degrees East (0.23 micron max deflection)



Telescope pointed 45 degrees West (0.24 micron max deflection)

TTS Deformation Analysis

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<u>Results Table: Linear displacement at center of doublet lens</u> in different orientations for Thorlabs Kinematic KS1R (units: microns) – relative to mount surfaces

Conditions	Linear X Displacement	DX From Zenith	Linear Y Displacement	DY From Zenith	Linear Z Displacement	DZ From Zenith
Zenith	0.141	0	-.070	0	-0.150	0
+45 degrees about Z	0.129	-0.012	-0.132	-0.062	-0.144	+0.006
-45 degrees about Z	0.097	-0.044	+0.003	+0.073	-0.167	-0.017
+45 degrees about X (45 south)	0.122	-0.019	-0.074	-0.004	-0.146	+0.004

<u>Very small change in deflections, well below 0.5 micron allowance</u>

TTS Kinematic Doublet Mount Deformation Analysis

Analysis: Hand Calculations to check Deformation for Spherical End on kinematic base

1. **Assume Tool Steel E=228x10^9 GPa**
2. **Use equations from Roark and Young 5th Ed.**
   -Sphere on sphere (worse case than sphere on cylinder)
3. **Two load cases: 3.9N –Full weight, 3.5N –No lens or front plate weight**
4. **Accounts for dual rod full support mechanism**
5. **Neglects deflection of rod into aluminum**

<u>Net change in displacement</u> along axis of adjustment screw: <u>0.035 micron</u>s…similar to FEA Results, very small change

Tip Tilt Assembly Alignment

Assembly and Alignment of TTS (show animation):

1. **Screw Stage Mount to Optical Bench (two slotted pivot disks)**
2. **Assemble xy stage to base**
3. **Install 3 precision alignment screws to Lil Joe Mount**
4. **Mount Lil Joe with 4 SHCS's to Aluminum Mount**
5. **Tighten 4 screws holding CCD so springs are lightly loaded**
6. **Install 3 spring loaded plunger mechanisms**
7. **Install Thorlabs KS1R tip/tilt/z mount**
8. **Clock doublet (any reference on doublet for initial assembly?)**
9. **Adjust doublet tip and tilt and CCD x and y so spot is on at center of CCD and spot geometry is good**
10. **Adjust theta z: remove face plate, loosen set-screw, move lens in theta z and tighten set screw**
11. **Replace face plate**
12. **Check theta z on CCD, if OK stop, otherwise go to step 6**

Tip/Tilt Sensor: Alignment

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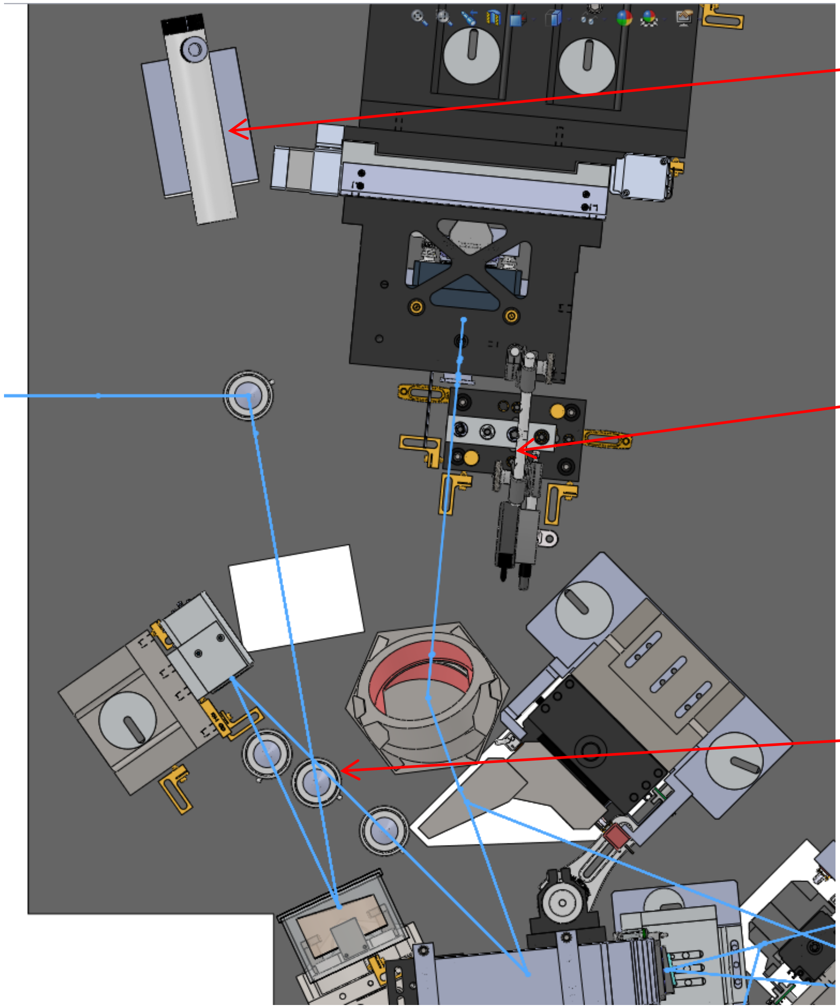

Alignment Telescope

High Precision Planar Face

3 Conical Alignment Posts: aligned with beam axis during OAP alignment

Tip/Tilt Sensor Alignment

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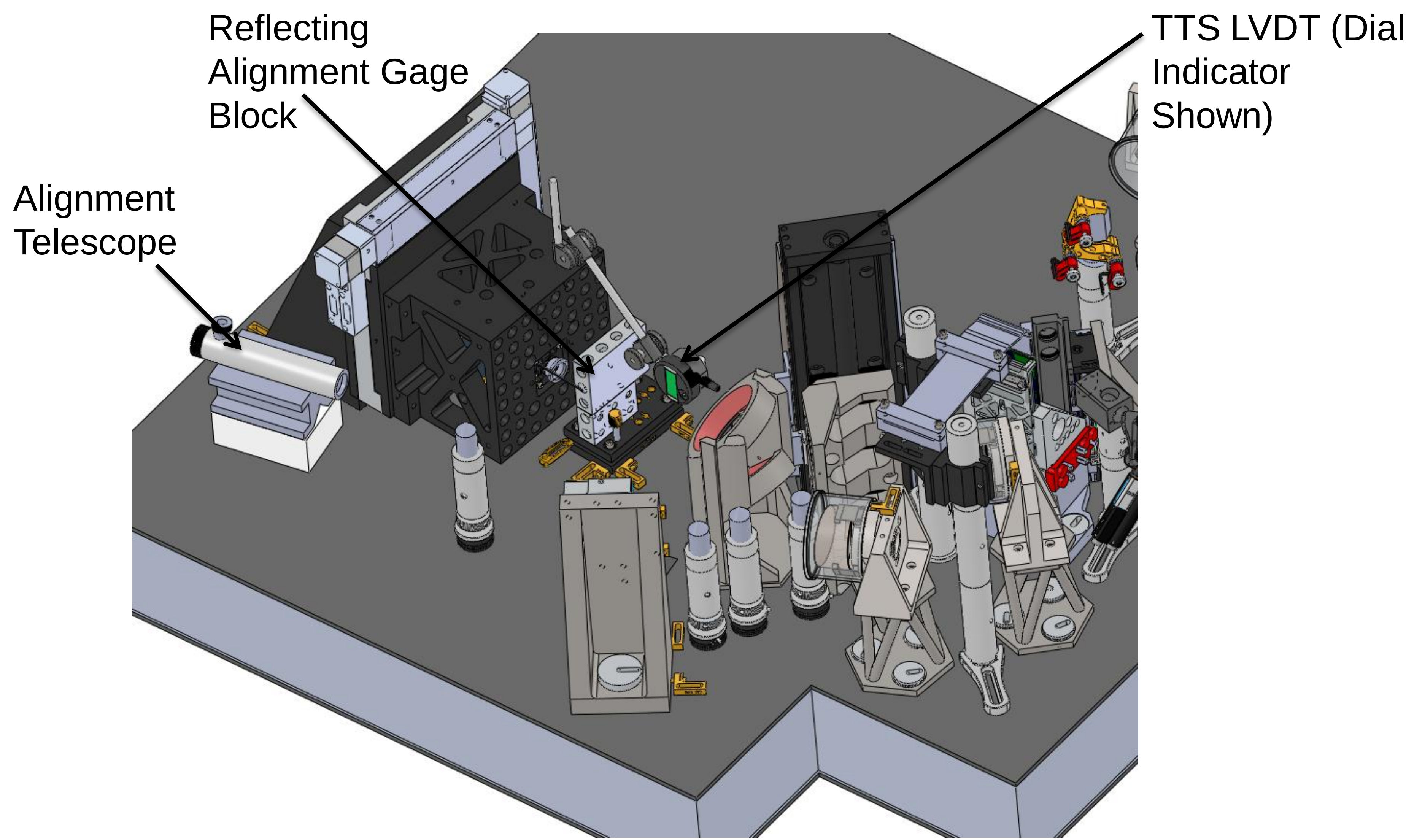
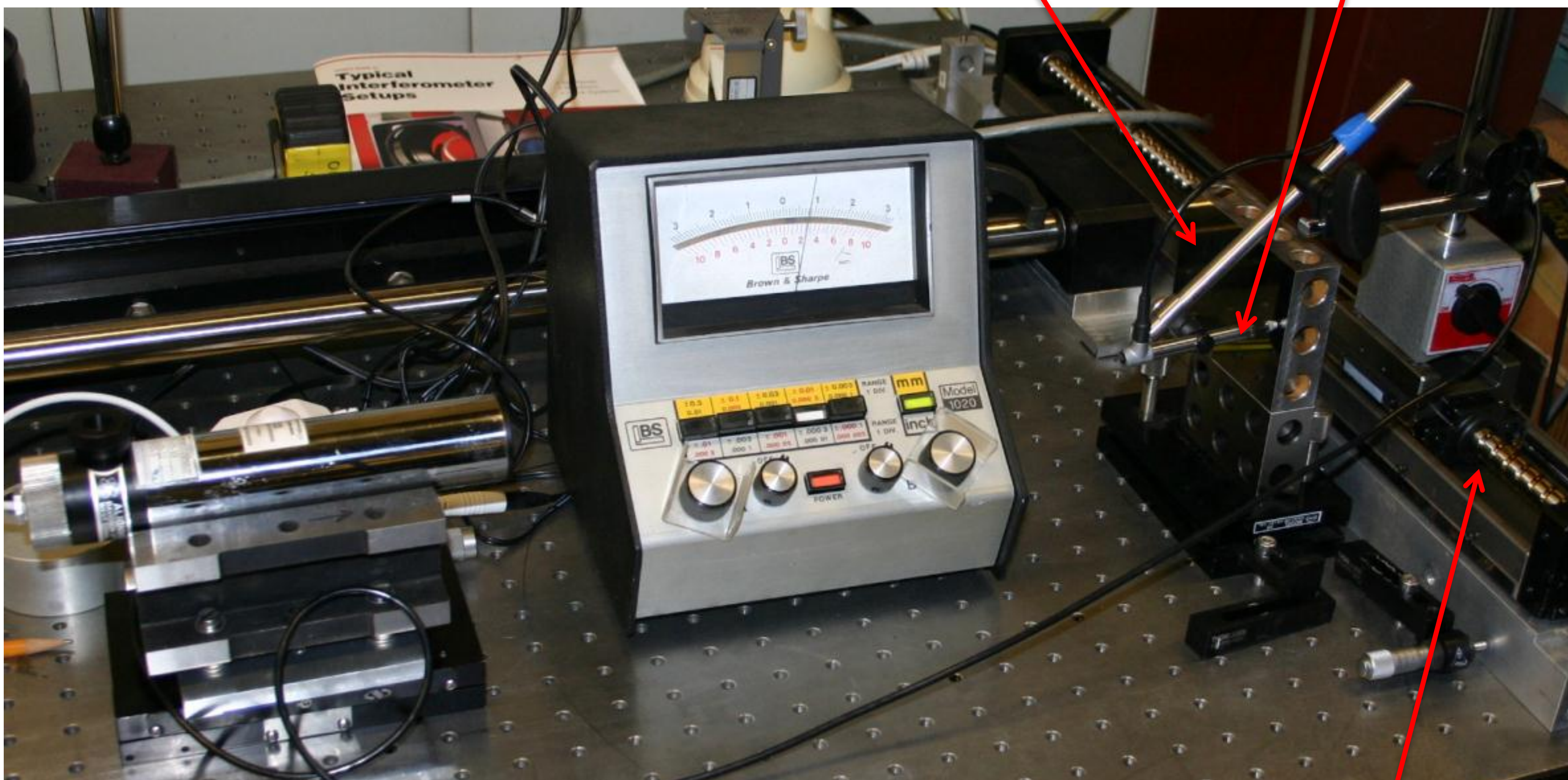


Tip/Tilt Sensor Alignment

Single Axis Test Rig

Reflecting Alignment Gage Block

TTS LVDT
(<1 micron resolution)



High Precision Stage

Tip/Tilt Sensor

Conclusions:

- **Latest design beats the 2.5 micron goal accounting for both flex of metal parts and deflection of the roller bearings, however neglects table flex**
  - **<u>Worst case estimated change in deflection: 1.9 microns</u>**
  - **0.1 microns for lens mount**
  - **0.8 microns for linear bearings (rough estimate from IKO)**
  - **1.0 microns for all other major structural parts**
- **Need to design base to be large to minimize local table loading**
- **Can successfully align with alignment telescope technique**
  - **Need to also do alignment testing with OAP's in place and conical posts (still being made)**

- **<u>Net Uniform Thermal Deformation: worst case of 56 microns for change in 20 C</u>**
- **Still assessing overall thermal deformation and if/how to address**

TTS Dichroic Stage

- **Overview/Requirements**

- **Deflection analyses**
  - **FEA**
  - **Moment Rigidity**

- **Motion control**
  - ***Motion requirements***
  - ***Selection of Stages***
  - ***Sizing Motors***

- **Summary**

TTS Dichroic Stage

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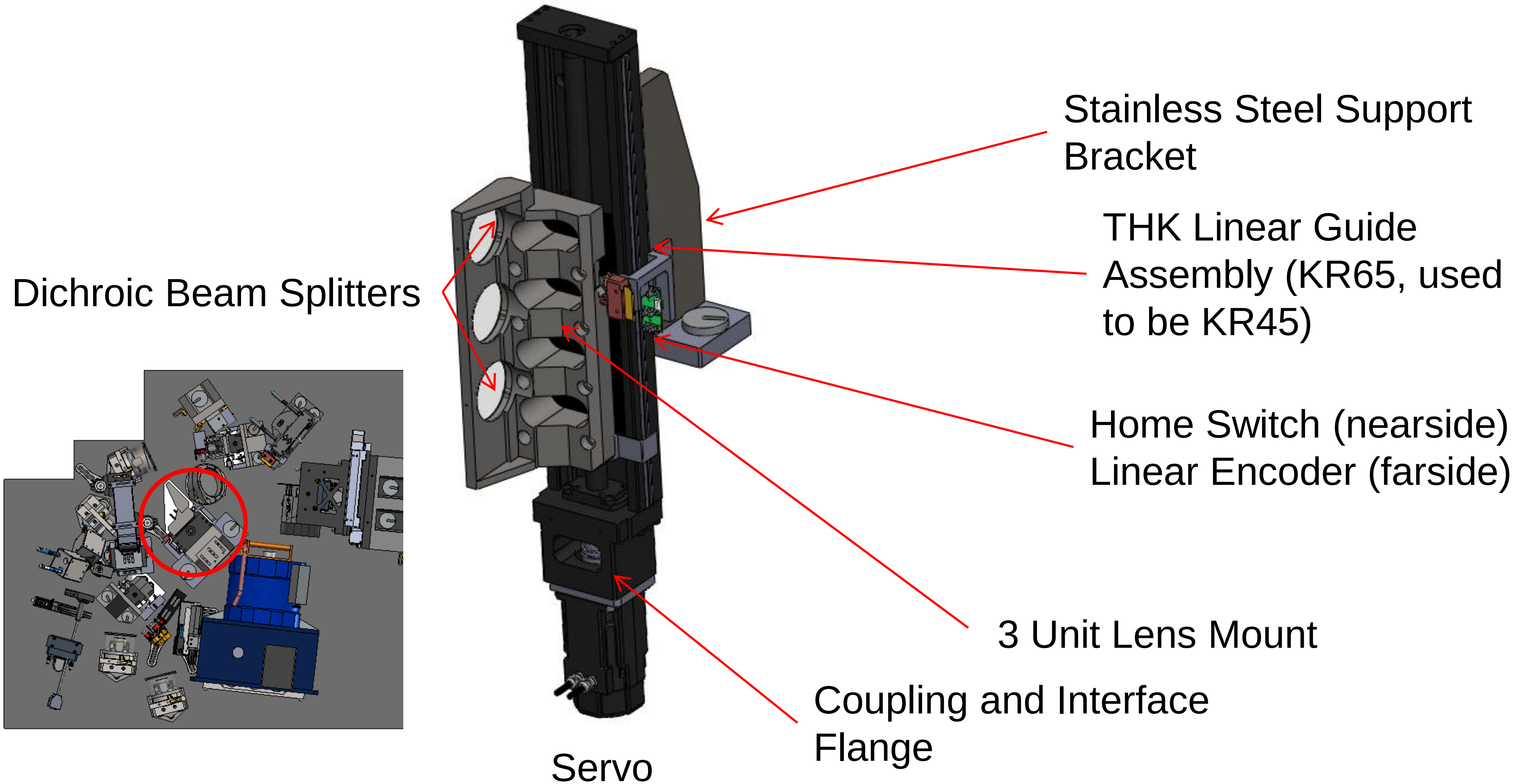
Dichroic Tower Description:

-Holds array of three 75mm dichroic beam splitters (DBS)
-Need to be able to remotely control which DBS is in beam path



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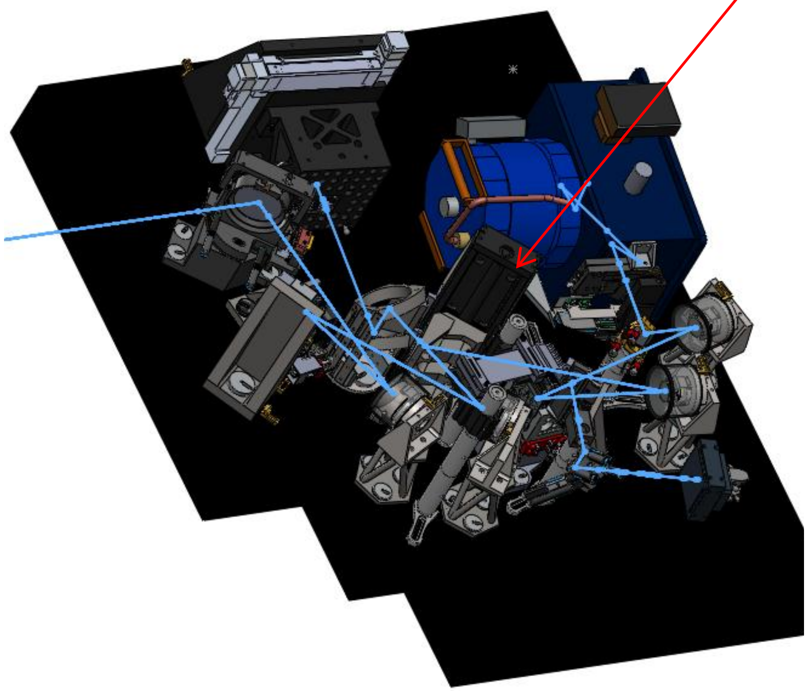
TTS Dichroic Stage

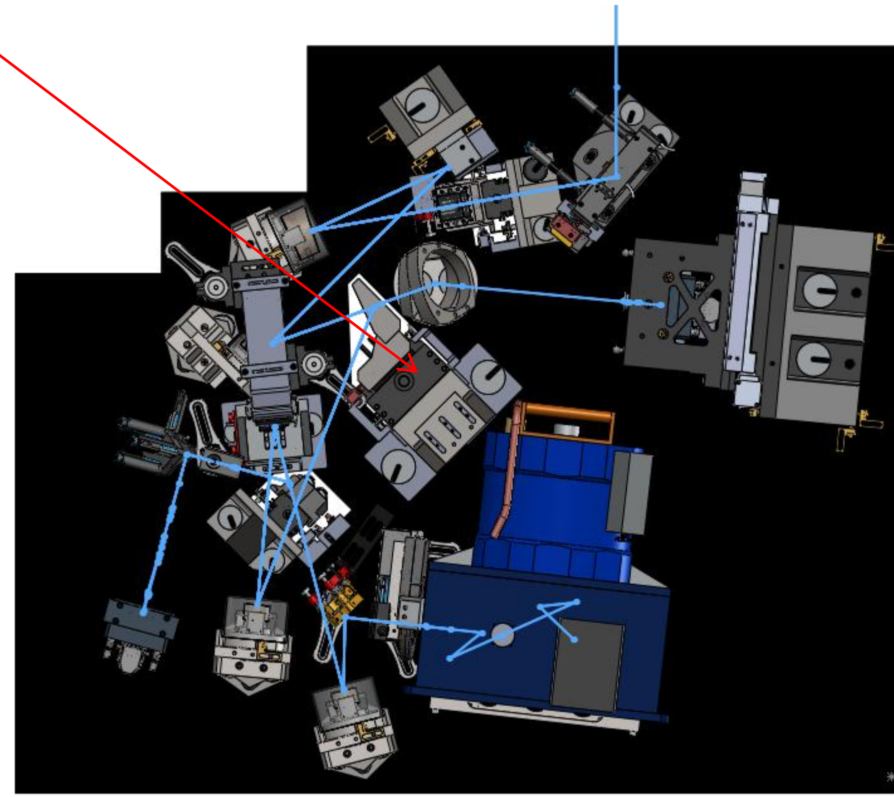
Integrated in Main Assembly:

-Space Constraints

Dichroic Tower



View 1



Top View

TTS Dichroic Stage

Objective:

1. Determine maximum deflection of dichroic beam splitters for worst case condition

Dichroic Tower Analysis Assumptions and Conditions:

1. Rigid bracket base is fixed, no deformation of optical table surface (will assess separately)
2. Linear carriage assembly is preloaded, rigid relative to rail
3. Assembly is initially aligned with telescope facing straight up, aligned with gravity vector
4. Newport lens mounts are approximated as block of 6061 Aluminum with similar dimensions
5. Linear rails consist AISI1055 Steel
6. Assess deformation for gravity, thermal change (30 C)
7. Movement in x-y plane not critical
8. Tip/Tilt movement critical, goal is to be under <u>2 arcseconds</u>
9. Worst case change in gravity vector: 45 degrees. This is equivalent to 3 hours of viewing/ tracking a celestial body starting or ending with telescope optical axis aligned with gravity vector
10. Dichroic lenses modeled with same density as glass, with low modulus of elasticity (contributes to load, but not structurally supportive)

TTS Dichroic Stage

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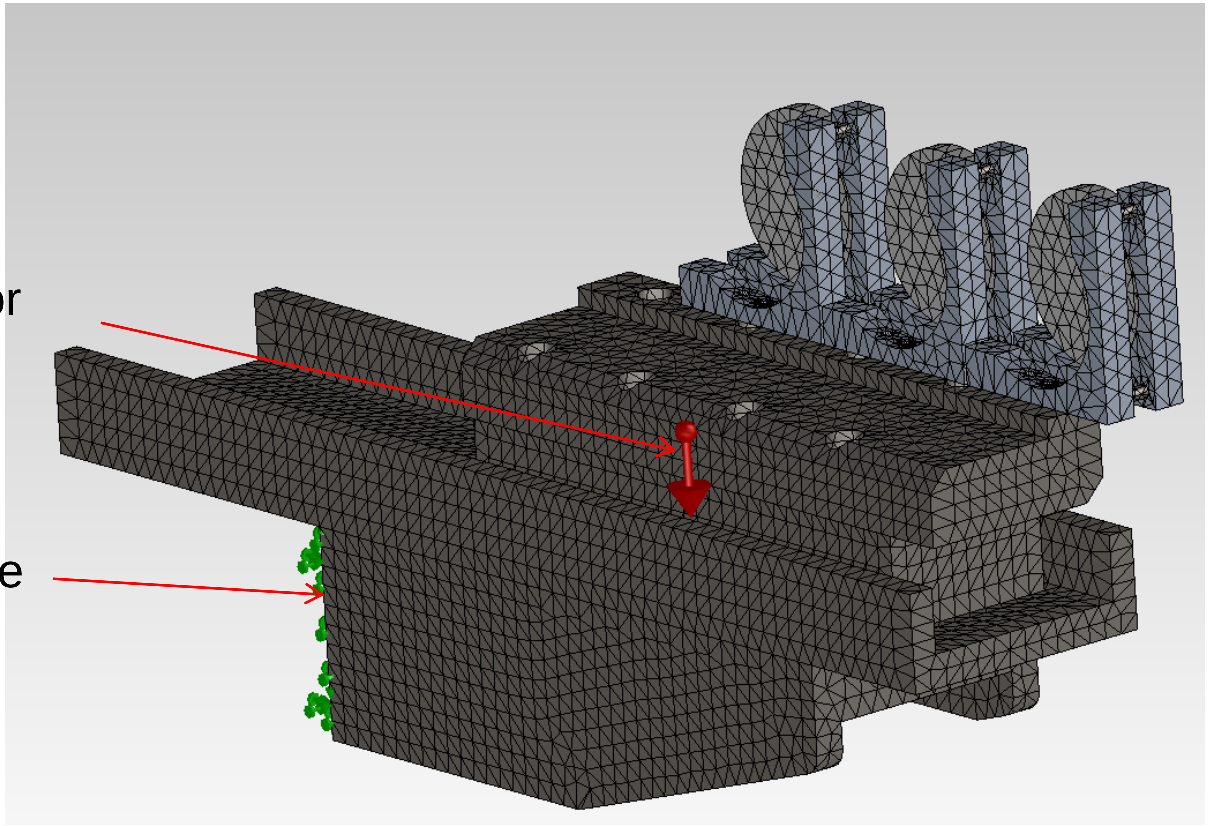
Simplified Meshed FEA Model:

Gravity Vector

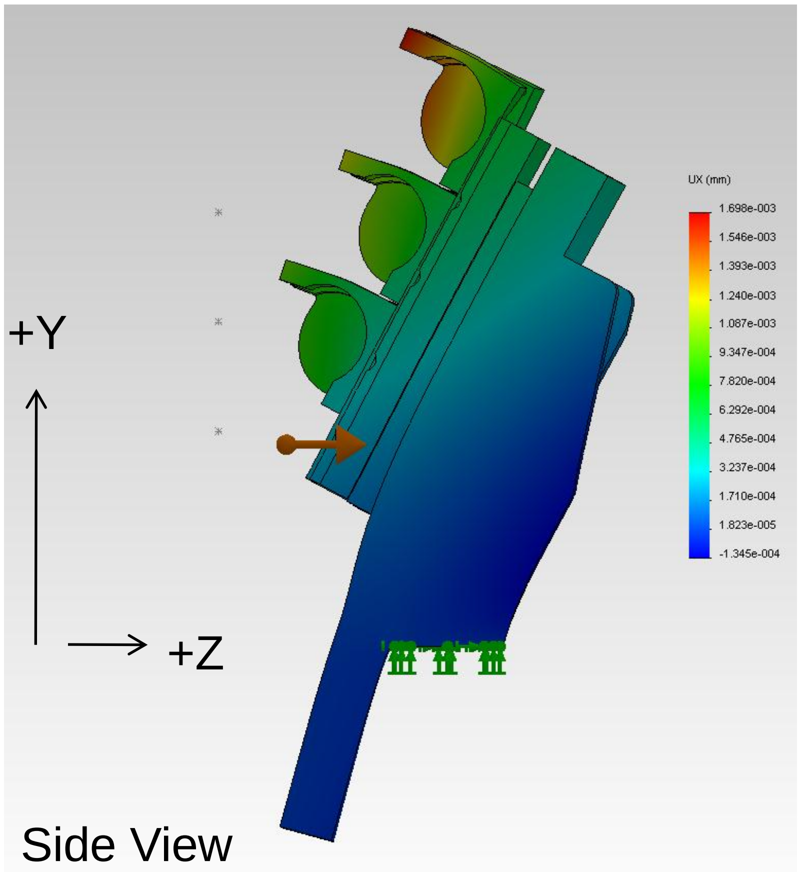
Fixed Base

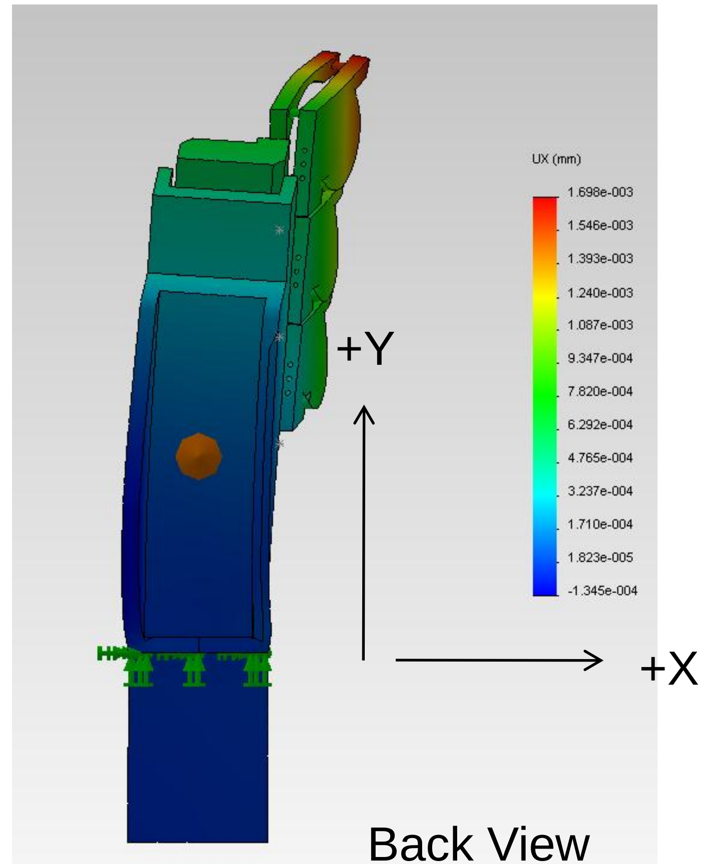


Meshed View

TTS Dichroic Stage

Gravitation induced flex with change in telescope position (exaggerated by 50,000x):





Case A: Telescope pointing 45 degrees

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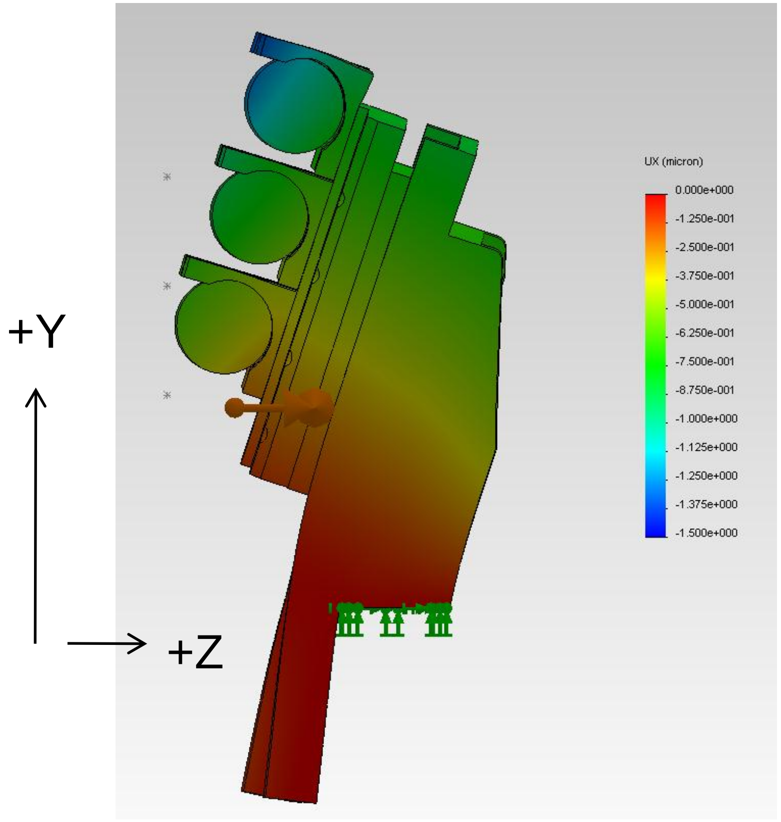
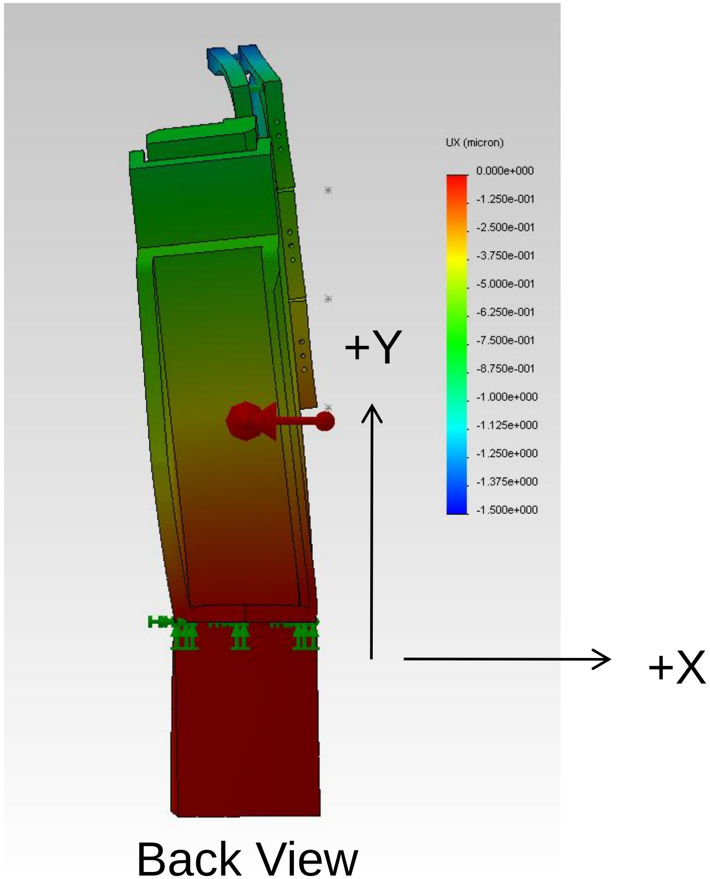
Gravitation induced flex with change in telescope position (exaggerated by 50,000x):



Side View



Back View

Case A: Telescope pointing straight up “0 degrees”

75mm Dichroic Tower Deformation Analysis

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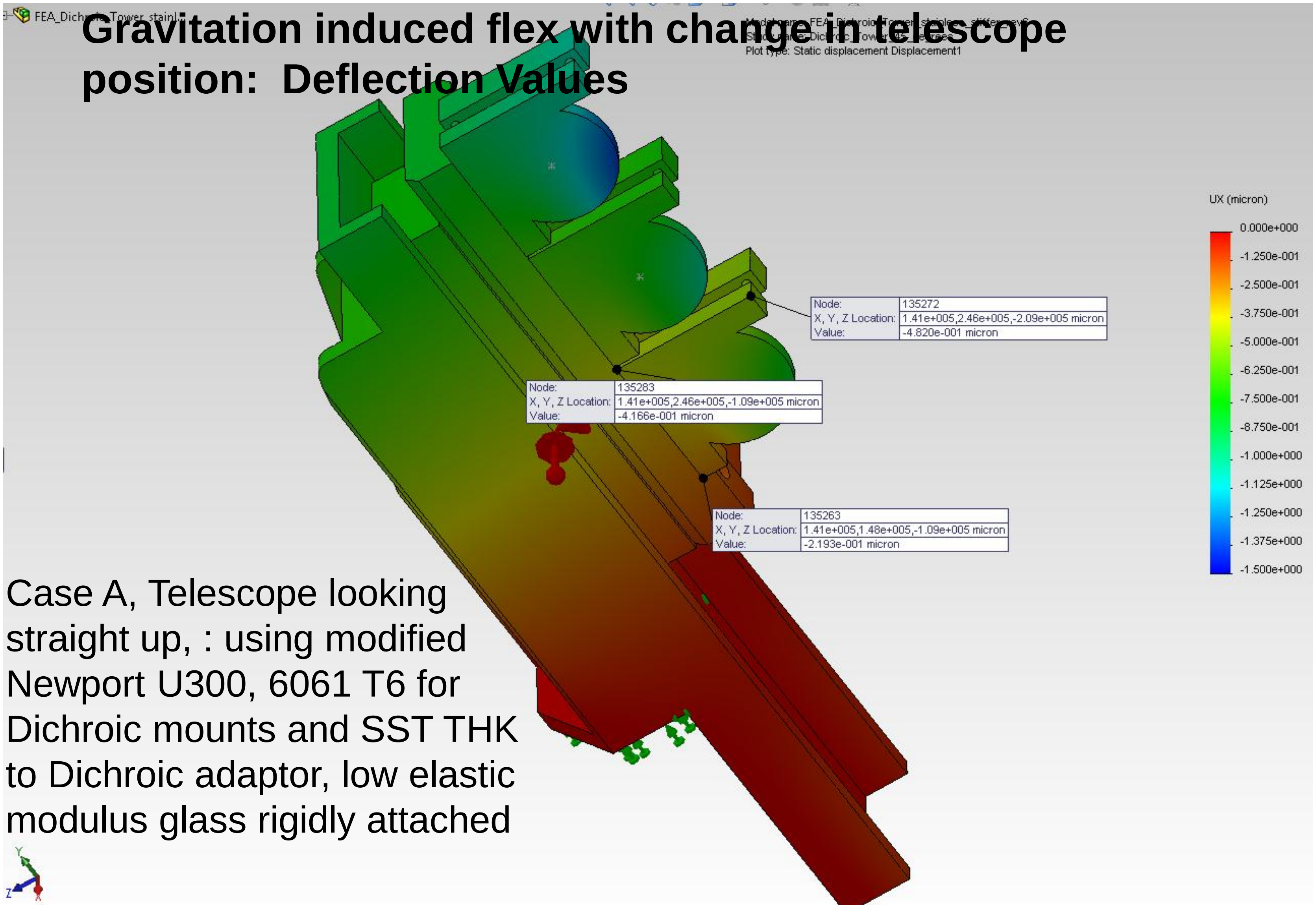
Gravitation induced flex with change in telescope position: Deflection Values



Case A, Telescope looking straight up, : using modified Newport U300, 6061 T6 for Dichroic mounts and SST THK to Dichroic adaptor, low elastic modulus glass rigidly attached

75mm Dichroic Tower Deformation Analysis

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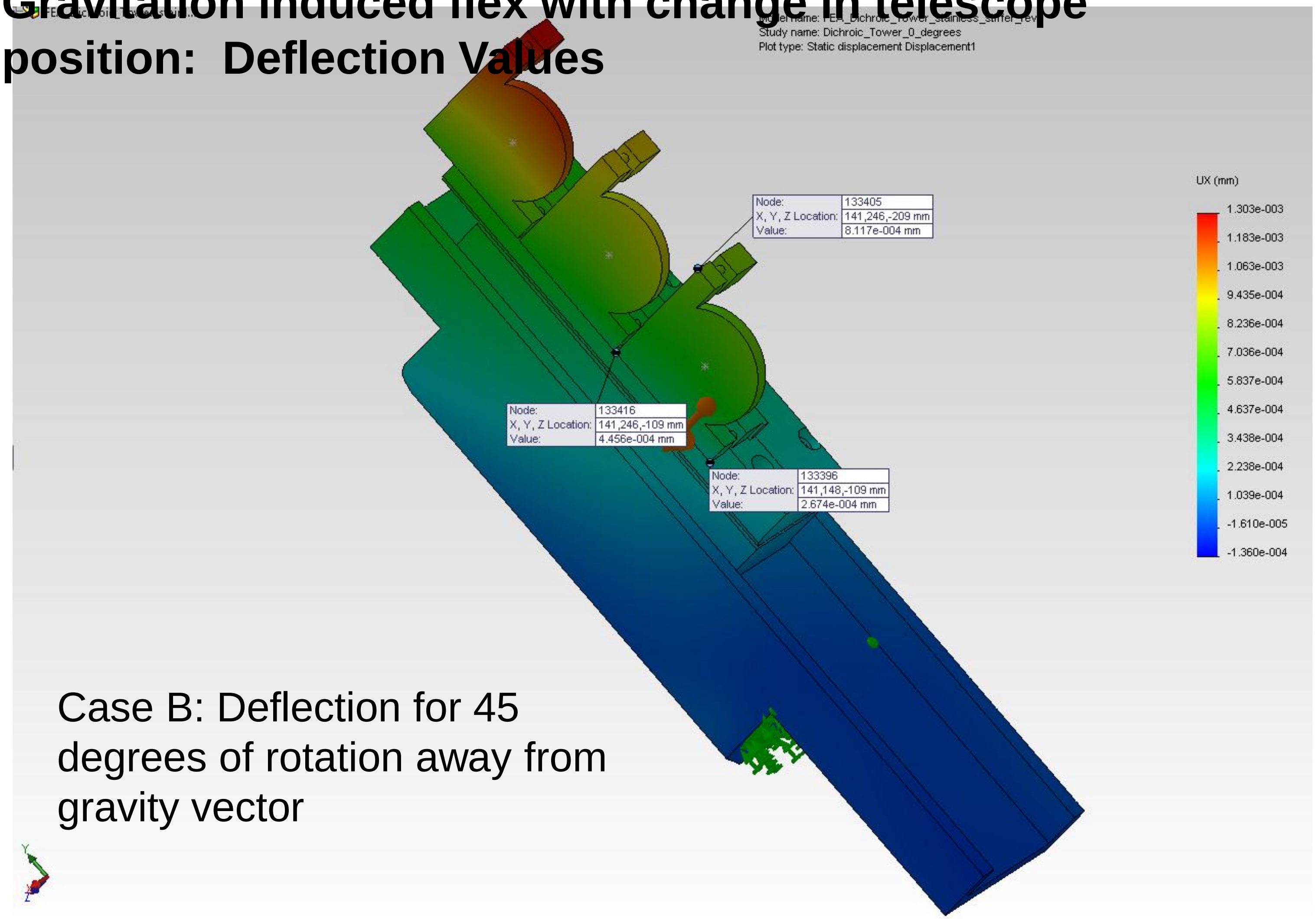
Gravitation induced flex with change in telescope position: Deflection Values



Case B: Deflection for 45 degrees of rotation away from gravity vector

TTS Dichroic Stage

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Results Table: Angular deformation of bottom dichroic beam splitter for 3 hour (45 degree) tracking with vertical stage fully extended: does not account for stage carriage deflection or table deformation

Material	Net Change in Angular Deflection arcseconds
Fifth Iteration Design: 304 Stainless Steel, Thicker Lens Mounts, improved base	0.9
Fourth Iteration Design: 304 Stainless Steel, Detailed 6061 Lens Mounts	1.7
Third Iteration Design: 303 Stainless Steel stiffer THK mount, Block Lens mount	1.5
Second Iteration Design:303 Stainless Steel, Block Lens mount	3.1
First Iteration Design: 6061 T6 Aluminum, Block Lens mount	5.3

TTS Dichroic Stage

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Stage Carriage Deflection: THK data

THK Actuator Rigidity Chart Information

The Mark of Linear Motion

Load Notation

PR: Radial load

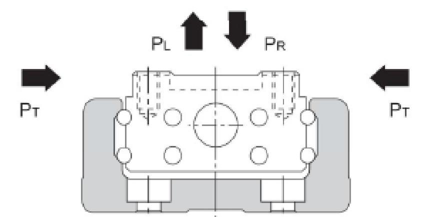
PL: Reverse-radial load

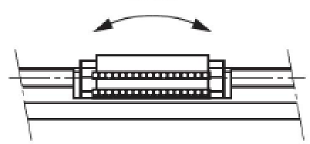
PT: Lateral load (Horizontal)

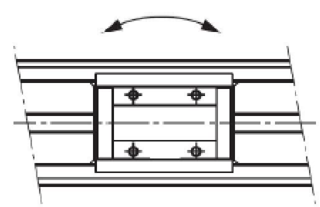
MA Moment in the pitching direction

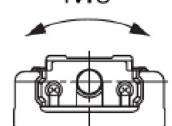
MB Moment in the yawing direction

MC Moment in the rolling direction









Clearance Notation

0: Normal Clearance

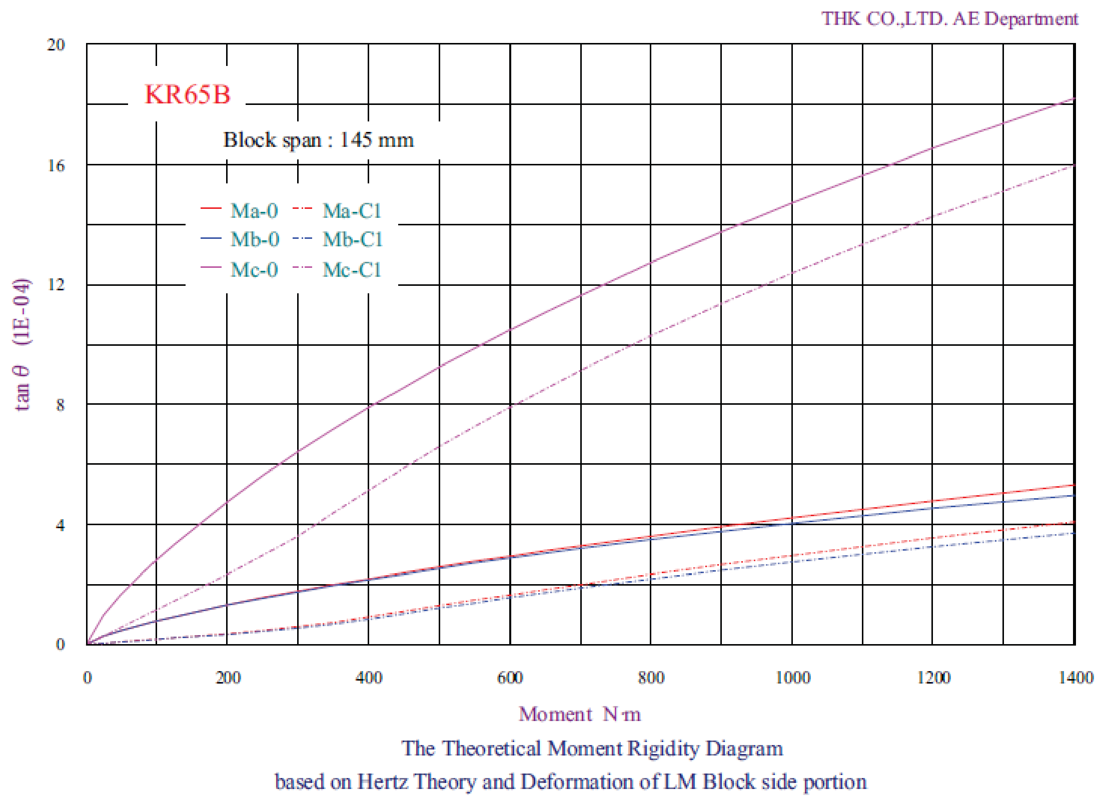
C1: Light Preload

We are interested in M_c and M_B for tip/tilt error

Note:
All data is theoretical based on hertz contact theory.
If applied load exceeds data on chart, please contact THK.

TTS Dichroic Stage

Stage Carriage Deflection: THK data



TTS Dichroic Stage

Carriage Deflection:

- **1.5 N-m load (small)**
- **Preloaded Linear guide (THK precision series)**
- **Assumed linear moment-rigidity diagram**
- **Assume carriage moment about other two axes does not affect deflection about this axis**
- **Result checked by Calvin Louie (Clouie@THK.com) of THK, results agree**

Material	Net Change in Angular Deflection
KR65, Third Iteration	.37 arcseconds
KR45: First Design Iteration	1.86 arcseconds

Net Angular Deflection due to carriage and structural deflection: 1.5+.37=1.87 arcseconds

TTS Dichroic Stage Motion Control

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Motion Control Data:

- Y axis
  - 3 discrete stopping positions
  - Mechanism: Linear slide THK Ball screw KR6505B+580LP1-000H (5mm lead)
  - direct drive motor: MagMotor S28-H-200FBE NEMA34
  - coupling: (no backlash) Miki Pulley SFC020DA2-8B-8B
  - Travel: Approx 205mm
  - Repeatability: 0.5 millimeter required
  - Controller: Galil
  - End of travel limits and home: Hall effect (Cherry VN101501) per Barry
  - Secondary limits: electromechanical switch (Honeywell Microswitch DT-2RV22-A7)
  - Primary (motor rotation) encoder: TBD
  - Secondary (load) encoder: Renishaw magnetic incremental encoder with index (5 micron resolution, common to Calibration stage)
  - Primary to Secondary ratio: (2000*4):1000 = 8:1

- X and Z axes
  - Shim and nudge, then fix permanently

WFS Steering Mirrors & OAP’s

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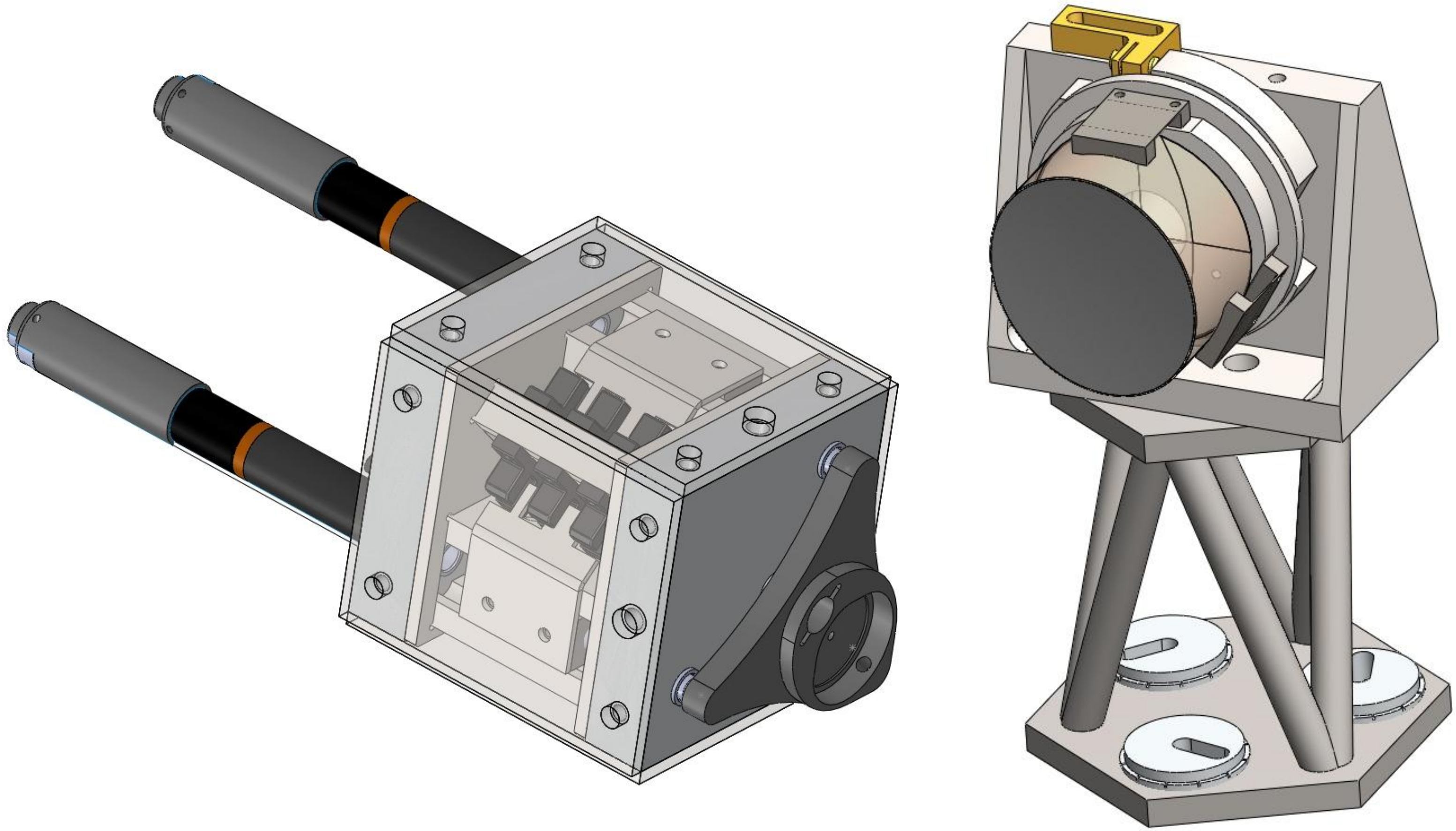
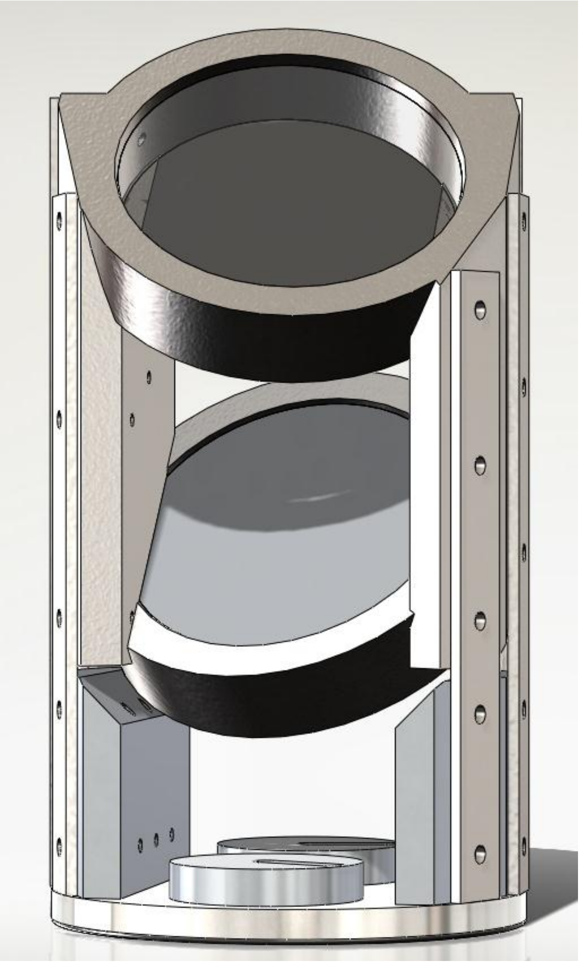
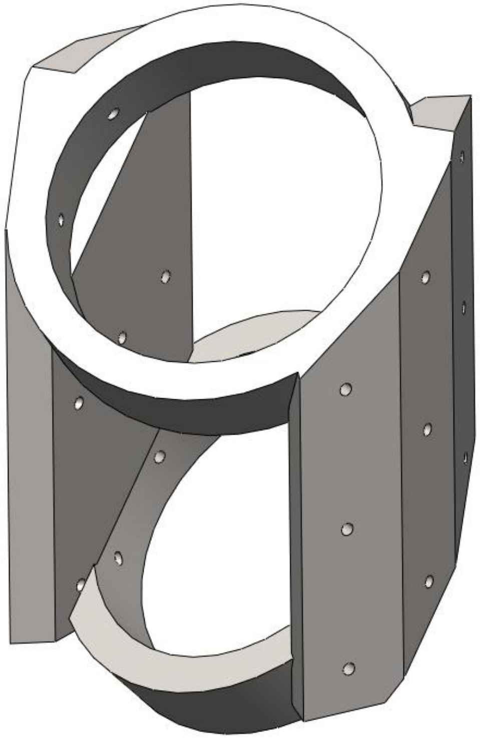
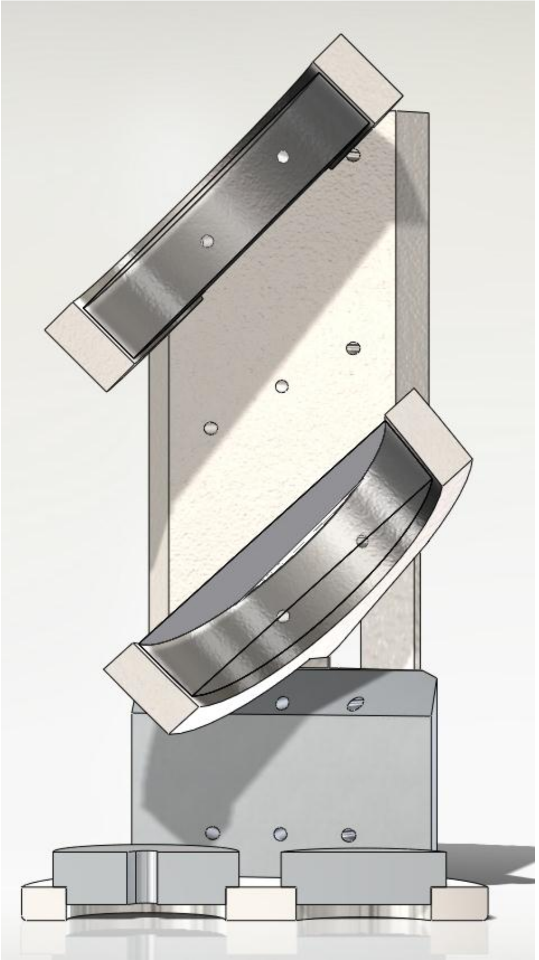


Tip/Tilt Mirror Periscope







Periscope 3D Printing Supplier

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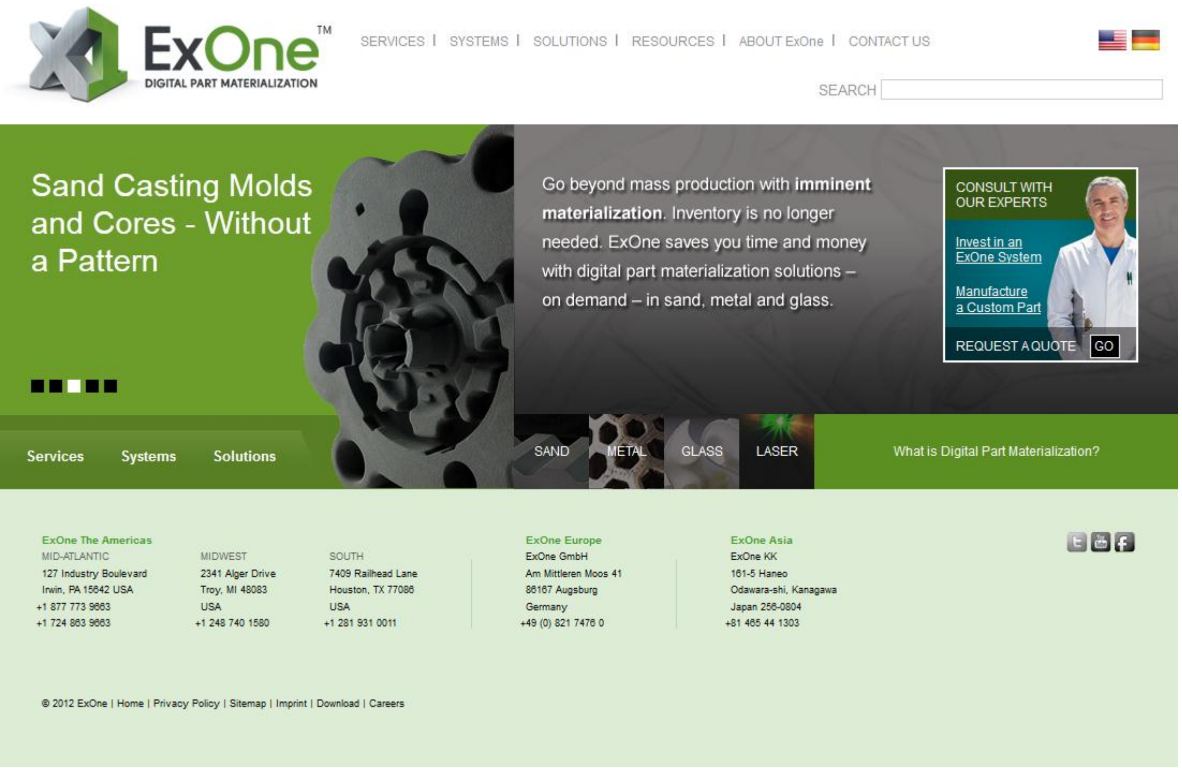
A material additive metal 3D printing process, first step produces a porous SST part which is later infused with bronze



MATERIALS

	S3	S4 (Non-Annealed)	S4 (Annealed)
Alloy Family	316 SS+Bronze	420 SS+Bronze	420 SS+Bronze
UTS	59 KSI (406 MPa)	99 KSI (682 MPa)	72 KSI (496 MPa)
Yield	34 KSI (234 MPa)	66 KSI (455 MPa)	67 KSI (462 MPa)
Modulus	21.5 MPSI (148 GPa)	21.4 MPSI (147 GPa)	21.4 MPSI (147 GPa)
Elongation	8.00%	2.30%	7.0%
Hardness	60 HRb	20-25 HRc	30 HRc
Machinability	N/A	N/A	Only in Annealed Process
Density	90-95%	90-95%	90-95%
Welding	Use silicone bronze & TIG weld	Use silicone bronze rod & TIG weld	Use silicone bronze rod & TIG weld
Polishing	Yes	Yes	Yes
Wire EDM	Yes	Yes	Yes
Ram EDM	Yes	Yes	Yes

ProMetal Material Sample

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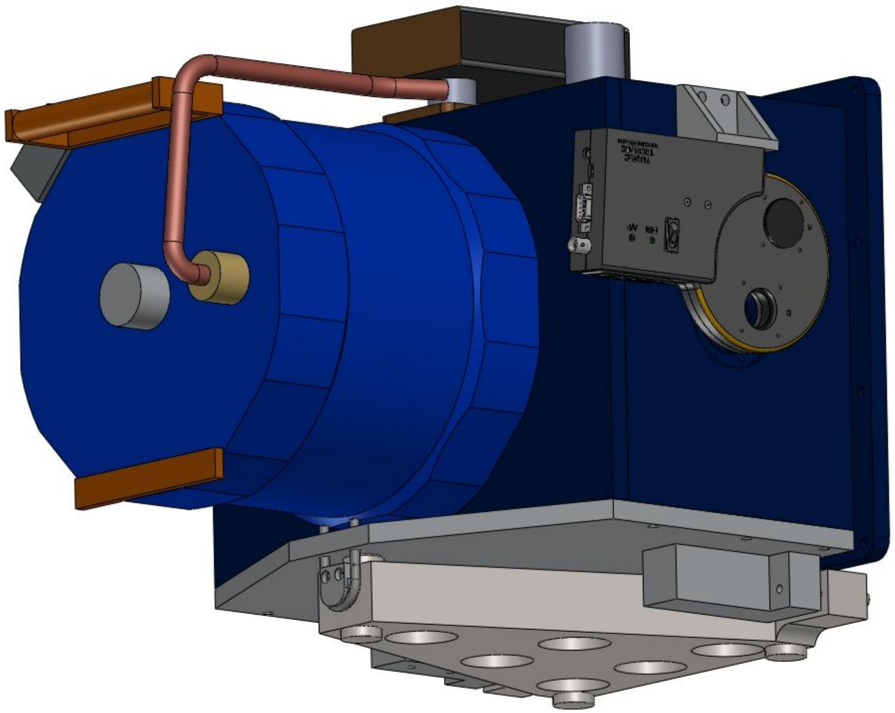
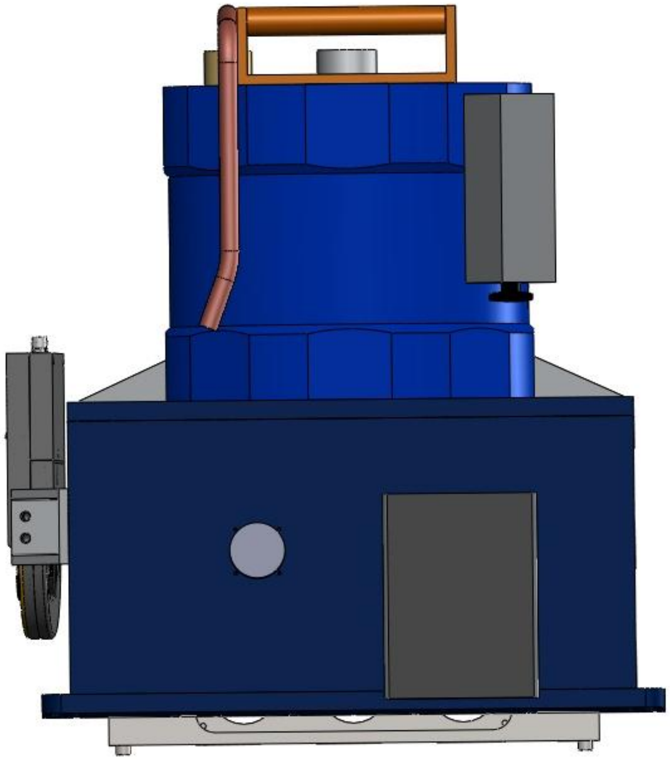
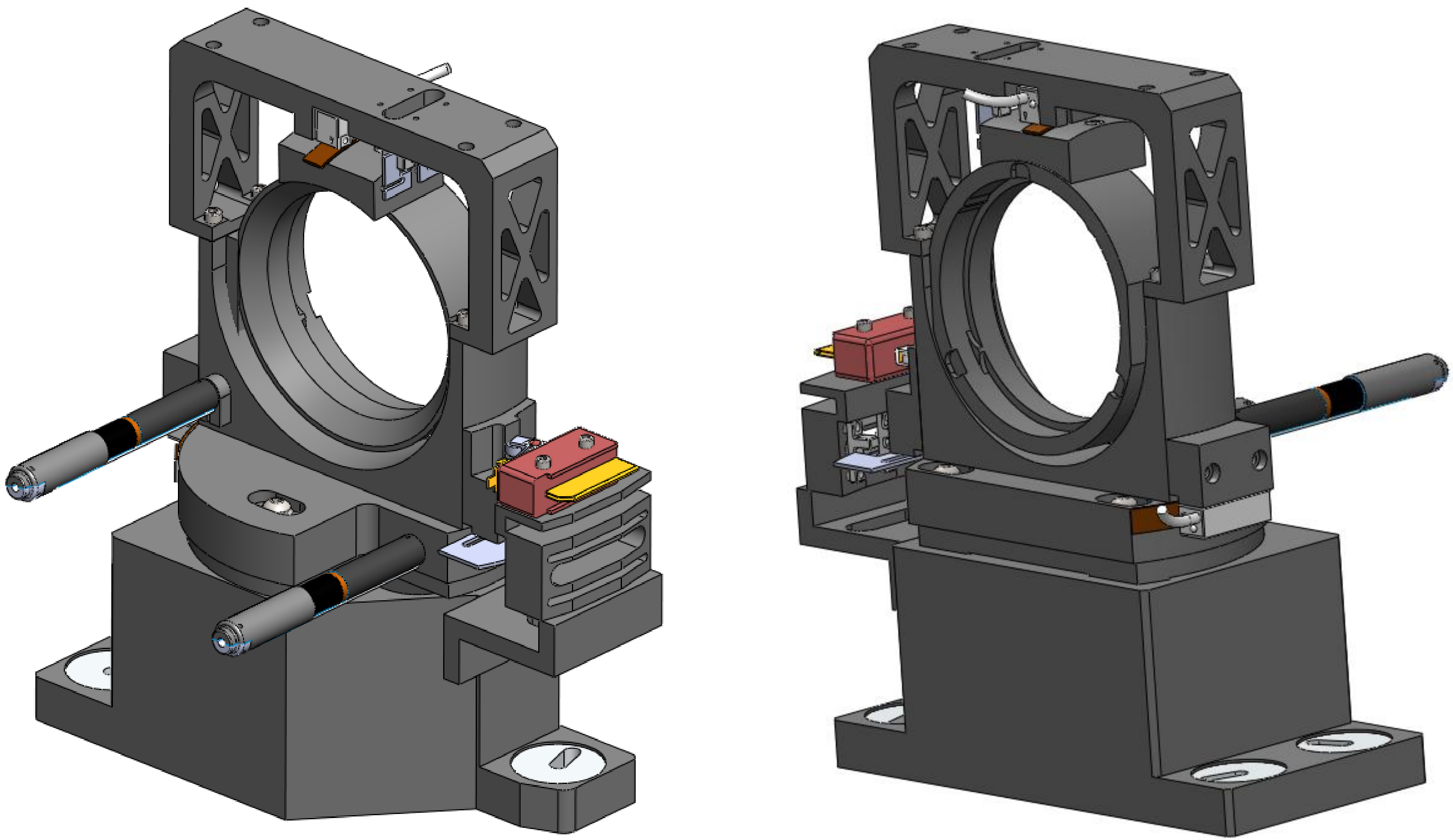
IRCAL Mount

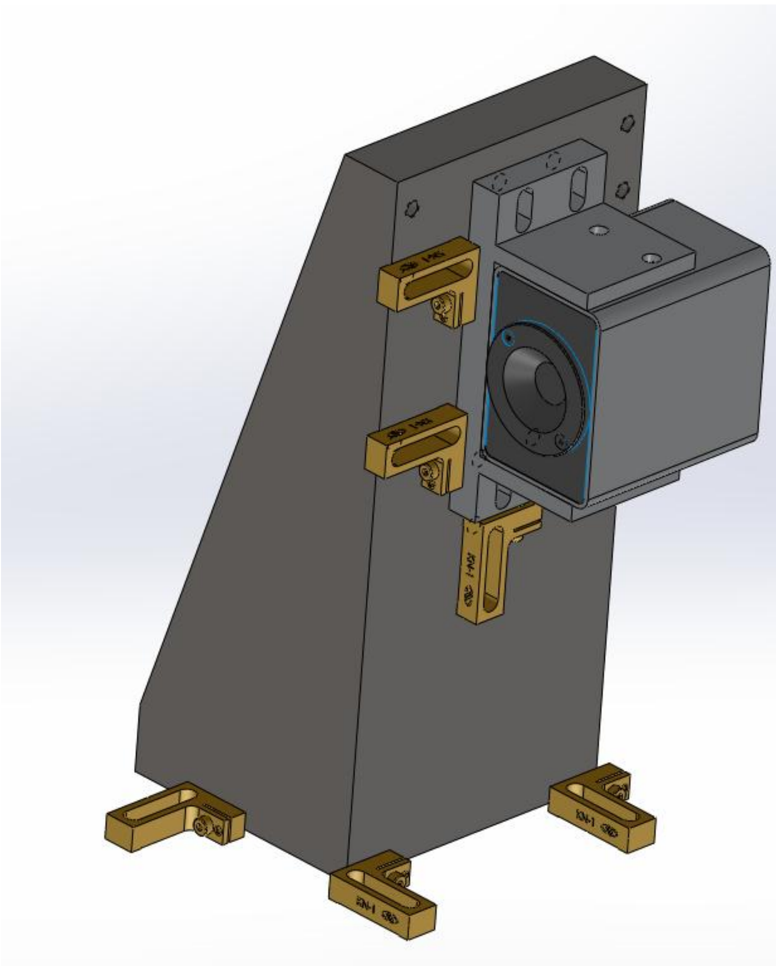


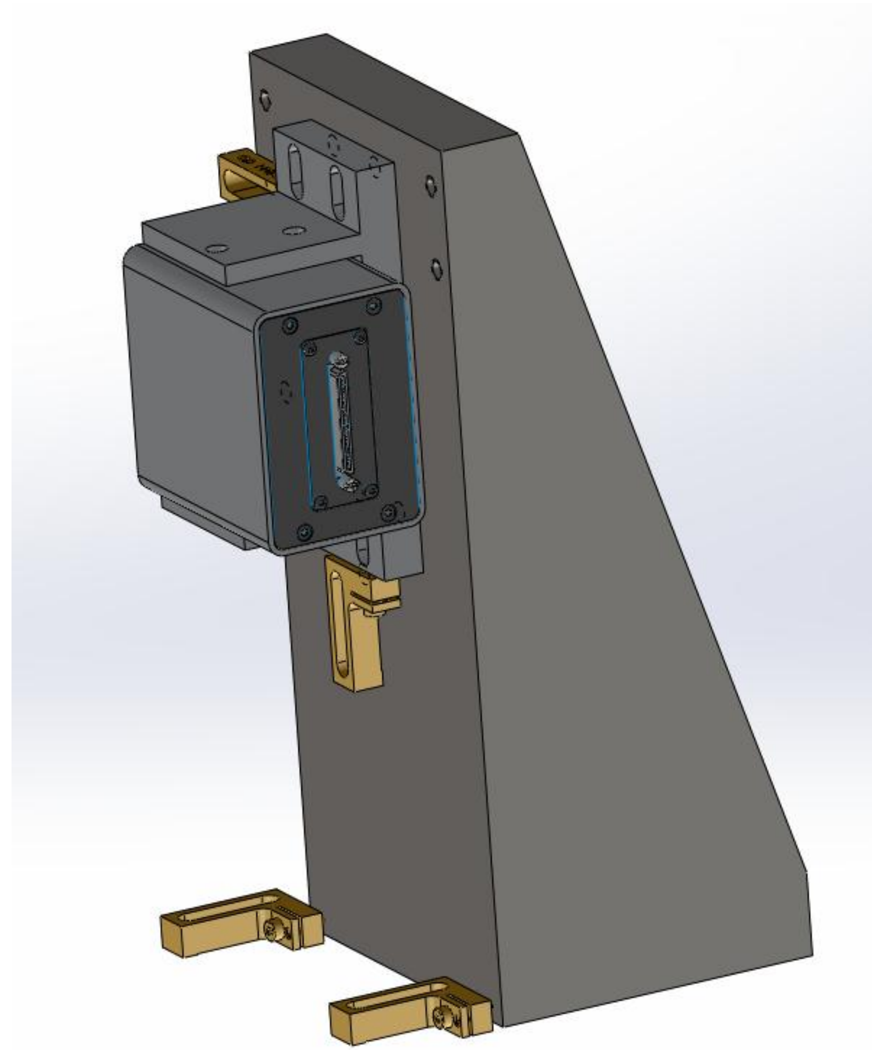


FM1



Woofer





Calibration Stage

Design Review Agenda

- Overview/Requirements
- Motion control
  - *Motion requirements*
  - *Selection of Stages*
  - *Sizing Motors*
- Deflection analyses
  - FEA
  - Moment Rigidity
- Summary

Calibration Stage

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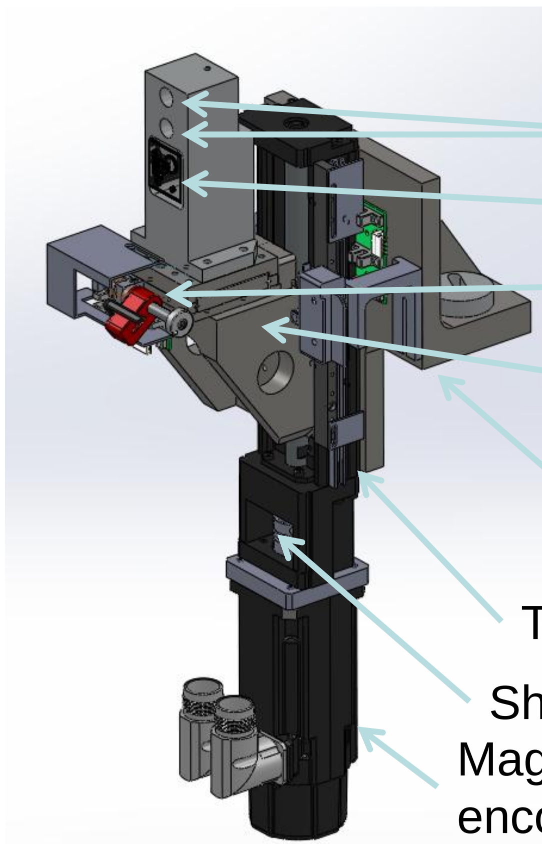
Overview/Requirements:

- Positioning stage for Flea camera, white light calibration fiber, laser calibration fiber, reflecting sphere for OAP alignment
- All items must be able to move into and out of the beam path
- Required x-y positioning accuracy of Flea: 5 microns
- Required x-y positioning accuracy of Optical Fibers: 9 microns



Optical fiber receptacles

Flea camera

X axis actuator

X stage mount

THK to optical table bracket

THK SKR33 linear Actuator (y axis)

Shimpo coupling

Magmotor brushed servo (integrated encoder)

Calibration Stage Motion Control

Requirements Continued:

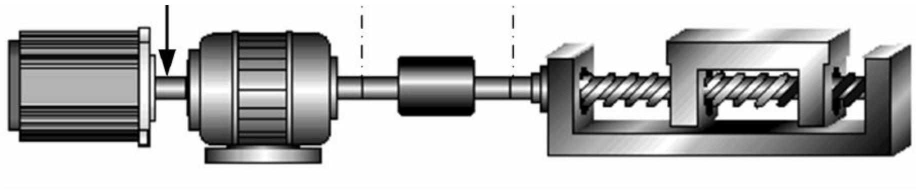
- •Must move able to move all 3 items in and out of beam at focus, all items must be clear of beam during normal operation
- •Must clear surrounding assemblies
- •Must move desired item into place within 60 seconds
- •Must be less than 5 micron deflection (x and y) for worst case change in gravity vector of 45 degrees
- •Use Trapezoidal velocity profile (1/3 accel., 1/3 constant vel.,1/3 decel)
- •Frequency of Use: Flea camera might be used several times per night (most often used component)

Axis	Range/ Precision/ Time
y	100mm/2 micron 4 seconds
x	<5mm/2 microns 60 seconds
z	<5mm/20 microns 60 seconds

Calibration Stage Motion Control

Servo Sizing:

-Assess: Load Inertia , peak speed, peak torque without friction, peak torque with friction …pick motor/gearbox combo



Maximum Motor Torque= $T_g = J_{Ltot}\,\alpha + T_L$

Where:

Equivalent moment of inertia= $J_{Ltot} = J_{reducer} + \frac{1}{\varepsilon N^2}\left[J_{leadscrew} + \frac{M_1}{\sigma}\left(\frac{P}{2\pi}\right)^2\right]$=7.06x10

α –angular acceleration (rad/sec^2)=29.6 rad/sec^2

$J_{Ltot}\,\alpha$ =0.00021 Nm

$J_{reducer} = 0$

N - reducer ratio=1.0 (no reduction used)

ε –efficiency of the reducer=1.0 (none used)

M_1 – mass of components riding on ball screw block (including block)(Kg)=3kg

σ –efficiency of the lead screw=0.9

P -lead of ballscrew=0.006m

$J_{leadscrew} = M_{leadscrew}\frac{r^2}{2} = 4.2\text{x}10^{-6}\,\text{Kgm}^2$

$M_{leadscrew}$- mass of leadscrew (Kg)=1.06 Kg

r - radius of leadscrew (m) =0.0065m

$T_L = \frac{1}{N}T_F + \frac{1}{N\varepsilon}\frac{F}{\sigma}\frac{P}{2\pi}$=0.15Nm+0.0317Nm=0.181 Nm

T_F =Torque friction of lead screw = .15 Nm (due to preload to minimize backlash)

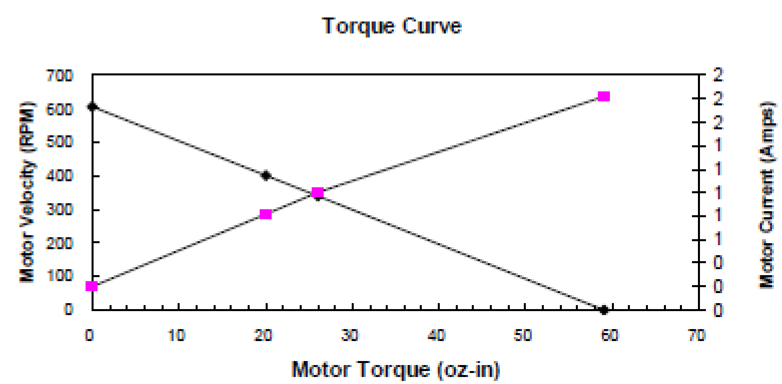
F -Force on stage block along axis of travel = 30 N

Effective force of friction torque (for Yaskawa software) =.15Nm*.9*2π/.006m=157N

T_g **Maximum Start Torque =0.181 Nm =25.6 oz-in**

Maximum Speed = 376 RPM

J_{Ltot} **=7.06x10^{-6}Kgm^2 7.06x10^{-2}Kgcm^2 .001oz-in-sec2**



Conclusion: -Use Magmotor S23M100FBE servo motor J_{Mot} **=.006oz-insec^2**

-Inertia ratio roughly equal to 6 -OK

Calibration Stage Motion Control

Additional Motion Control Data:

- Y axis
  - 5 discrete stopping positions
  - Mechanism: Linear slide THK Ball screw THK Ball screw SKR3306A+200LP1-000H(6mm lead), direct drive motor, Miki Pulley coupling
  - Travel: Approx 100mm
  - Repeatability: 2 micron or better
  - Controller: Galil
  - End of travel limits and home: Hall effect (Cherry VN101501) per Barry
  - Secondary limits: electromechanical switch (Honeywell Microswitch DT-2RV22-A7)
  - Primary (motor rotation) encoder: 8000 ppr (maker TBD)
  - Secondary (load) encoder: Renishaw magnetic incremental encoder with index (1 micron resolution)
  - Primary to Secondary ratio: (8000*4):6000 = 5.3:1

- X and Z axes
  - 4 discrete stopping positions
  - Mechanism: Linear slide New Focus 9067 stage with 8302 picomotors, 1 inch travel
  - Max picomotor force: 22 N
  - Required Travel: TBD, likely under 2 mm
  - Controller: Galil (discuss)
  - End of travel limits and home: no home flag or limit flags -discuss
  - Secondary limits: None (discuss)
  - Primary (motor rotation) encoder: None
  - Secondary (load) encoder: New Focus enclosed optical Linear Encoder(.08 micron resolution with index mark)

Calibration Stage FEA

Objective:

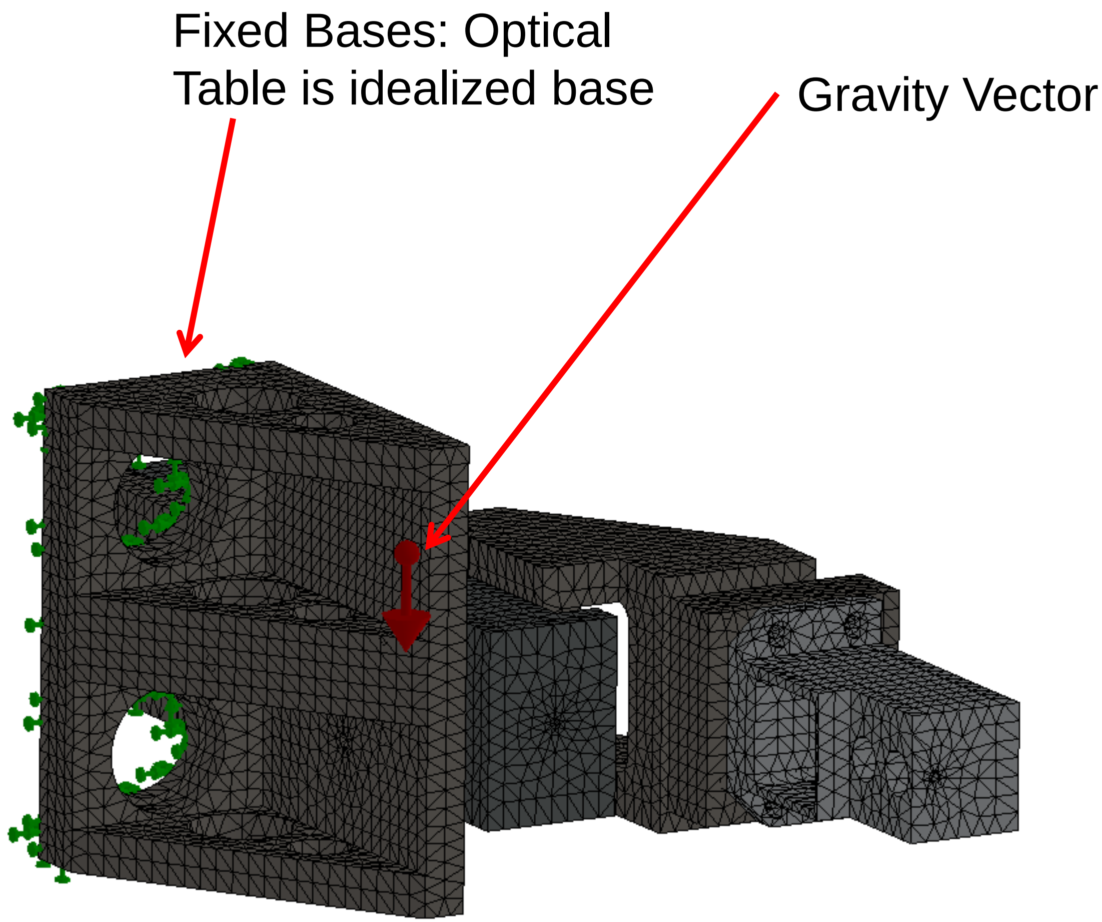
1. Assess maximum angular and linear deflection of Flea camera due to 90 degree change in gravity vector

Assumptions and Conditions:

1. THK bracket is rigidly fixed to optical table, no deformation of optical table surface
2. Beam height is approximately 7.5” above the Optical Bench mounting surface
3. THK bracket, THK to x axes bracket and New Focus 9067 x-z stage are made of 304 stainless steel
4. THK stage is a 1055 steel
5. Flea mount is 6061 T6 aluminum
6. Deflection of lead screw is neglected and can be compensated for with load encoding (1 micron resolution)
7. Angular displacement due to stage moment rigidity (for THK and New Focus) will be treated separately
8. All parts are rigidly bonded/connected

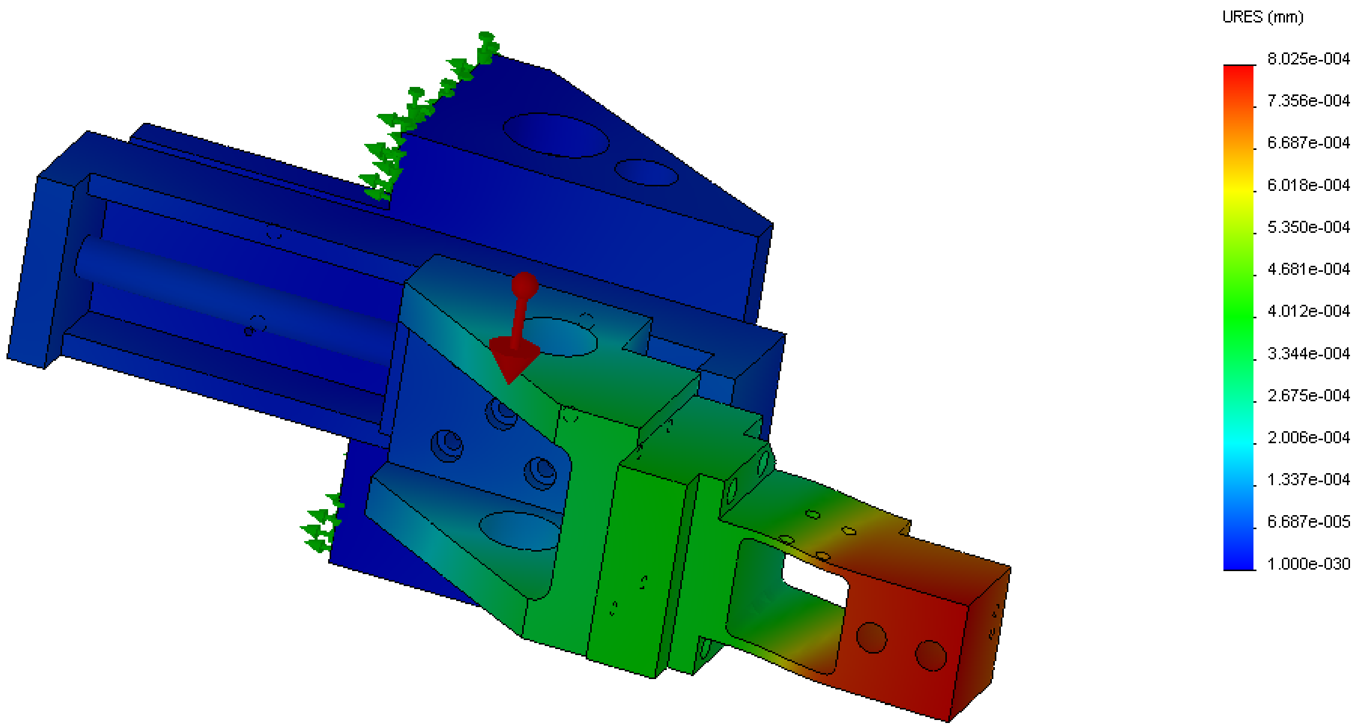
Calibration Stage FEA

Meshed FEA Model:



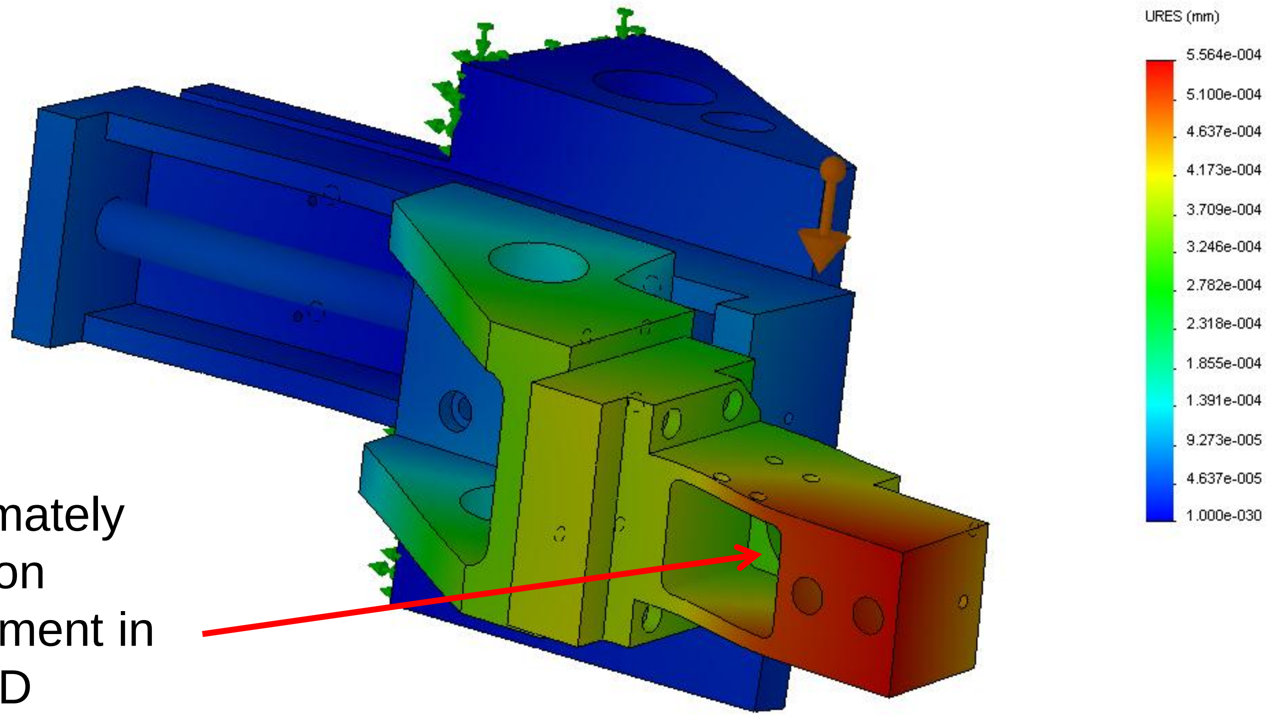
Calibration Stage FEA

Worst case gravitation induced flex (exaggerated by 40,000x): Iteration 1



Calibration Stage FEA

Worst case gravitation induced flex (exaggerated by 40,000x): Iteration 2

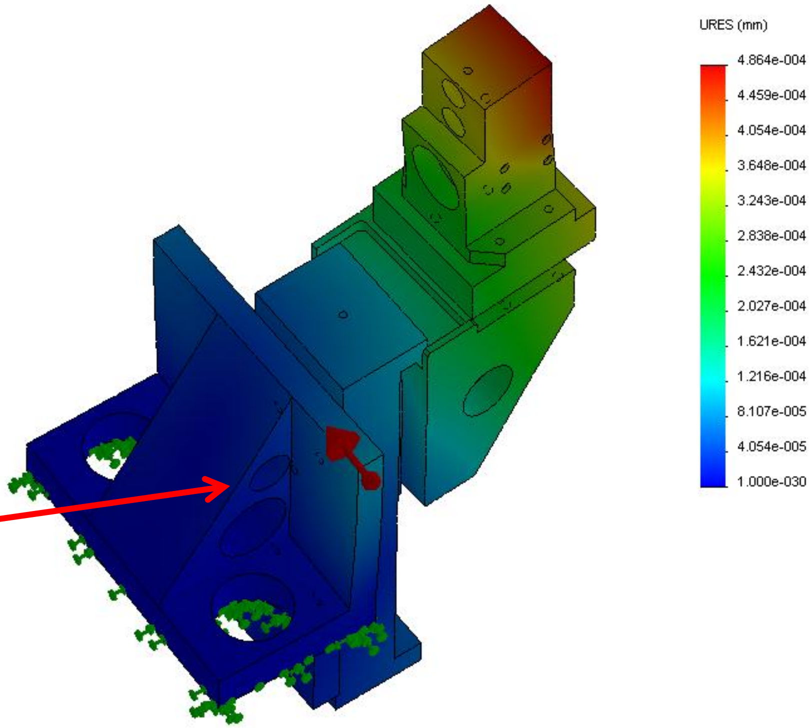


Approximately 0.3 micron displacement in Flea CCD

Calibration Stage FEA

Worst case gravitation induced flex (exaggerated by 40,000x): Iteration 3

Larger Central Web to improve machinability



Calibration Stage FEA

Results Table: Angular deformation of bottom dichroic beam splitter for 6 hour (90 degree) tracking with vertical stage fully extended: does not account for stage carriage deflection or table deformation

Conditions	Net displacement
Telescope pointed at zenith	<.5 microns
Telescope pointed at horizon	0.5 microns

Conclusion: **Stiffness of metal components looks adequate, however, stiffness of bearing interfaces still needs to be assessed**

Calibration Stage Moment Rigidity Analysis

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Stage Carriage Deflection: THK data

THK The Mark of Linear Motion

Actuator Rigidity Chart Information

Load Notation

P_R: Radial load

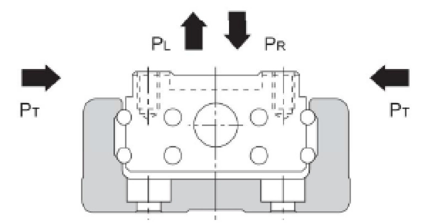
P_L: Reverse-radial load

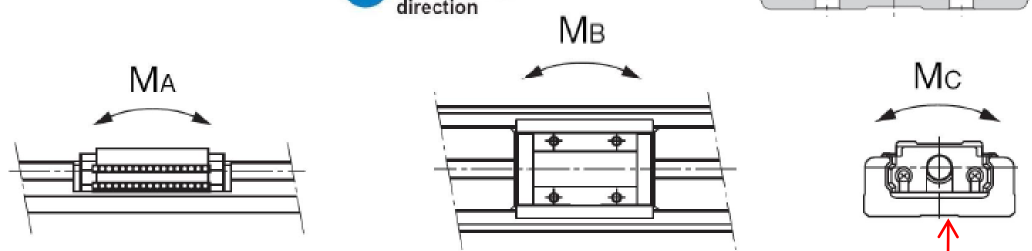
P_T: Lateral load (Horizontal)

M_A Moment in the pitching direction

M_B Moment in the yawing direction

M_C Moment in the rolling direction





Clearance Notation

0: Normal Clearance

C1: Light Preload

We are primarily interested in M_c and to lesser extent P_R P_r P_L,M_b M_A

Note:
All data is theoretical based on hertz contact theory.
If applied load exceeds data on chart, please contact THK.

Calibration Stage Moment Rigidity Analysis

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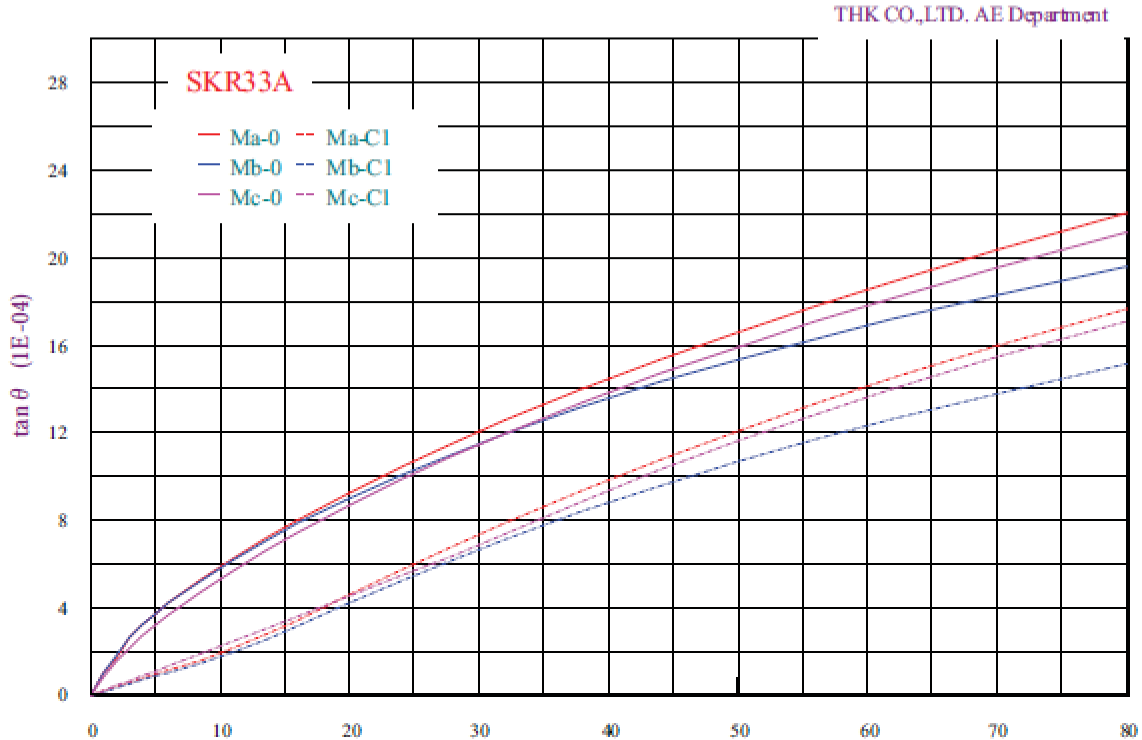
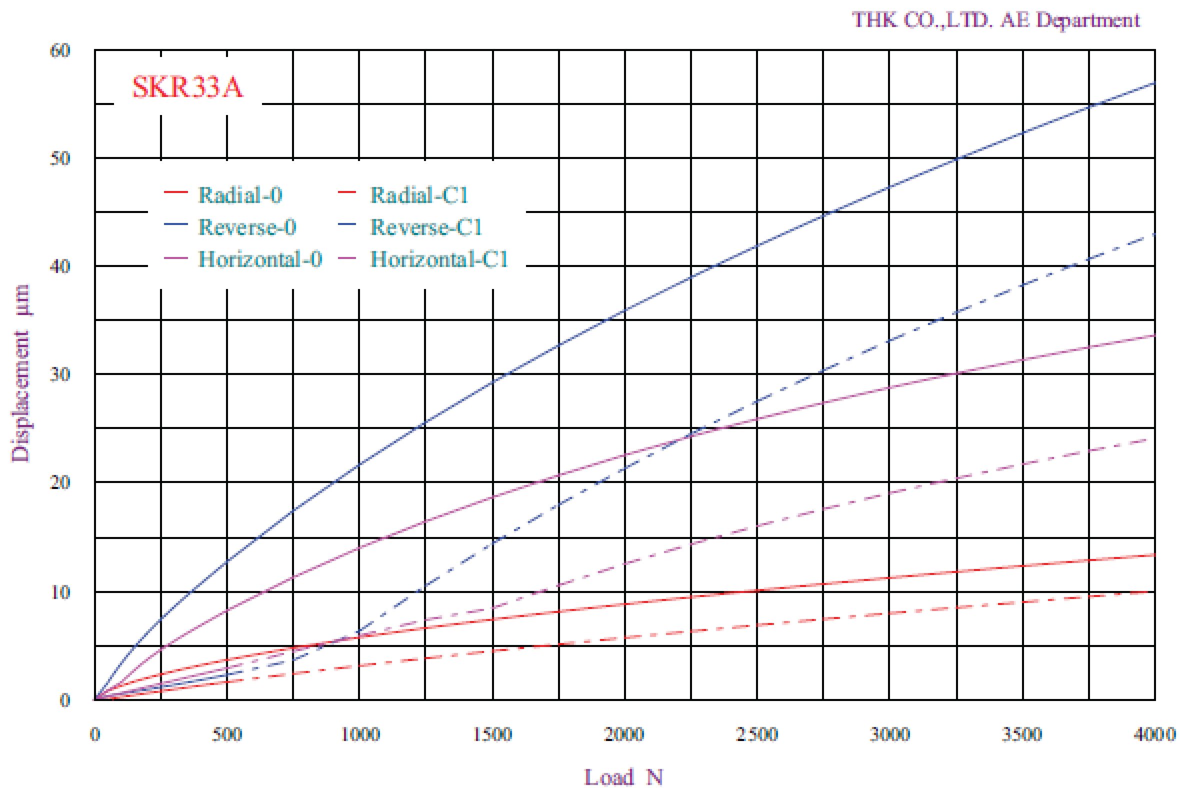
Stage Carriage Deflection: Moment Rigidity THK data



The Theoretical Moment Rigidity Diagram
based on Hertz Theory and Deformation of LM Block side portion

Calibration Stage Moment Rigidity Analysis

Stage Carriage Deflection: Normal load THK data



The Theoretical Rigidity Diagram
based on Hertz Theory and Deformation of LM Block side portion

Resulting linear deflection is approx. 0.4 microns for this mode

Calibration Stage Moment Rigidity Analysis

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Carriage Deflection:

- **4 N-m for THK**
- **0.76 N-m load (very small) for 9067**
- **Preloaded Linear guide (THK precision series)**
- **Assumed linear moment-rigidity diagram**
- ****Assumed 20.8 arcsec/N-m for 9067 (verify)**

Material	Net Change in Angular Deflection	Contribution to Displacement at Flea Camera Image Plane
KR33 Precision Preload	16 arcseconds	4.5 microns
New Focus 9067	10.4 arcseconds**	3.2 microns

Net angular deflection will far exceed 2 arcsec for this assembly, net displacement will exceed 5 micron limit for worst case!

- **7.7 microns due to carriage moment**
- **0.3 microns due to flexure in brackets**

Summary and Discussion Points

Conclusion Remarks:

•**Most of the net deflection will be due to angular deflection of linear bearings**

•**Net deflection due to linear bearings should be approx. 5 microns**

•**Stiffer "off the shelf" x linear stage will not fit in current prescription**

•**Need to position x and z of fibers and flea within 1.2 mm to use picomotor (1.2mm/min) and achieve 60 second positioning**

•**Some backlash (approx. 3 microns) will exist in THK stage, should try to approach end positions from one direction**

Wavefront Sensor

8 and 16 across Hartmann Sensor

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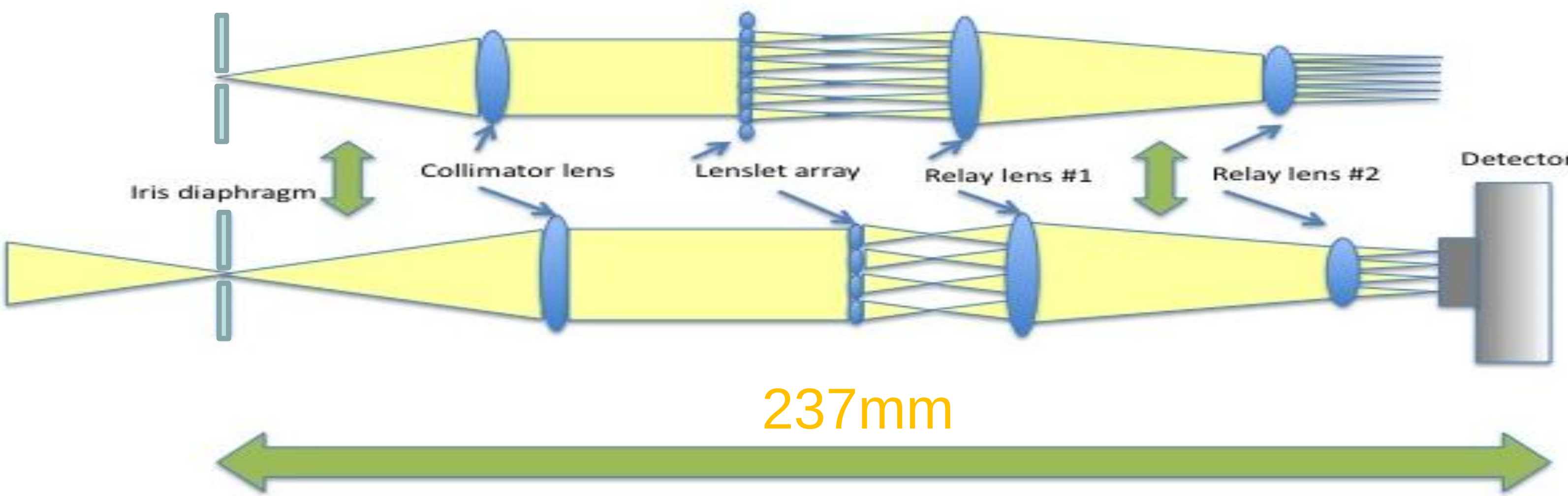

- The wavefront sensor package consists of an adjustable iris aperture (field stop), a collimating lens, a lenslet array, two relay lenses and the CCID66 detector.
- There are currently two configurations for the wavefront sensor – one with 8 subapertures across the pupil and another with 16 subapertures.

Wavefront Sensor
Mechanical Design

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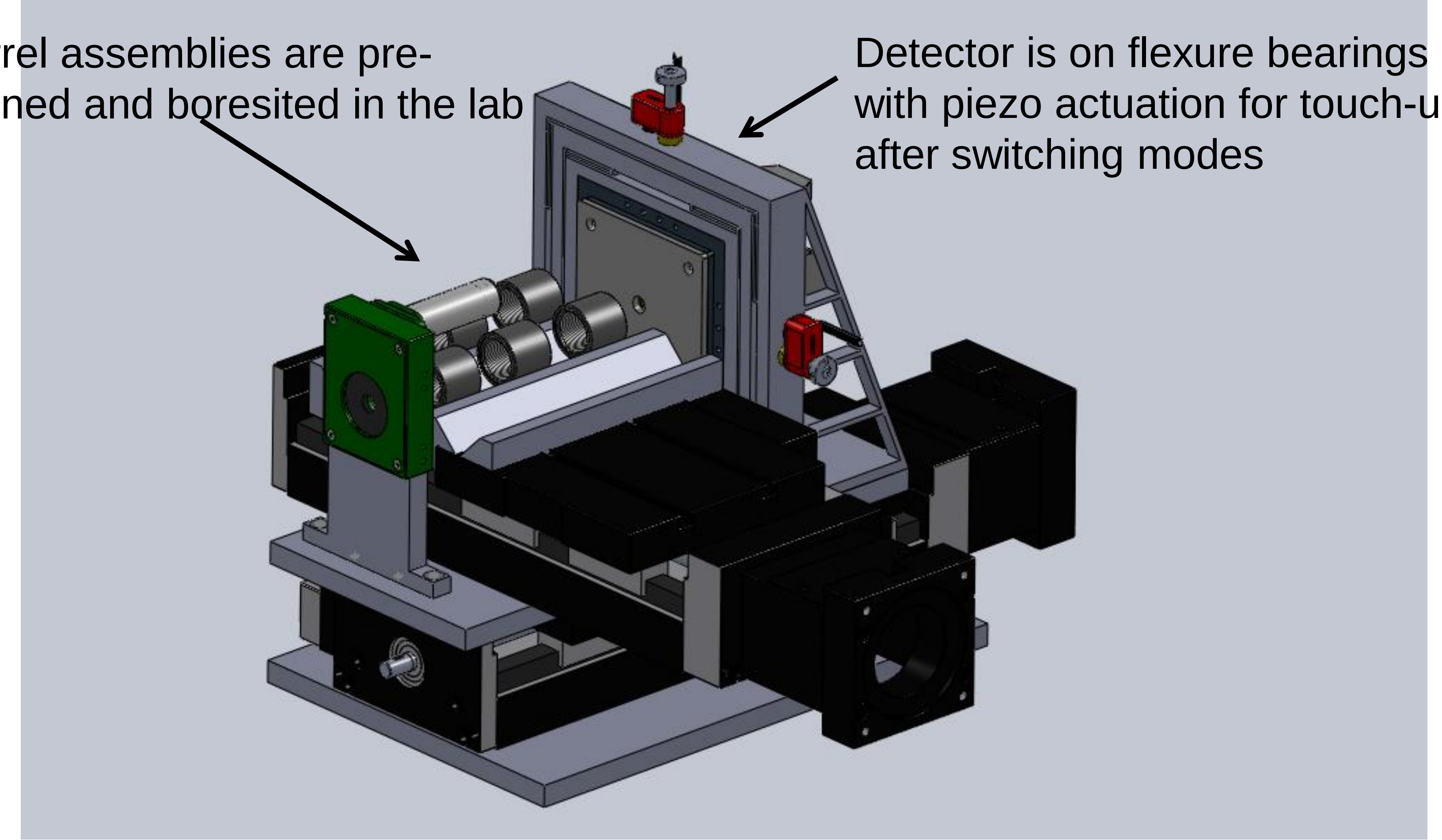
Barrel assemblies are pre-aligned and boresited in the lab

Detector is on flexure bearings with piezo actuation for touch-up after switching modes



Wavefront Sensor Optical Alignment Requirements

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Wavefront sensor parameters:

The CCID66 is a 160x160 pixel device with 21 micron pixels.
Each subaperture will contain 4x4 pixels, with a 1 pixel guard band between subapertures.

Configuration	Lenslet pitch (μ)	Relay magnification	Subaperture size (μ)	Plate scale arcsec/pixel
8-subaperture	300	0.35	105	1.3
16-subaperture	203	0.517	105	1.56

Wavefront sensor tolerances:

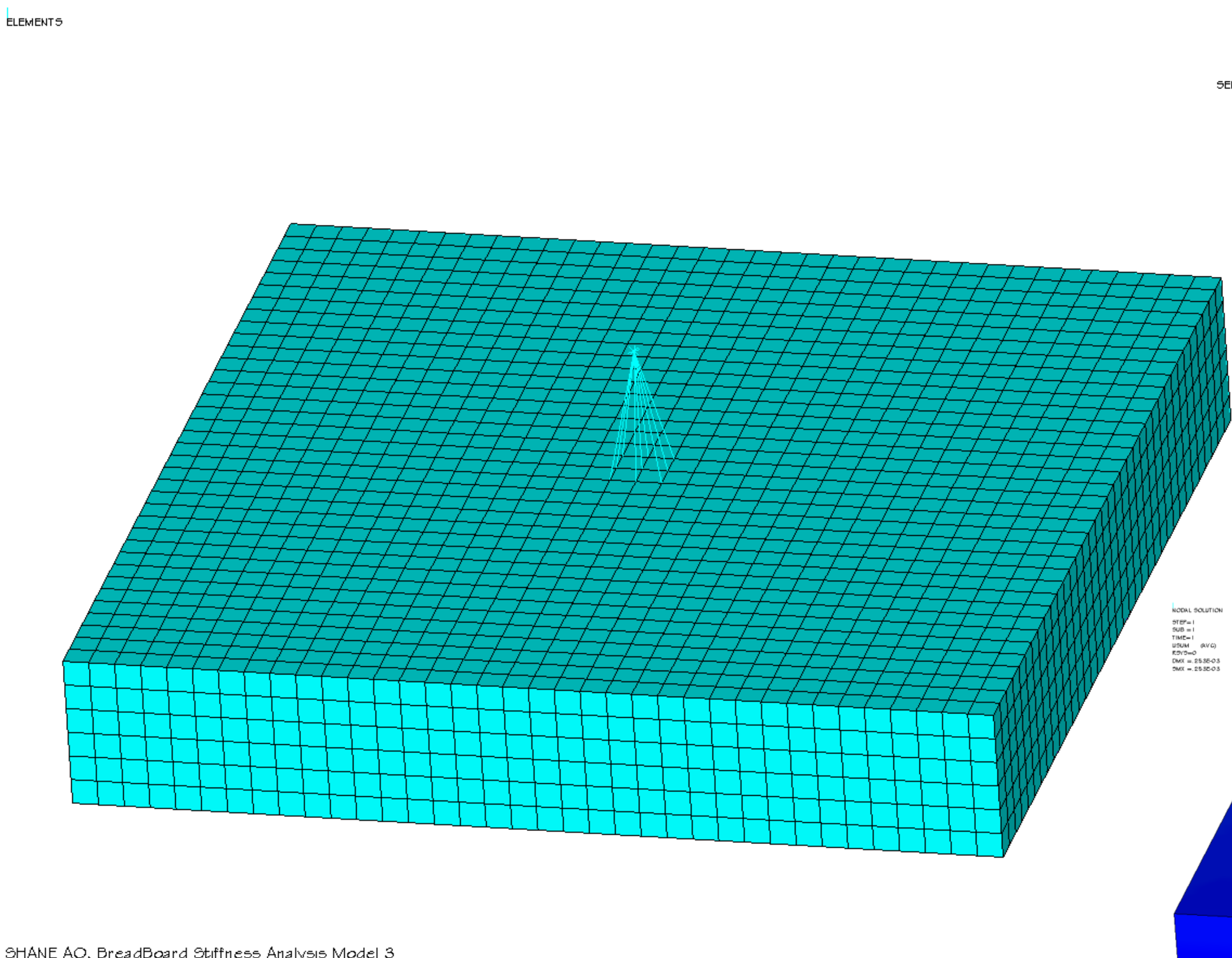
	x-y	Tip/tilt	z	rotation	Focal length
Iris	0.100 mm	N/A	0.350 mm	N/A	N/A
Collimator	10 μm	10 arcsec	±0.100 mm	N/A	2%
Lenslet array	2 μm	10 arcsec	±0.100 mm	0.1°	2%
Relay 1	10 μm	10 arcsec	±0.100 mm	N/A	2%
Relay 2	2.5 μm	10 arcsec	±0.100 mm	N/A	0.2%
Detectpr	2 μm	5 degrees	±0.100 mm	N/A	N/A

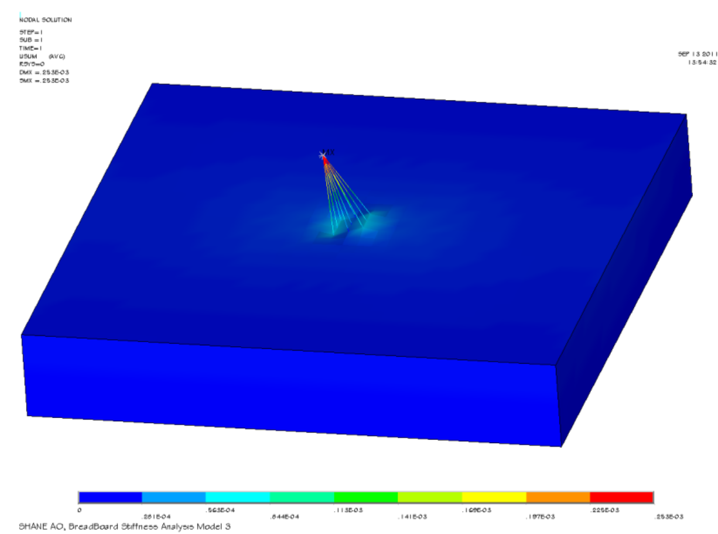
Table Flexure Analysis

Modeling Assumptions

- 20 lbs total system mass - assumed for WFS Dichroic Stage
- CG 5 inch above bench surface – based on stage CAD model
- Lateral gravity (parallel to bench)
- Rigid link connections to bench surface to simulate a rigid base of 3”x3”
- 36 inch square table
- All four edges restrained in (x/y/z) translation
- Results represent 100 in-lbs moment

Table Flexure FEA Model



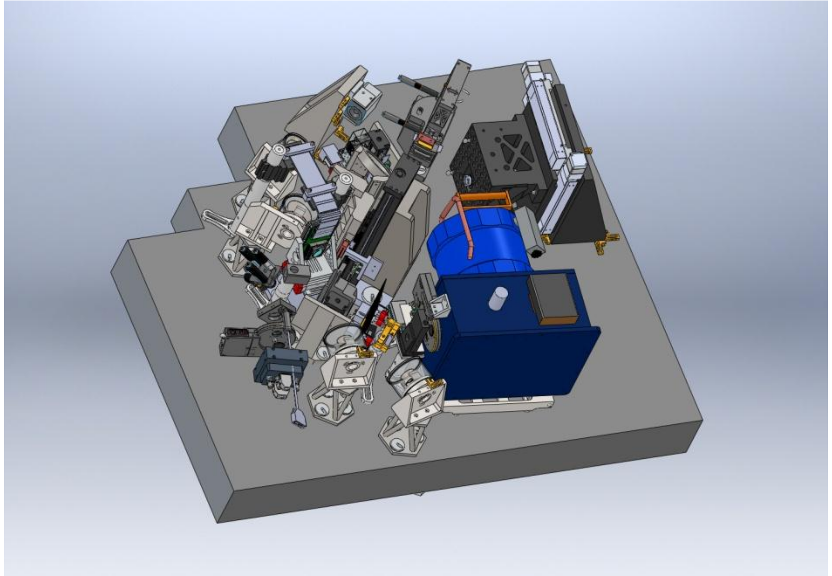


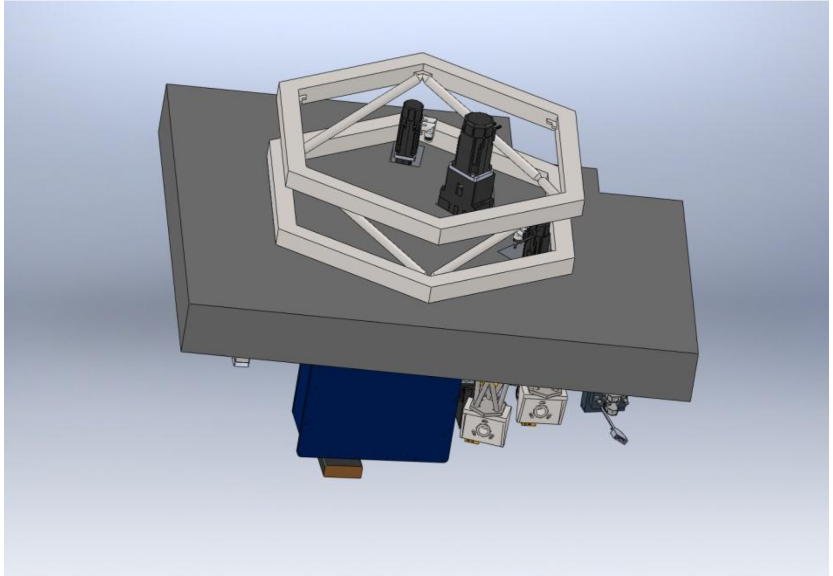
Bench Flexure for Lateral Gravity Load

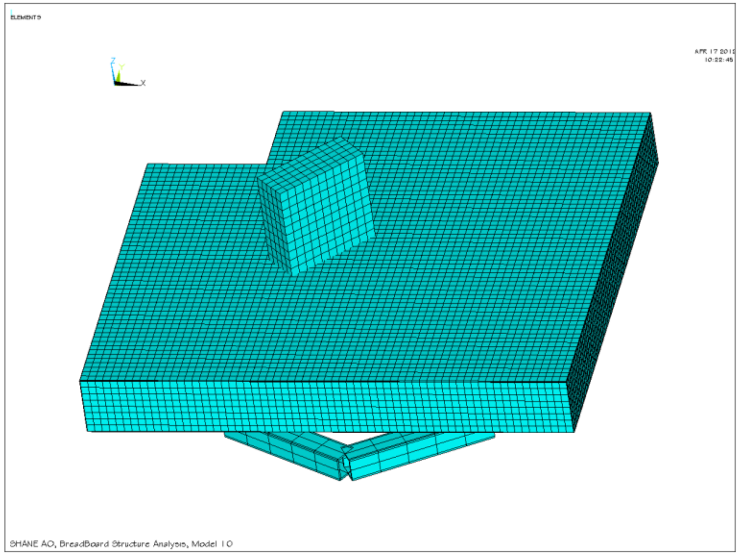
100 IN-LBS (20 lbs @ 5”) Component moment
3x3” base attachment on Bread Board
Simply supported BC on bottom perimeter of table

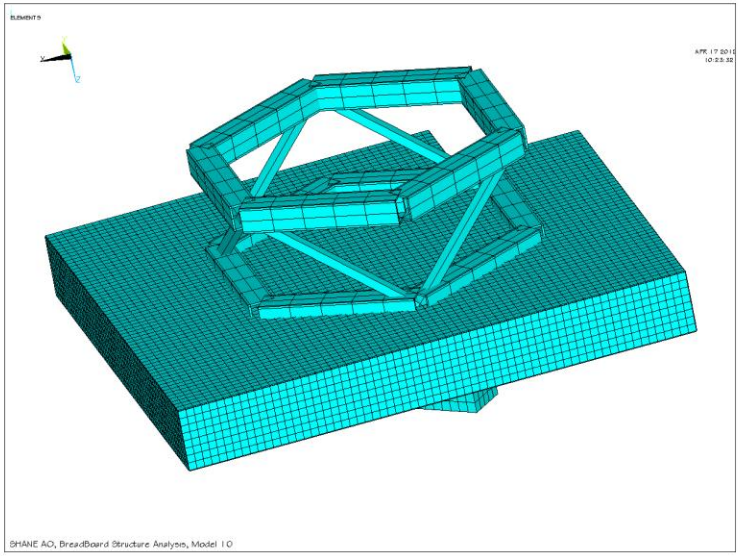
Case	Description	Material	Board Thickness (in)	T_{top} (in)	Flexure (arcsec)	Comments	
1	bench (VLAO)	Aluminum	2.2	.125	6.8	All skins same material Top skin = T_{top} Bottom skin = .1” Side skins = .0625” honeycomb core material unchanged Honeycomb properties developed for VLAO Entire perimeter of bottom edge is restrained	
2	bench	Aluminum		.125	4.6		
3				.125	3.6		
4				.25	2.5		
5	Standard skin thickness			**.1875**	**3.0**		
6			6	.5	1.35		
7	bench	Steel		.75	.85		
8				1	.59		
9				.75	1.43	Bottom skin = .1	Only bottom corners of table restrained
10				.75	.94	Bottom skin = .5	

Bench FEA Models (with & w/o Dichroic Stage)

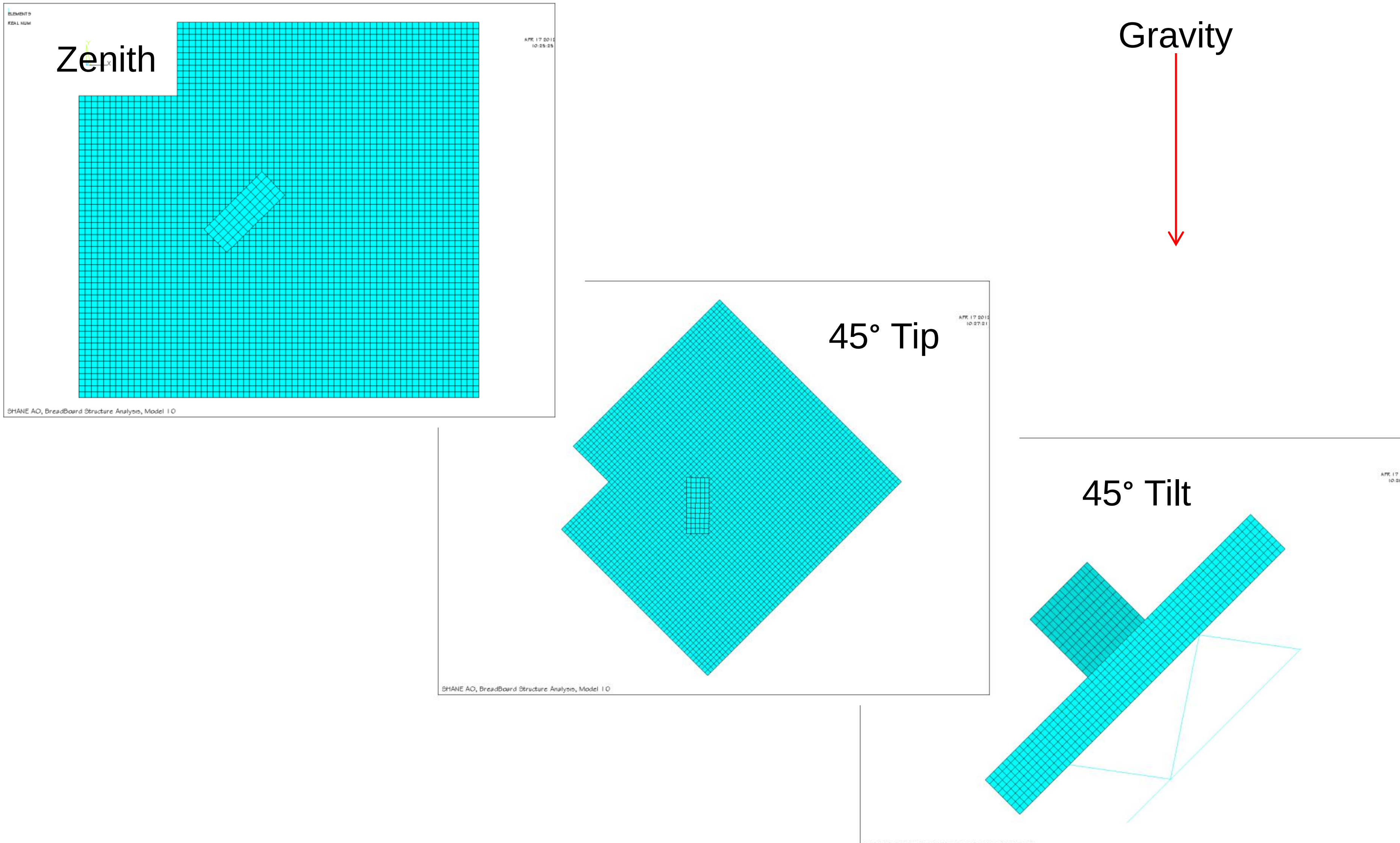








Gravity Orientations



Results Summary

	Maximum Deflection (mm)	Θ_X Flexure P-V (arc-sec)	Θ_Y Flexure P-V (arc-sec)	w/ Dichroic Θ_X Flexure P-V (arc-sec)	w/ Dichroic Θ_Y Flexure P-V (arc-sec)
Zenith	.050	[1]	[1]	[1]	[1]
Tip	.065	2.9	2.8	12.1	12.2
Tilt	.058	5.4	5.4	6.4	6.3

Note 1 – Flexure values based on net change from Zenith orientation, when instrument is installed and aligned

G(Zenith) Response

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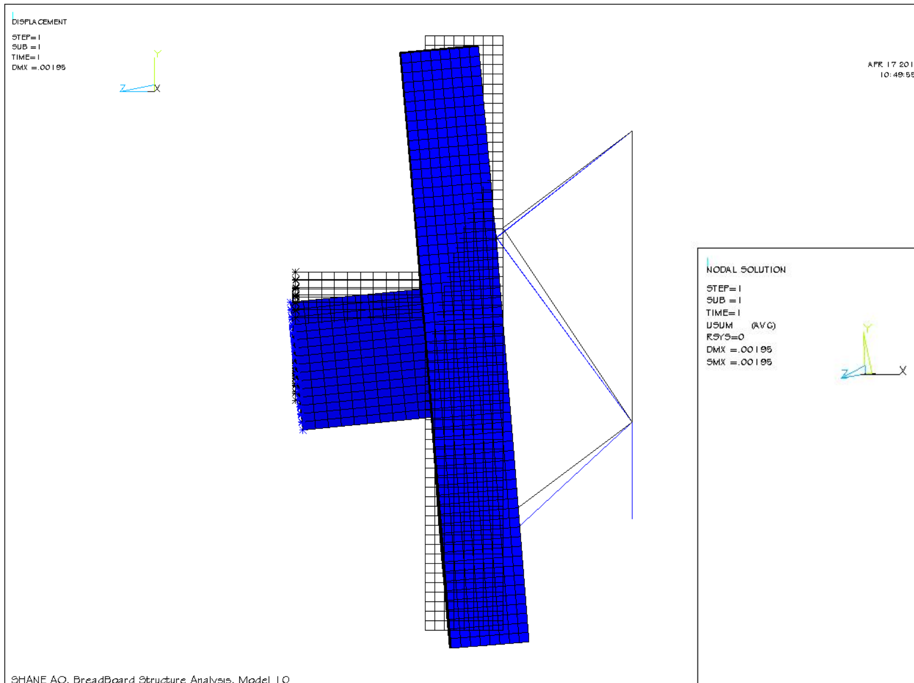
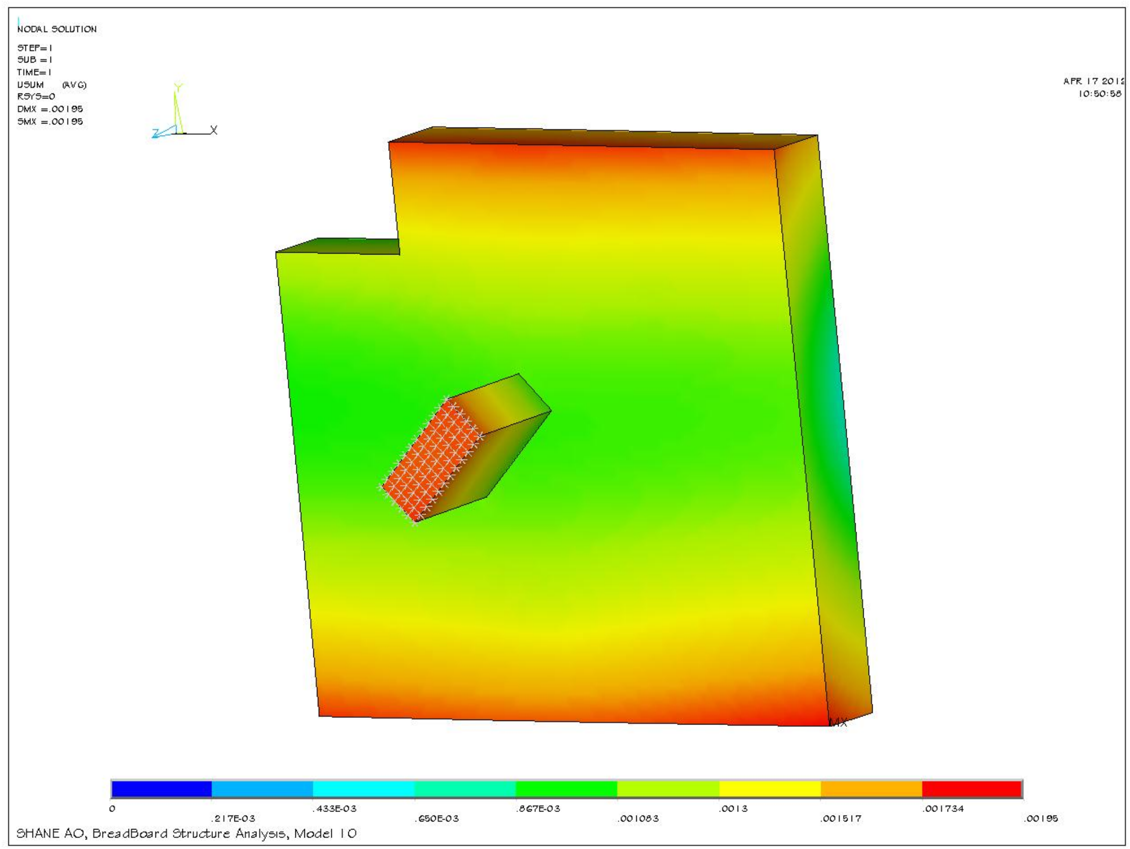


Maximum Displacement:

.00195” (.05 mm)



G(Tip) Response

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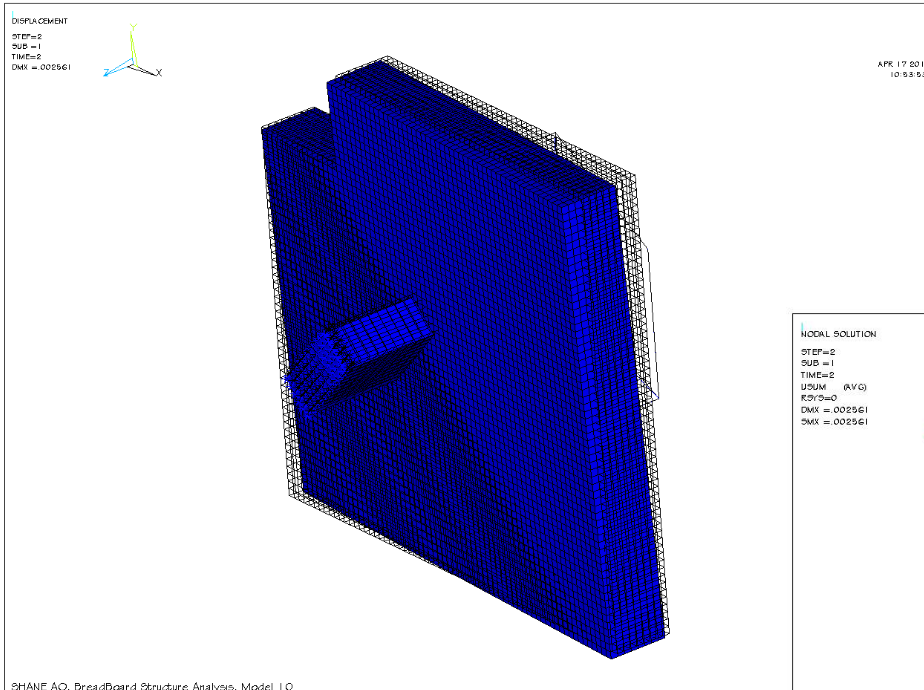
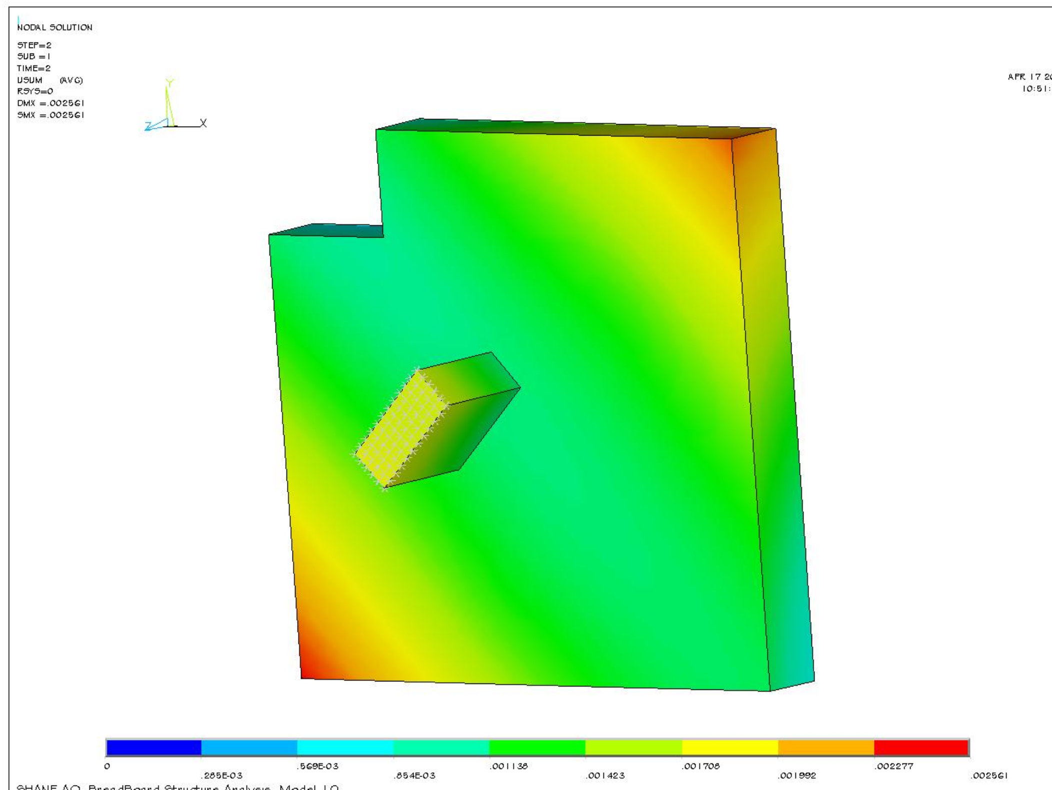


Maximum Displacement:

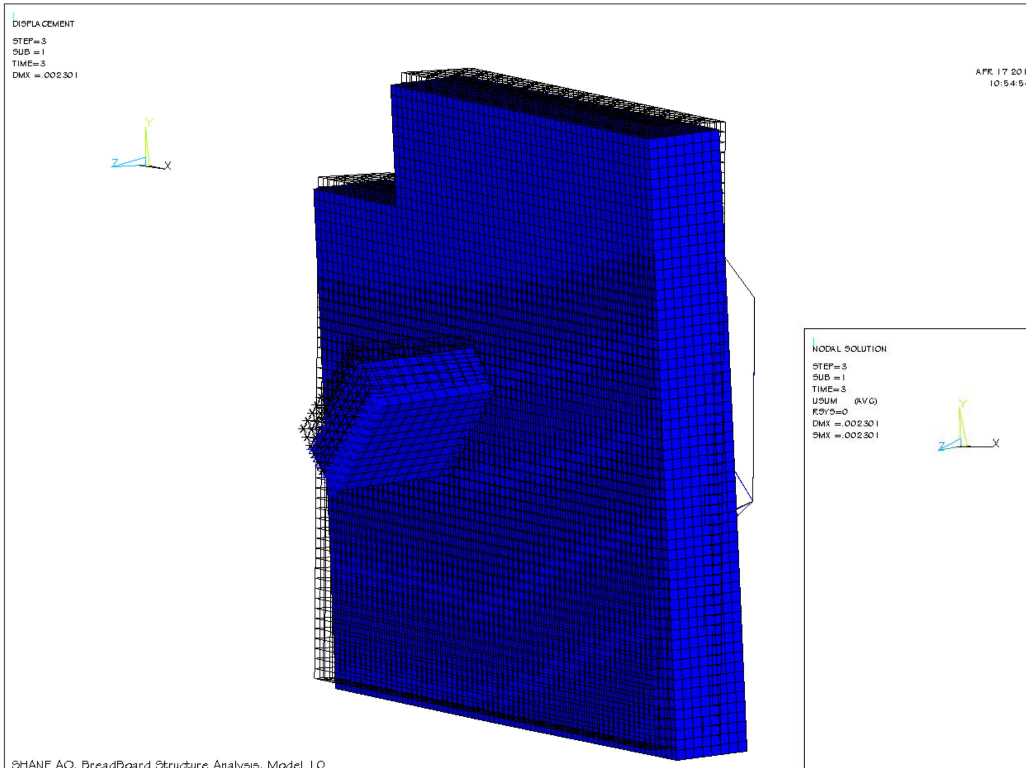
.00256” (.065 mm)

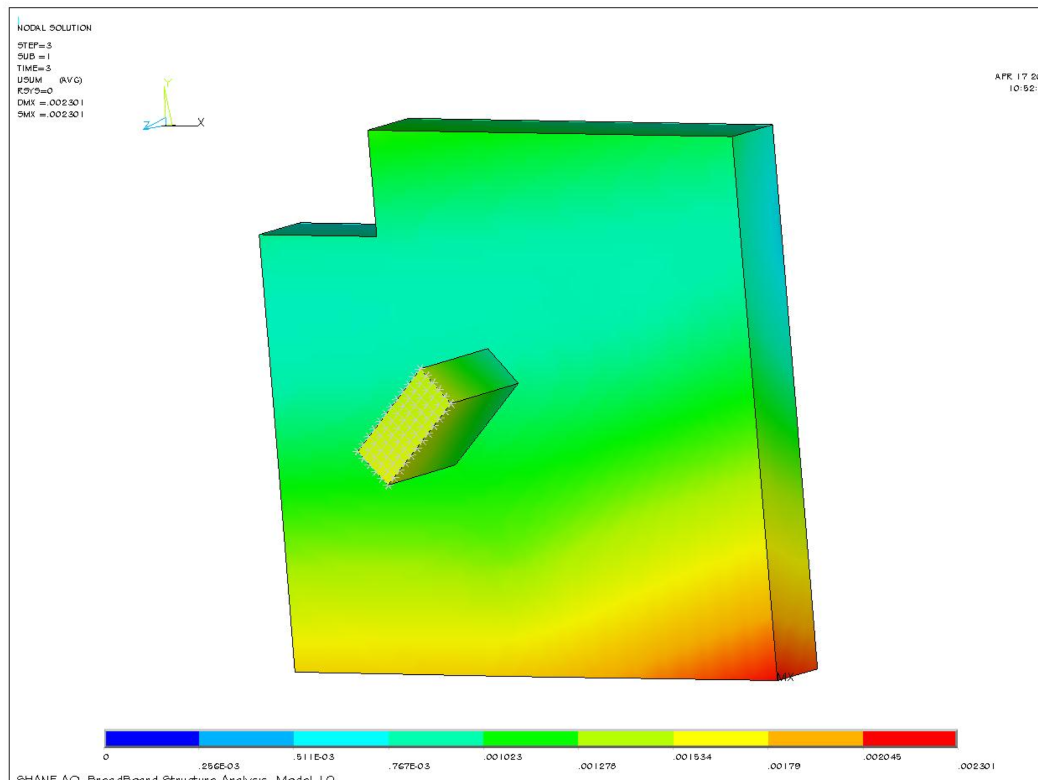


G(Tilt) Response

Maximum Displacement:

.0023” (.058 mm)





Without Dichroic Stage – Tip Response – X Rotations

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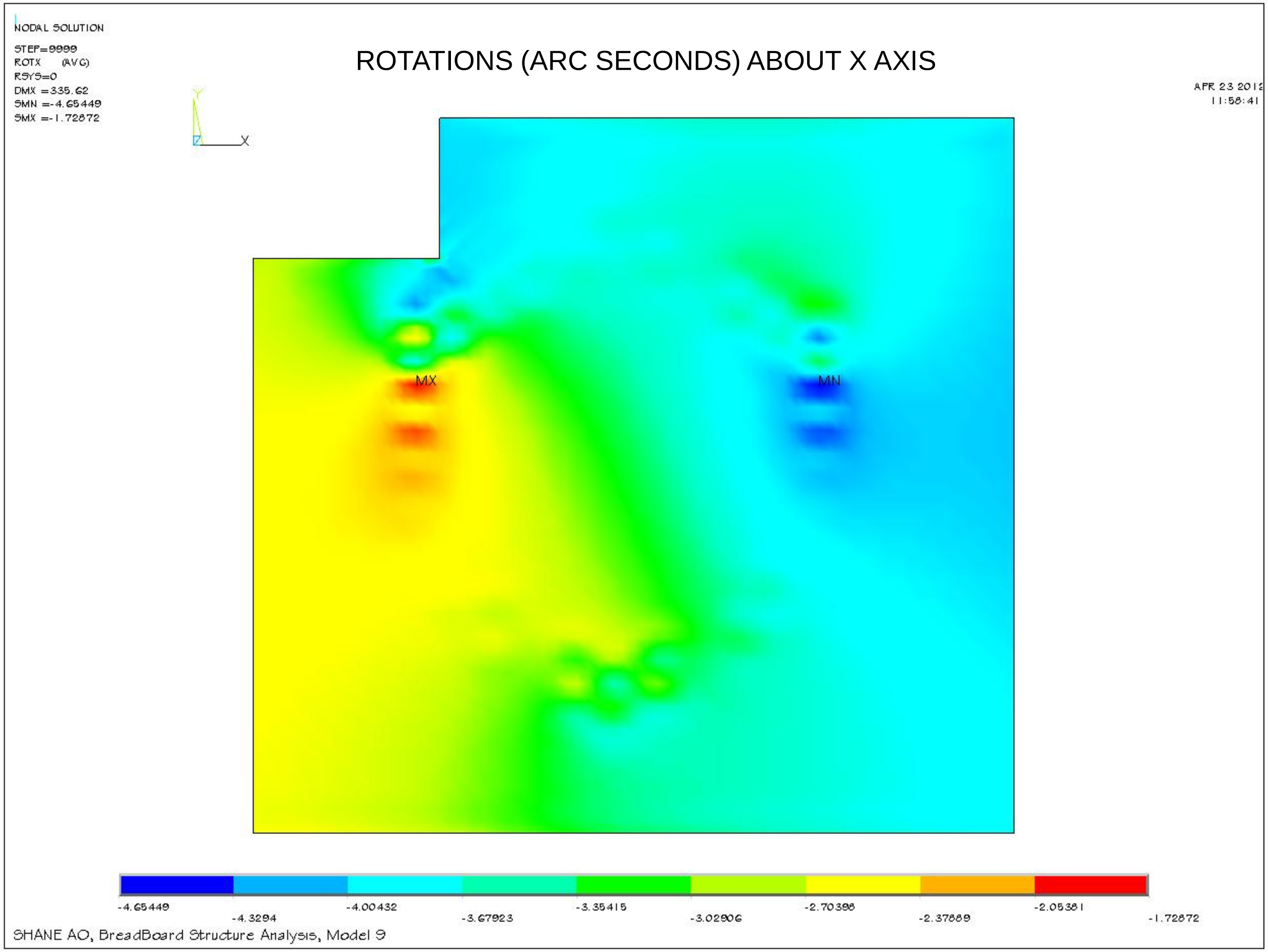

Without Dichroic Stage – Tip Response – Y Rotations

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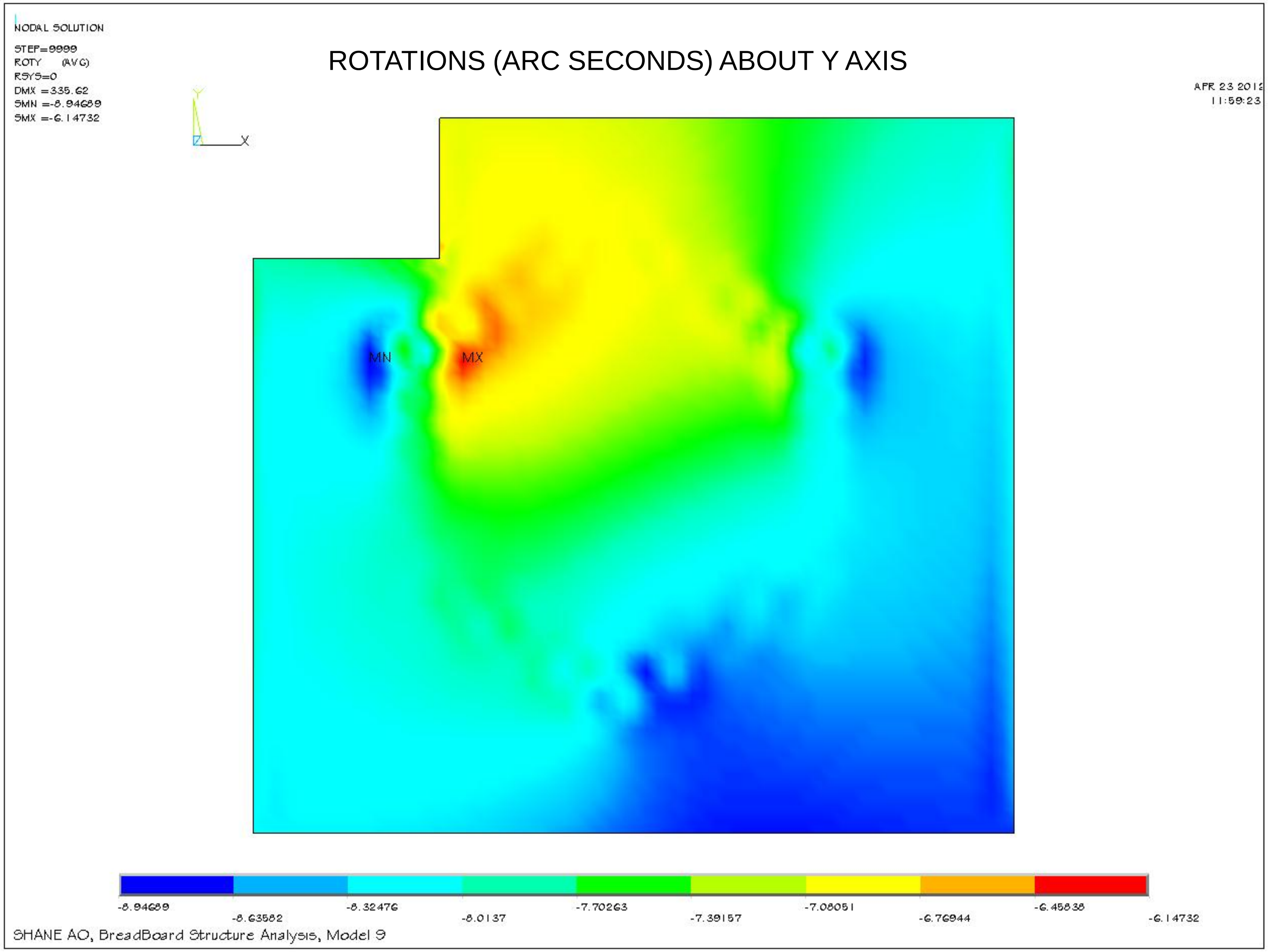

Without Dichroic Stage – Tilt Response – X Rotations

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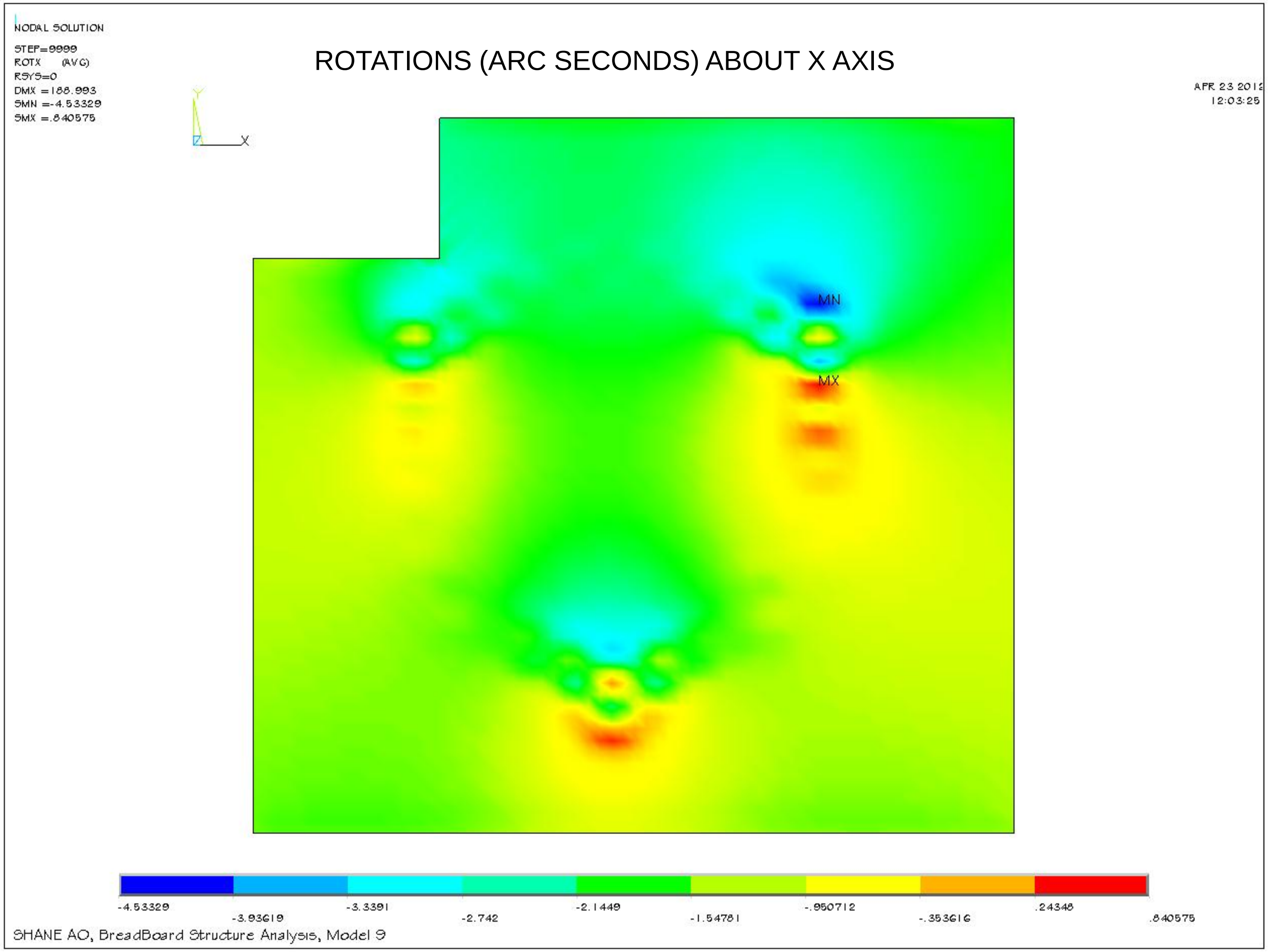

Without Dichroic Stage – Tilt Response – Y Rotations

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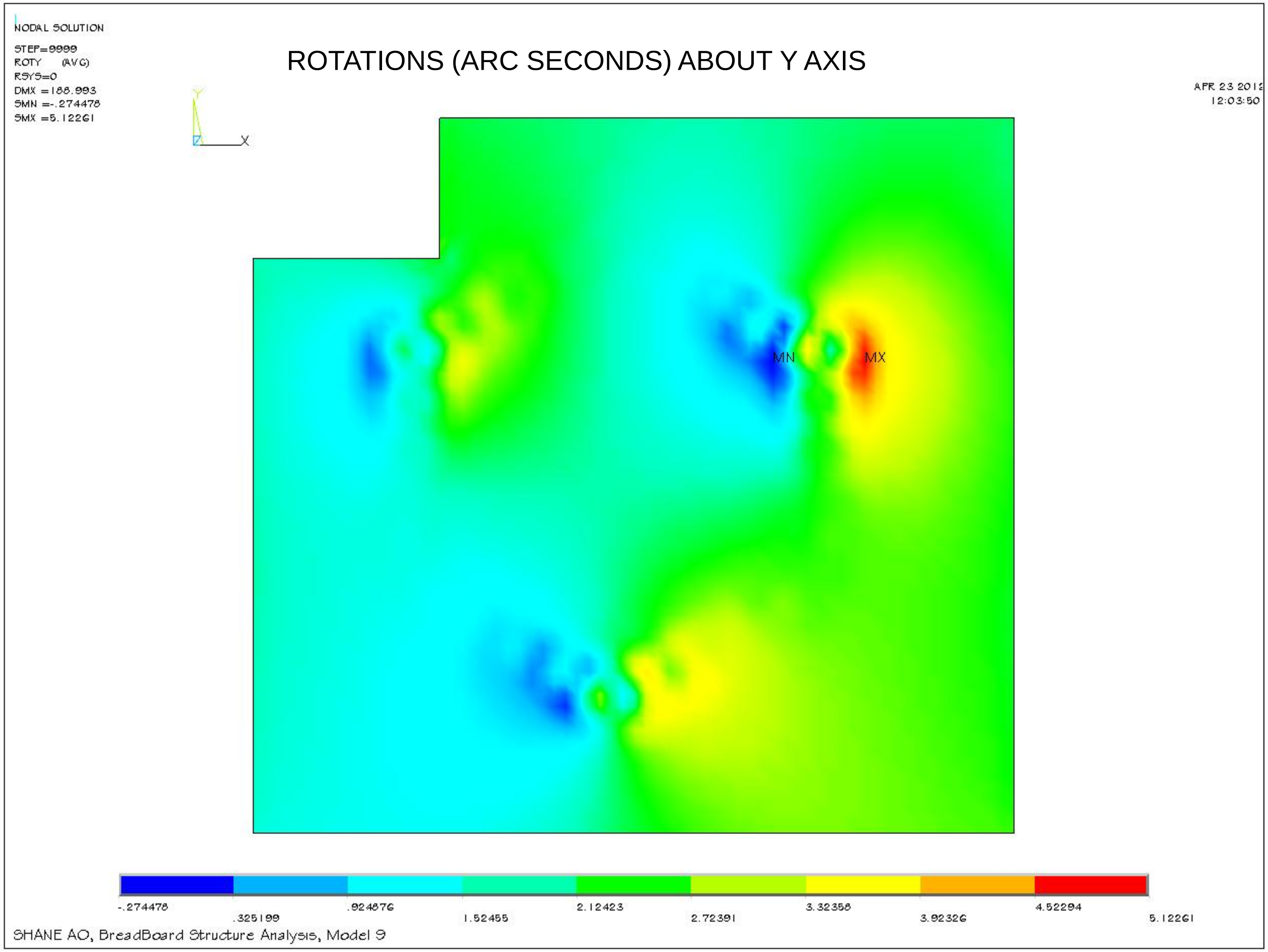

With Dichroic Stage – Tip Response – X Rotations

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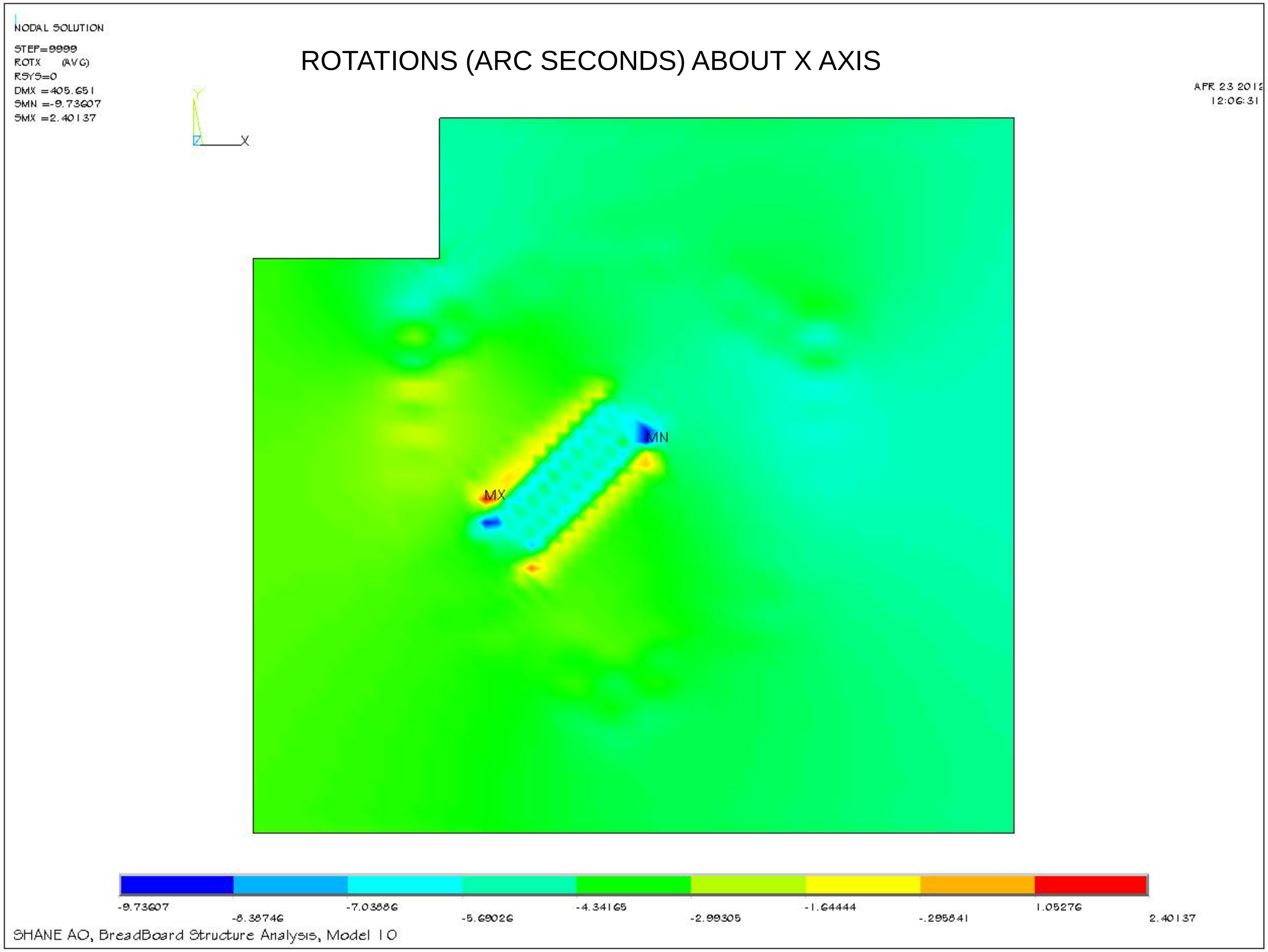

With Dichroic Stage – Tip Response – Y Rotations

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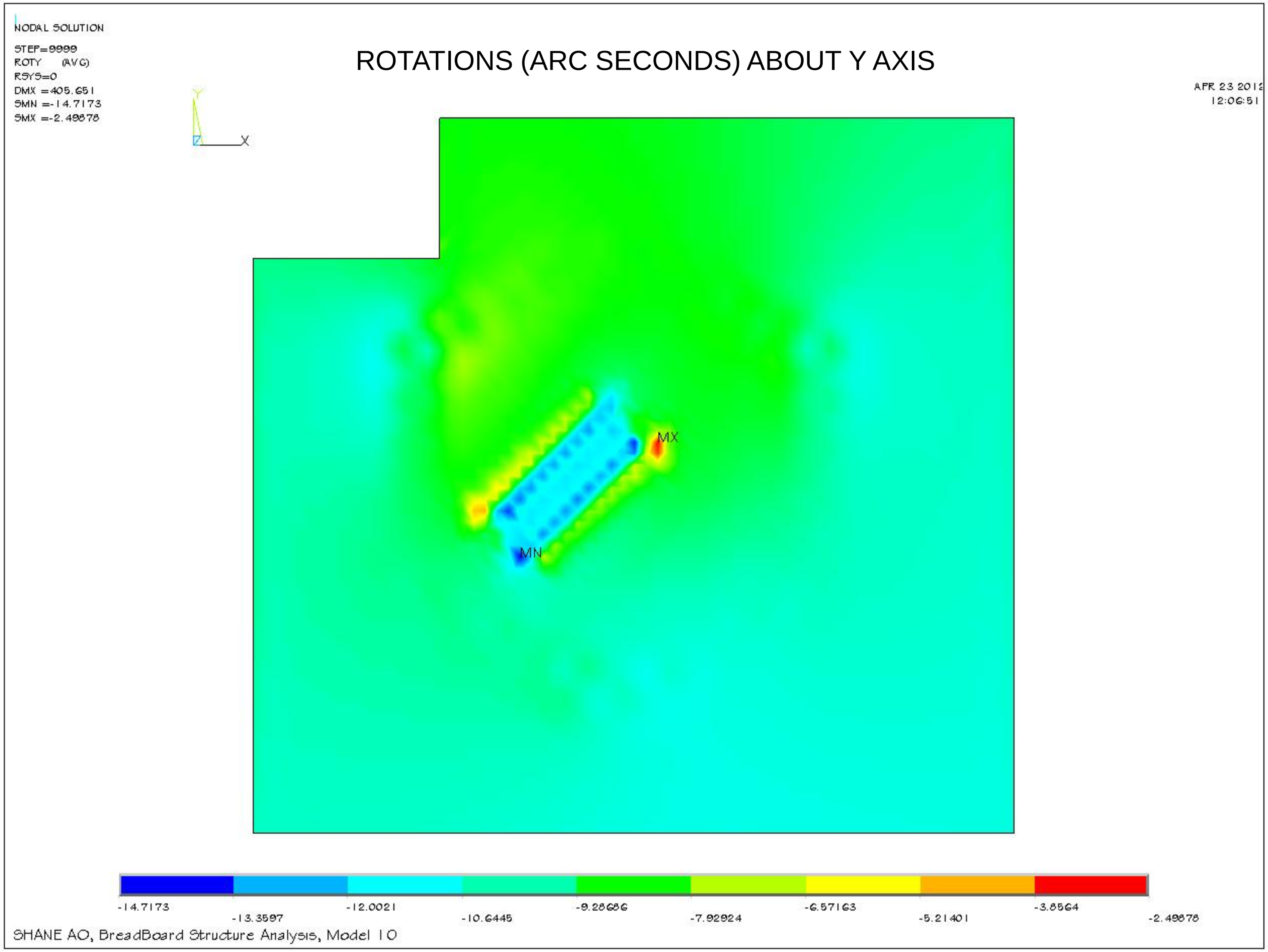

With Dichroic Stage – Tilt Response – X Rotations

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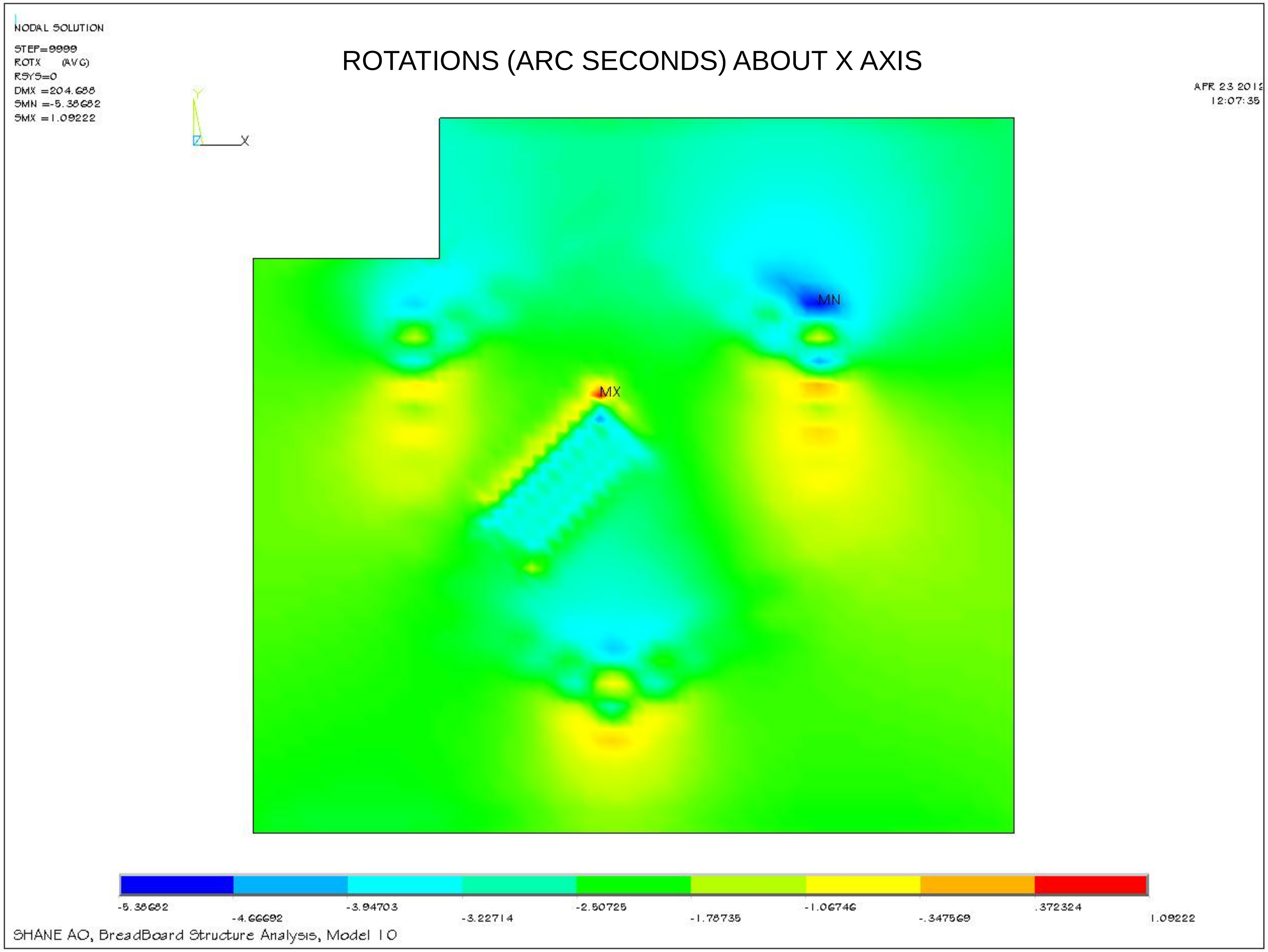

With Dichroic Stage – Tilt Response – Y Rotations

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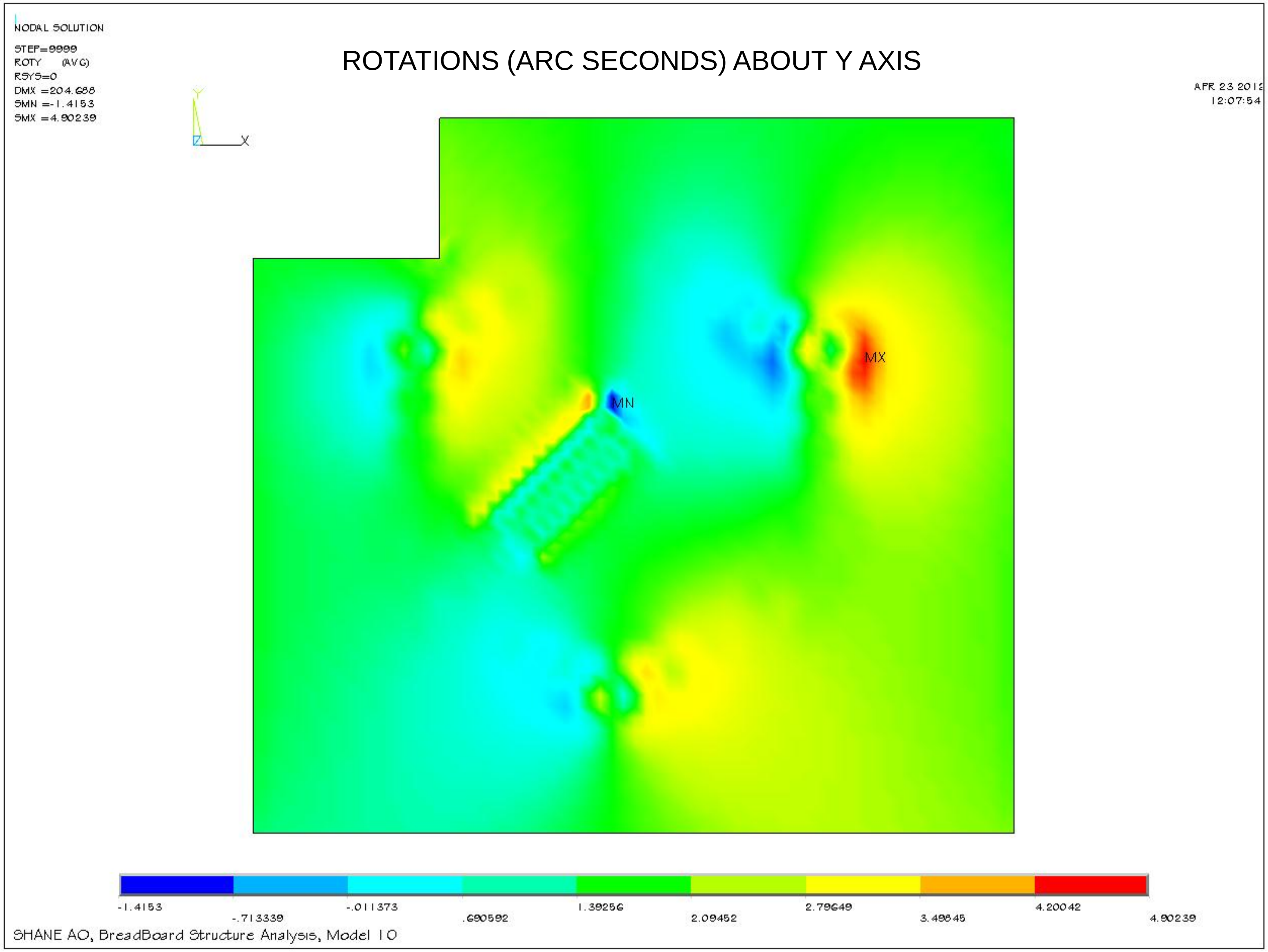

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Support Frame Design

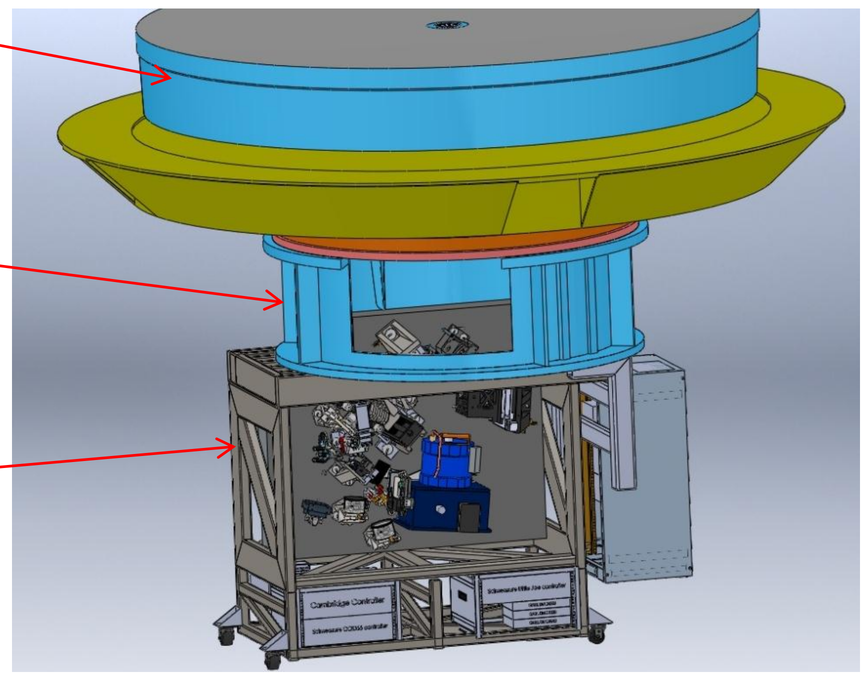
Agenda:

- **Functional Requirements for support frame**
- **Deformation analyses for Optical Bench support frame and Tub**

Primary Mirror

Tub

Optical Bench support frame



Bench to Telescope Mounting

Key Functional Requirements of support frame:

- <u>Must connect Tub structure to AO Optical Bench</u>
- Must limit rigid body Optical Bench deflection to less than 0.5mm (linear displacement)
- Must limit rigid body angular deflection of Optical Bench to less than 0.1 degrees
- Should weigh less than 1500 lbs (2500 lb lift capacity)
- No/minimal electrical disconnections and reconnections, electronics rack and Optical Bench must move as a single unit
- Must Roll without the need for an additional cart
- Should allow access to optical components, and ability to remove all Optical Bench components
- Must Fit through 38.75” wide door

Support Frame Deformation Analysis

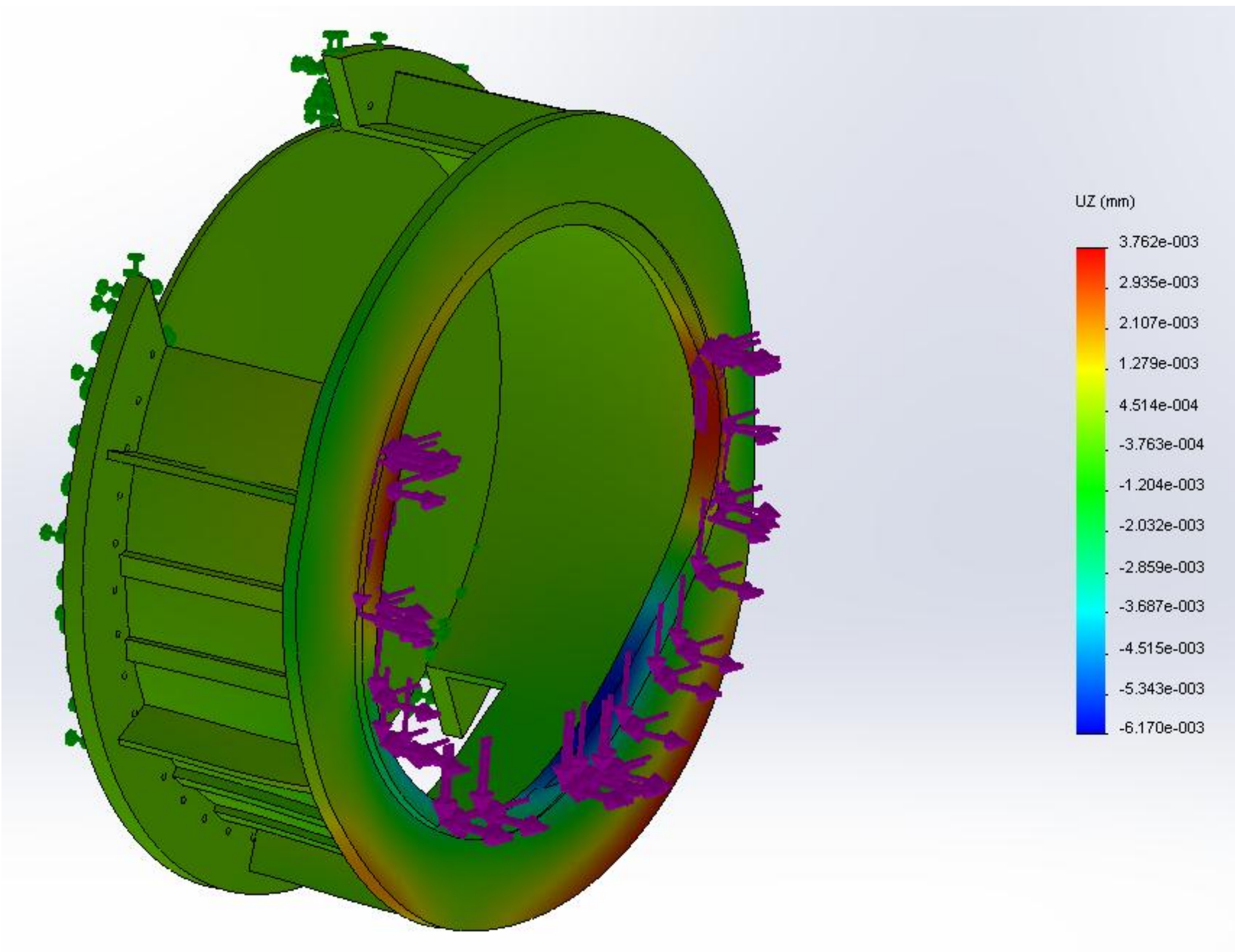
Objective: Determine deflection of Tub and support frame

Assumptions and Conditions:

1. 1500lb load (will be less than this)
2. Used equivalent moment and load for tub
3. 1010 Steel for all components, isotropic
4. Only looking at worst case orientation, telescope pointing at horizon
5. All joints are rigid
6. Neglect any deformation due to thermal expansion

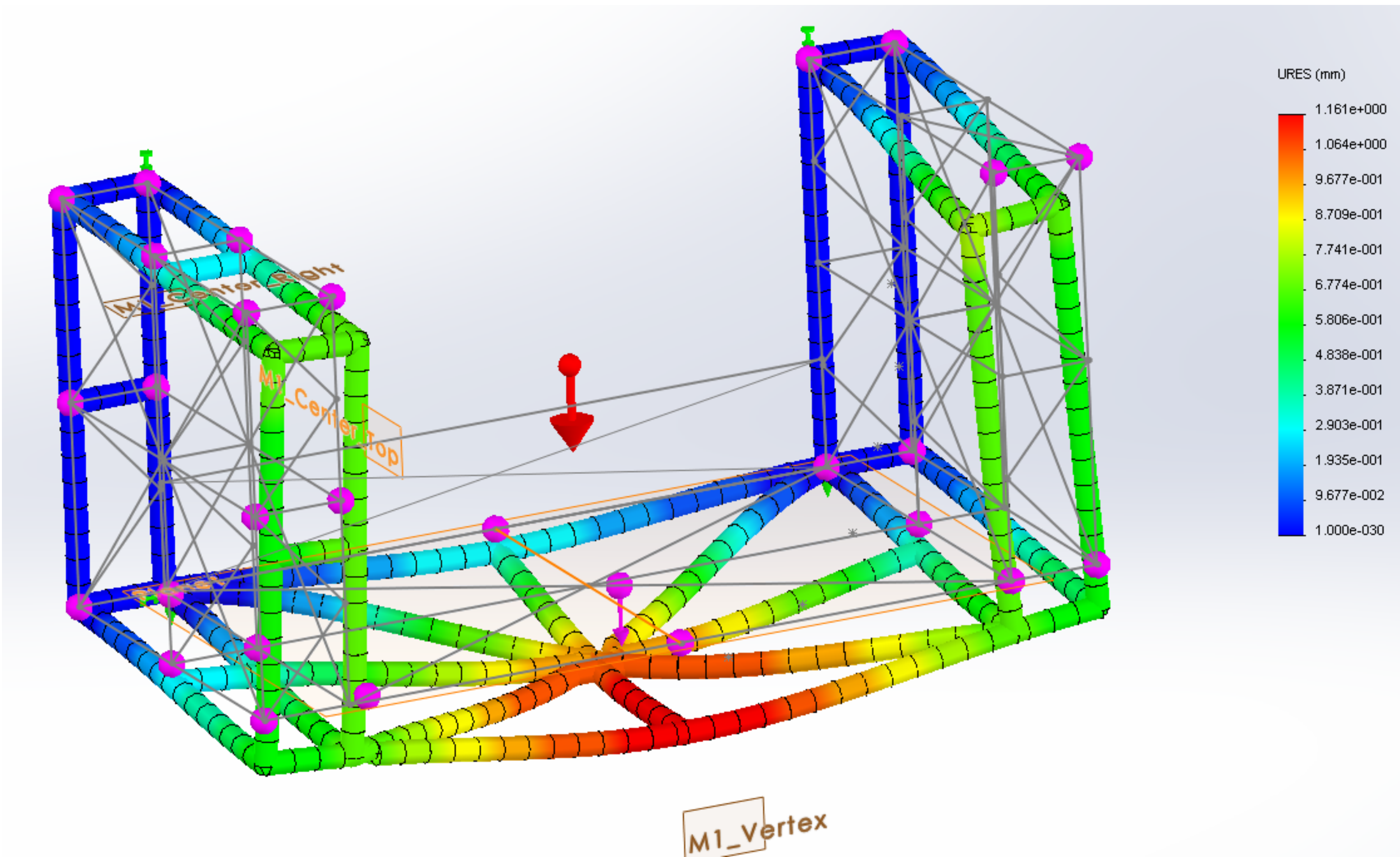
Support Frame Design

Tub Deflection: Approx. 10 microns deflection, very stiff, neglects bearing deflection



Tub to Optical Bench Frame Design

Iteration 1: Approx. 1.2mm deflection, Need more stiffness at Optical Bench support, all member 2"x2" square tube, ¼" wall
Max stress: 43×10^6 N/m^2



Tub to Optical Bench Frame Design

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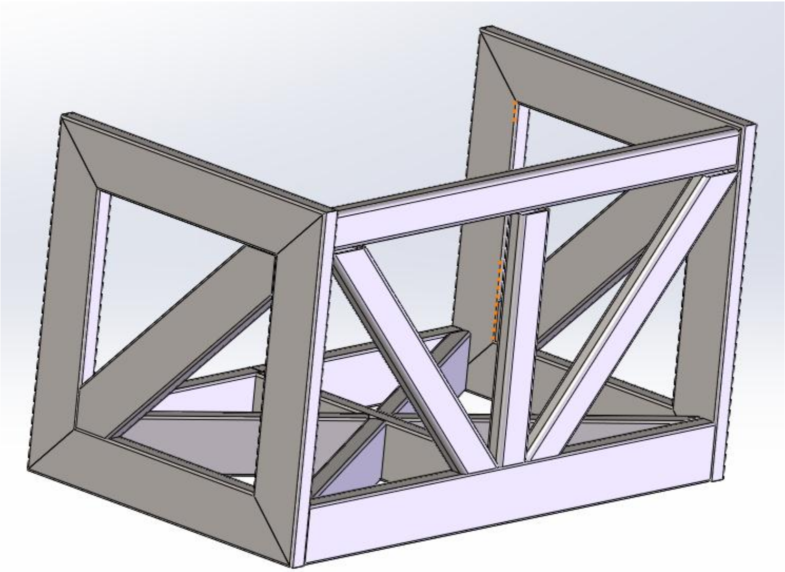
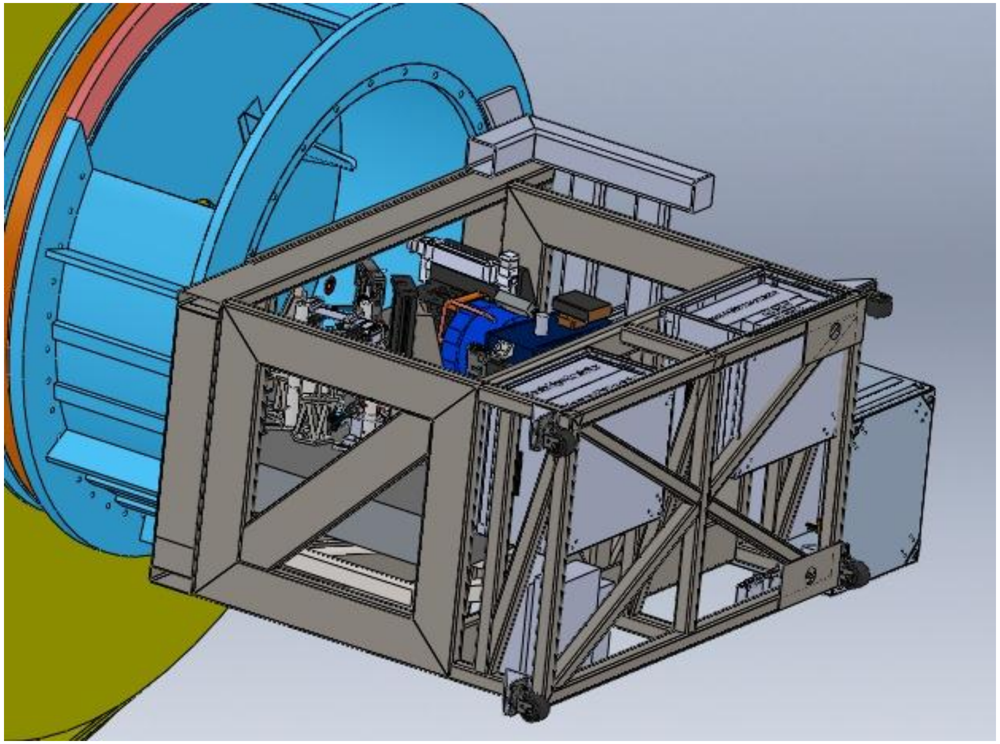
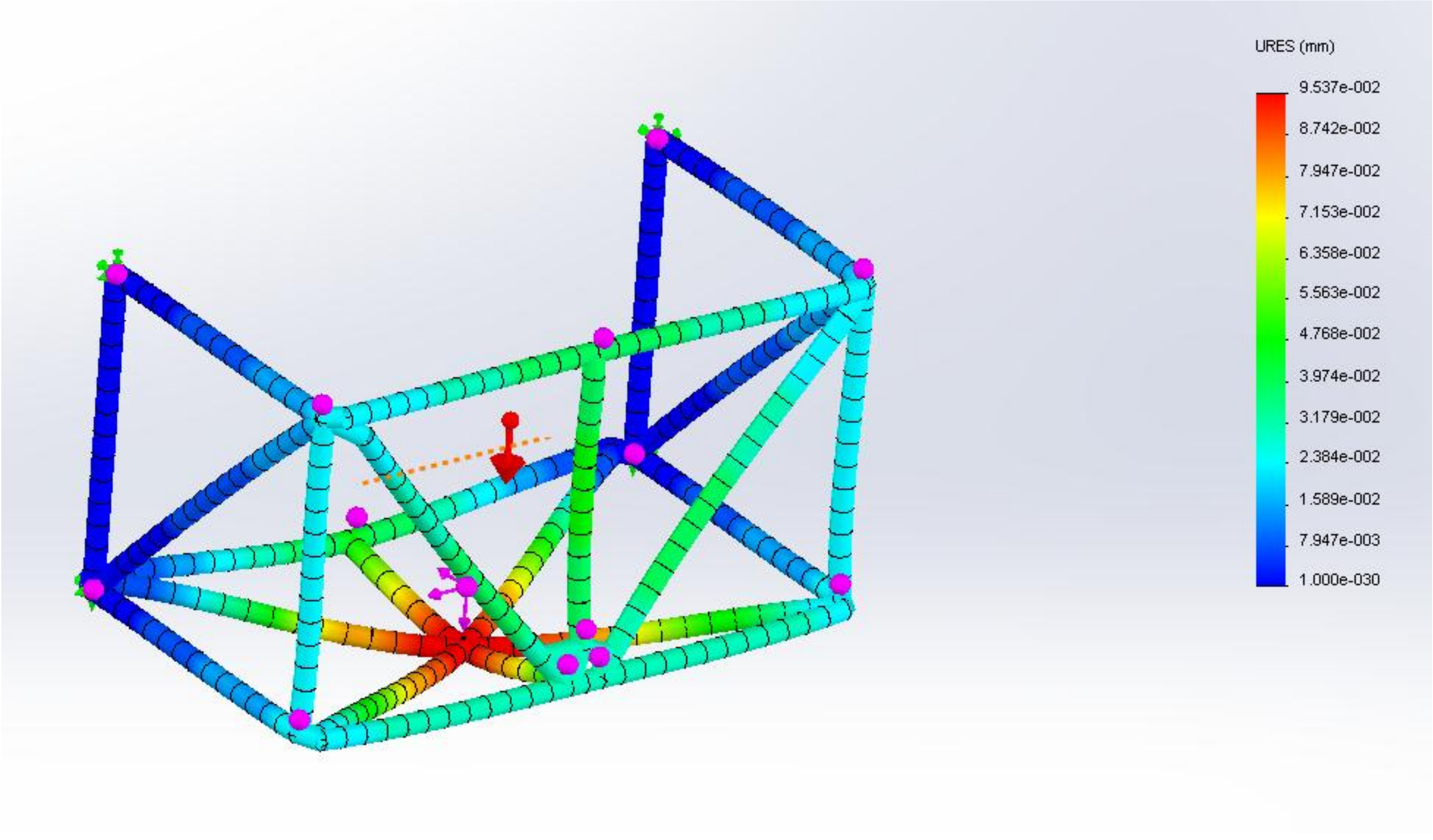
Iteration 6: Solid Model, thinner 0.125” side walls, fewer members with stiffer cross section, weight: 420 lbs





Tub to Optical Bench Frame Design

Iteration 6: Approx. 0.1 mm deflection



Tub to Optical Bench Frame Design

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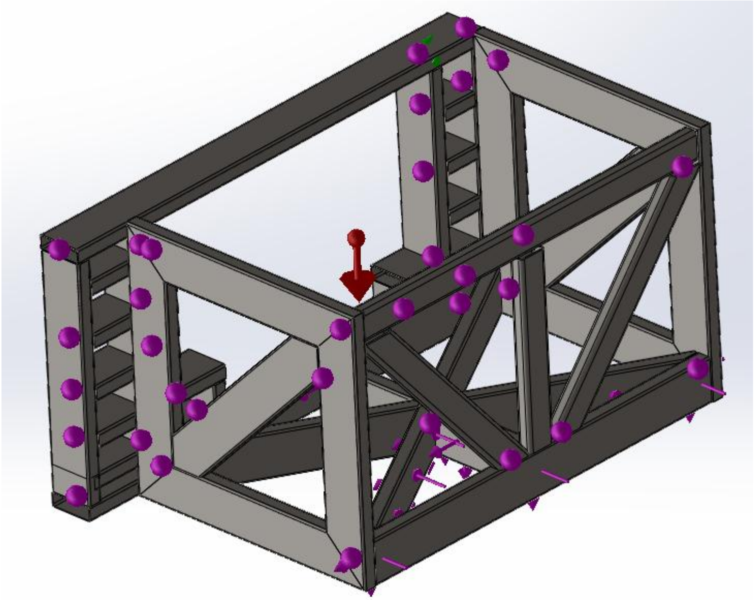
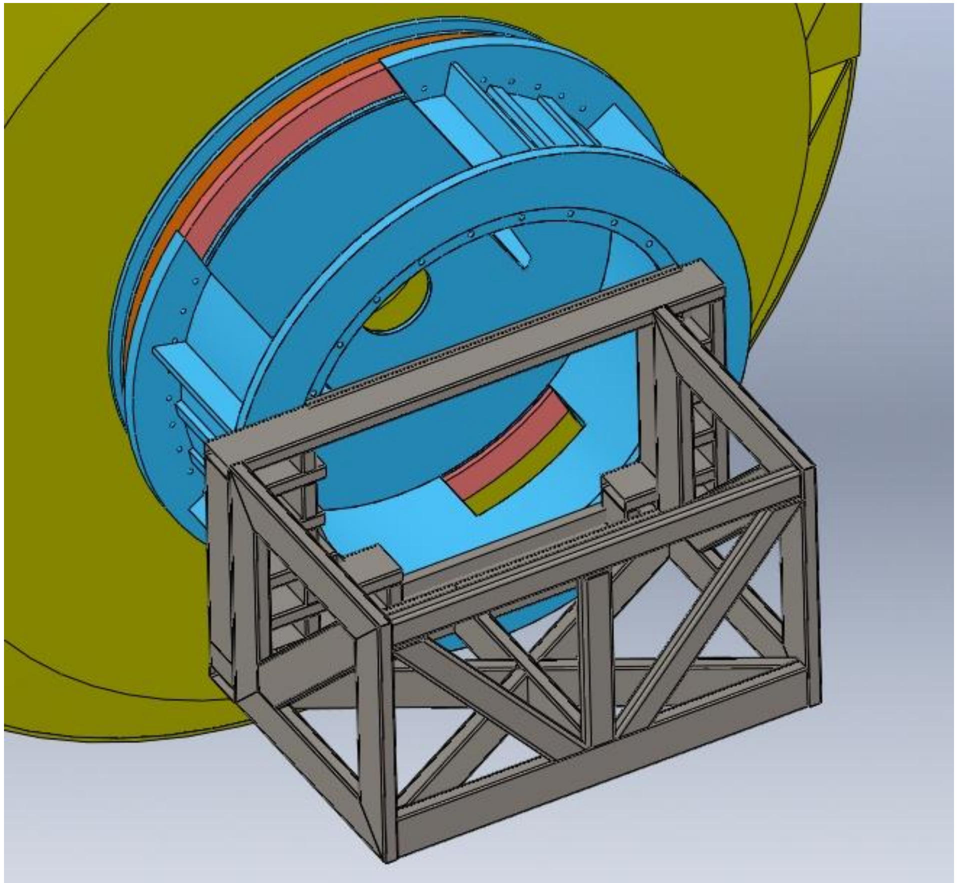
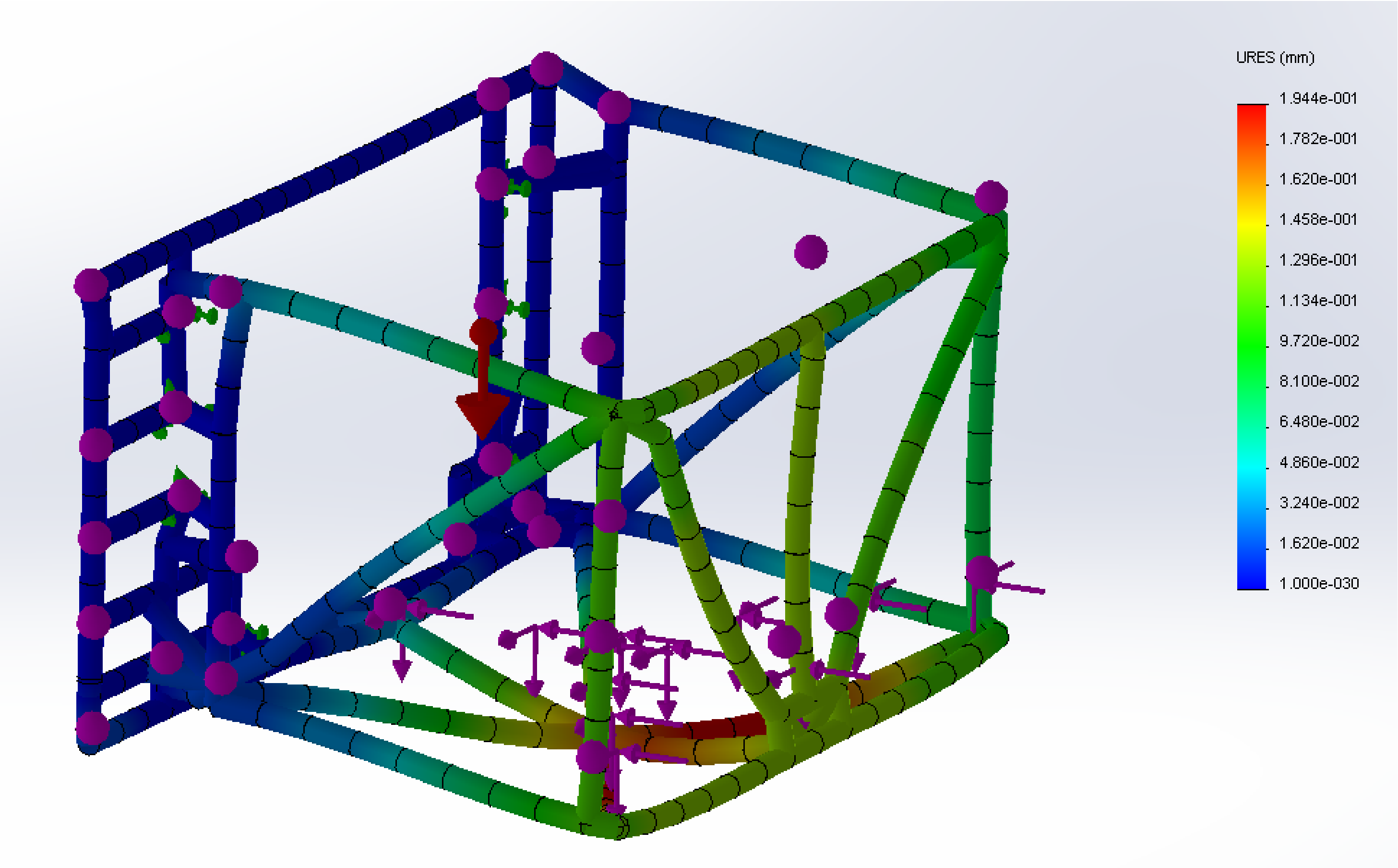
Support Frame Structural Analysis





Tub to Optical Bench Frame Design

Approx. 0.19 mm deflection
Max stress: 29×10^6 N/m^2 (UTS 36×10^7 N/m2)
Weight: 830 lbs



Tub to Optical Bench Frame Design

Conclusion:

-Tub deflection is small (less than 10 microns), neglect

-We can make a frame that deflects under 0.5mm allowance and still meet weight requirements

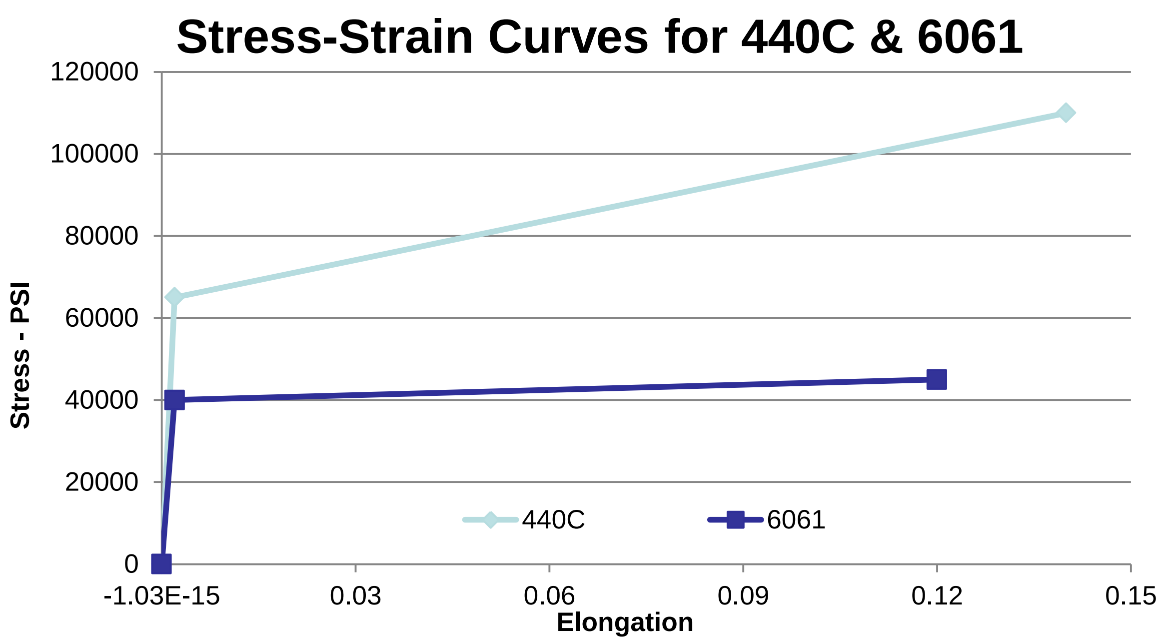
List of Items Still Left To Do

- Reduce weight of support frame and finalize electronics racks and locations
- Detail support frame tub connection geometry and fasteners
- Finalize optical bench shape, detail bipod attachment design, internal welding
- Cable Routing
- WFS steering mirror mounts
- WFS stage & configurations
- OAP3 support mount redesign
- Fixturing for temporarily holding IRCAL to bench during alignment
- Hexapod attachment scheme to bench
- Hexapod strut design
- Electronics cooling system
- Alignment fixturing
- 2 axis rotation test rig
- Optical component deflection sensitivity analysis with Zemax

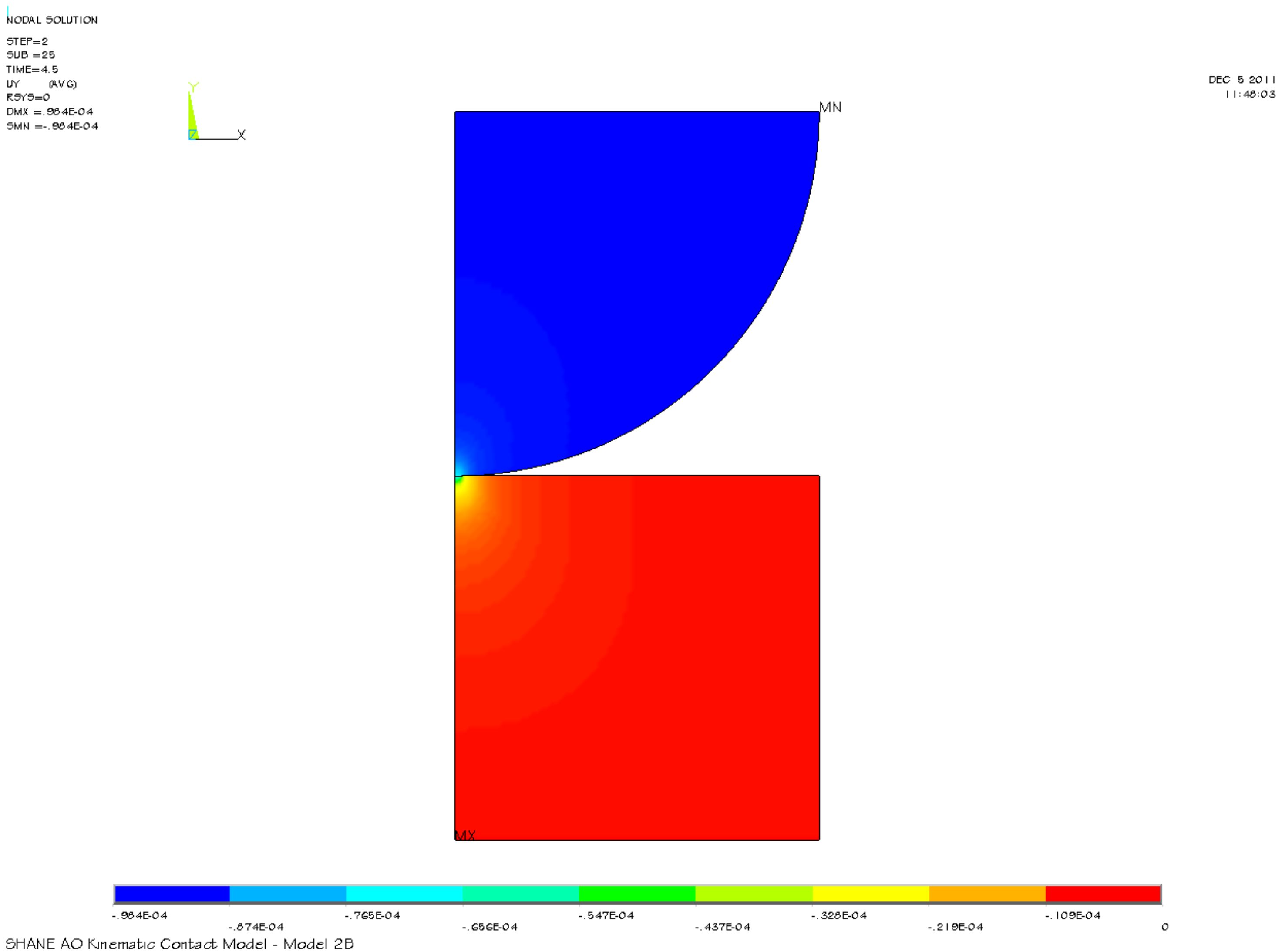
Addendum:

Material Properties

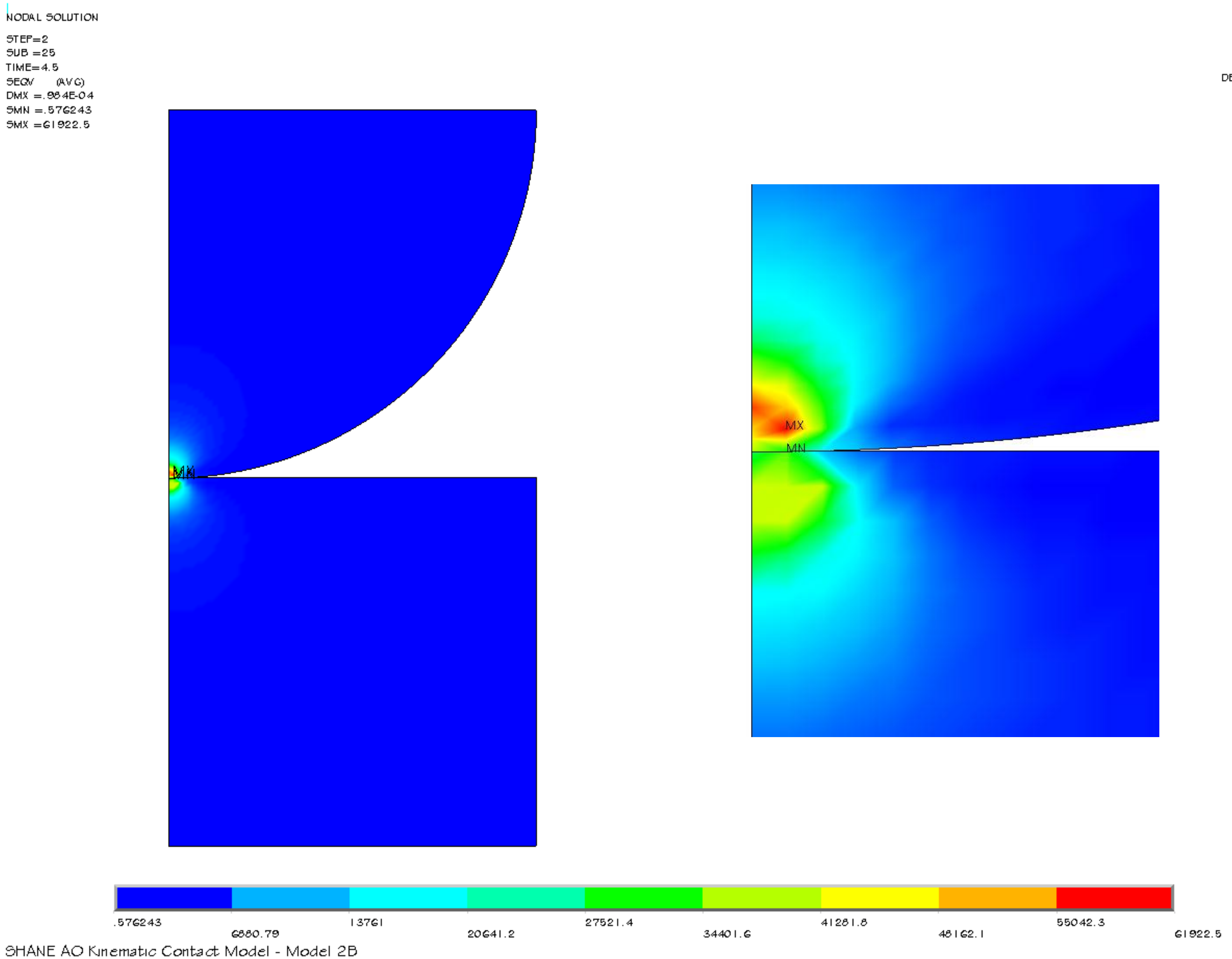
Material	Elastic Modulus psi	E2 psi	Poison's Ratio ν	σ(yield) psi	σ(TS) psi	% Elongation
440C	2.85E+07	3.26E+05	0.283	6.50E+04	1.10E+05	14
6061	1.00E+07	4.24E+04	0.33	4.00E+04	4.50E+04	12
Saphire	5.00E+07	--	0.275	--	--	--



Aluminum Base – 20 N Deflections



Aluminum Base – 20 N Stress



Aluminum Base – 30 N Deflections

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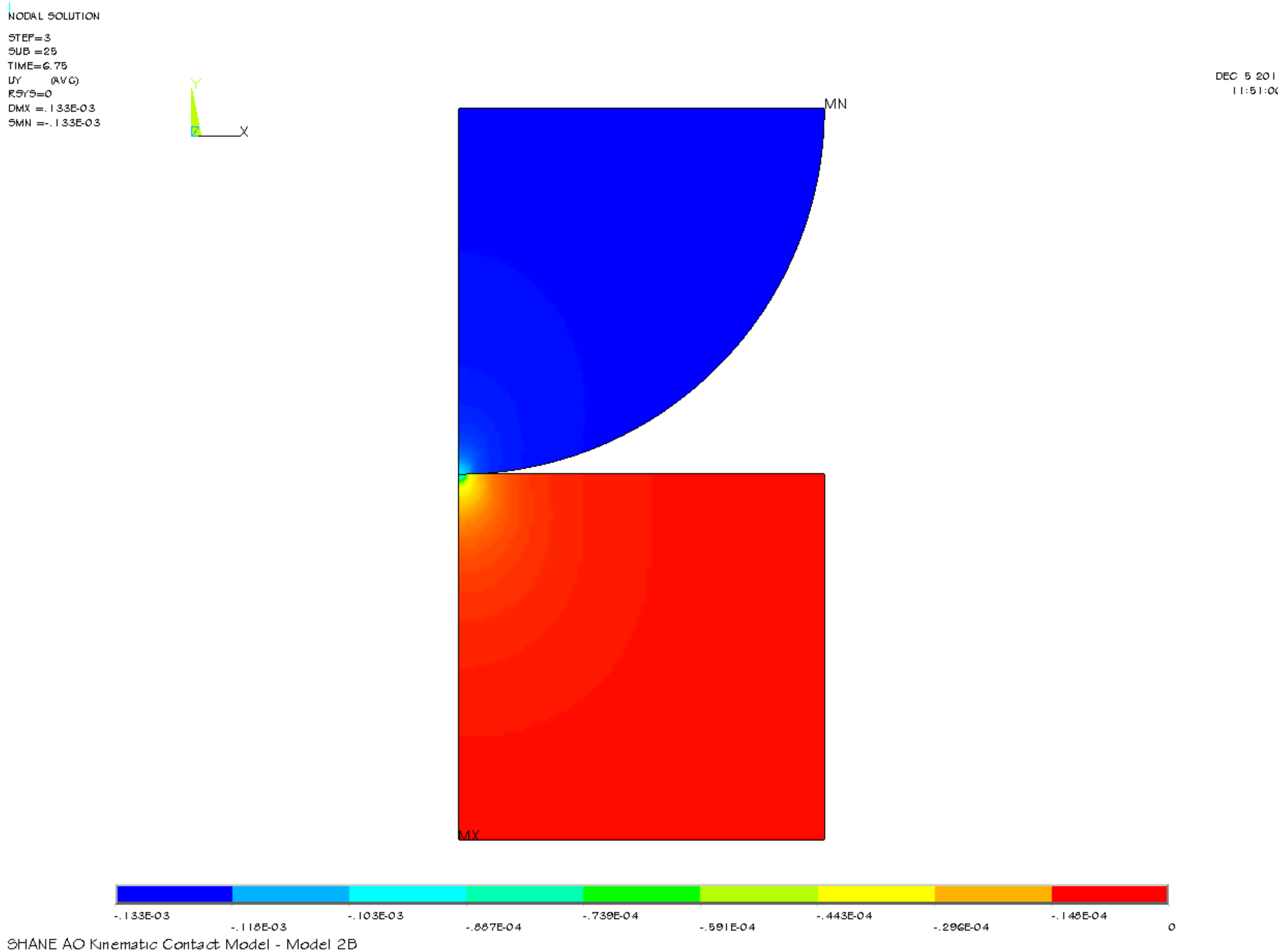
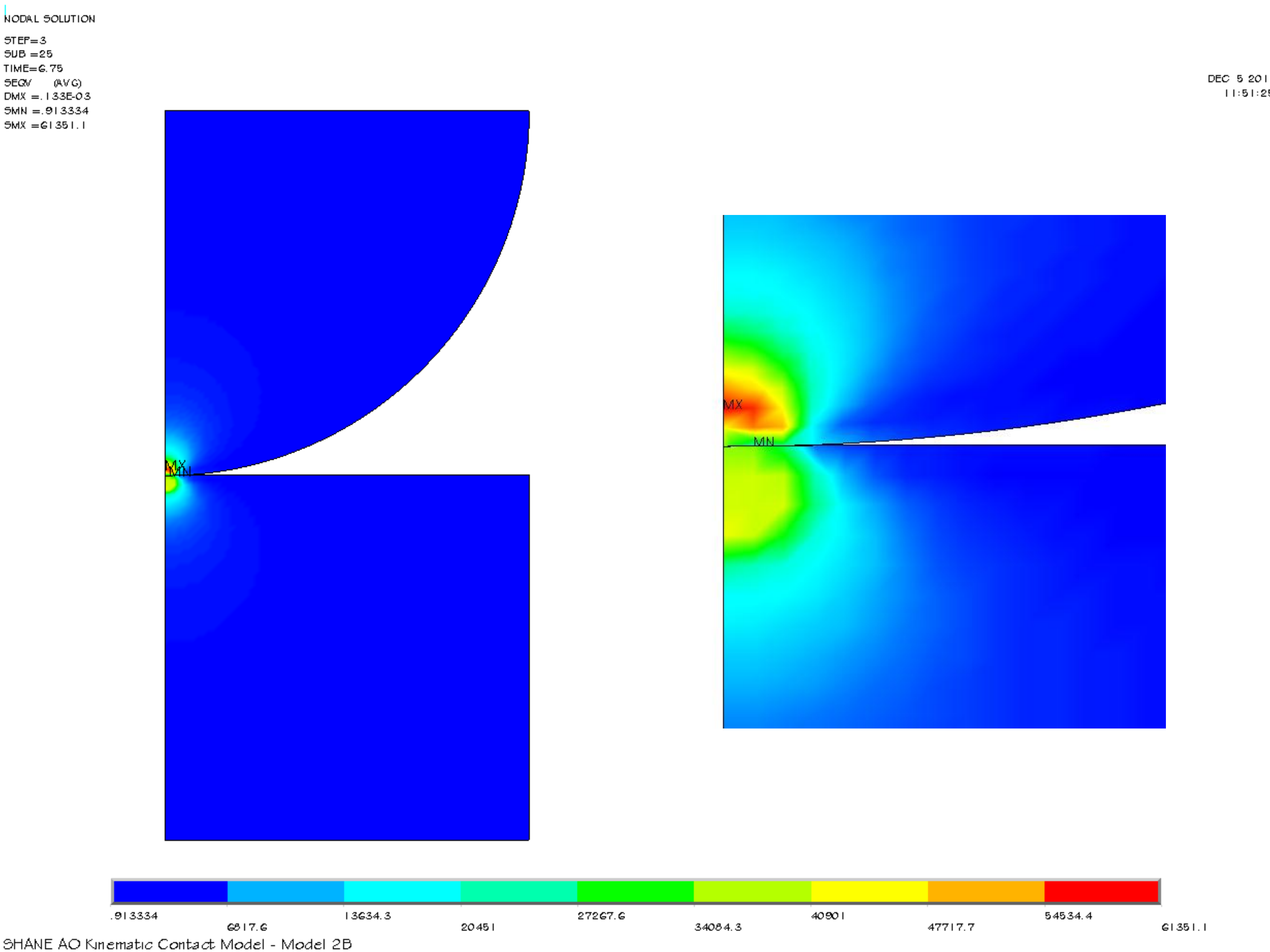


Aluminum Base – 30 N Stress



Sapphire Base – 20 N Deflections

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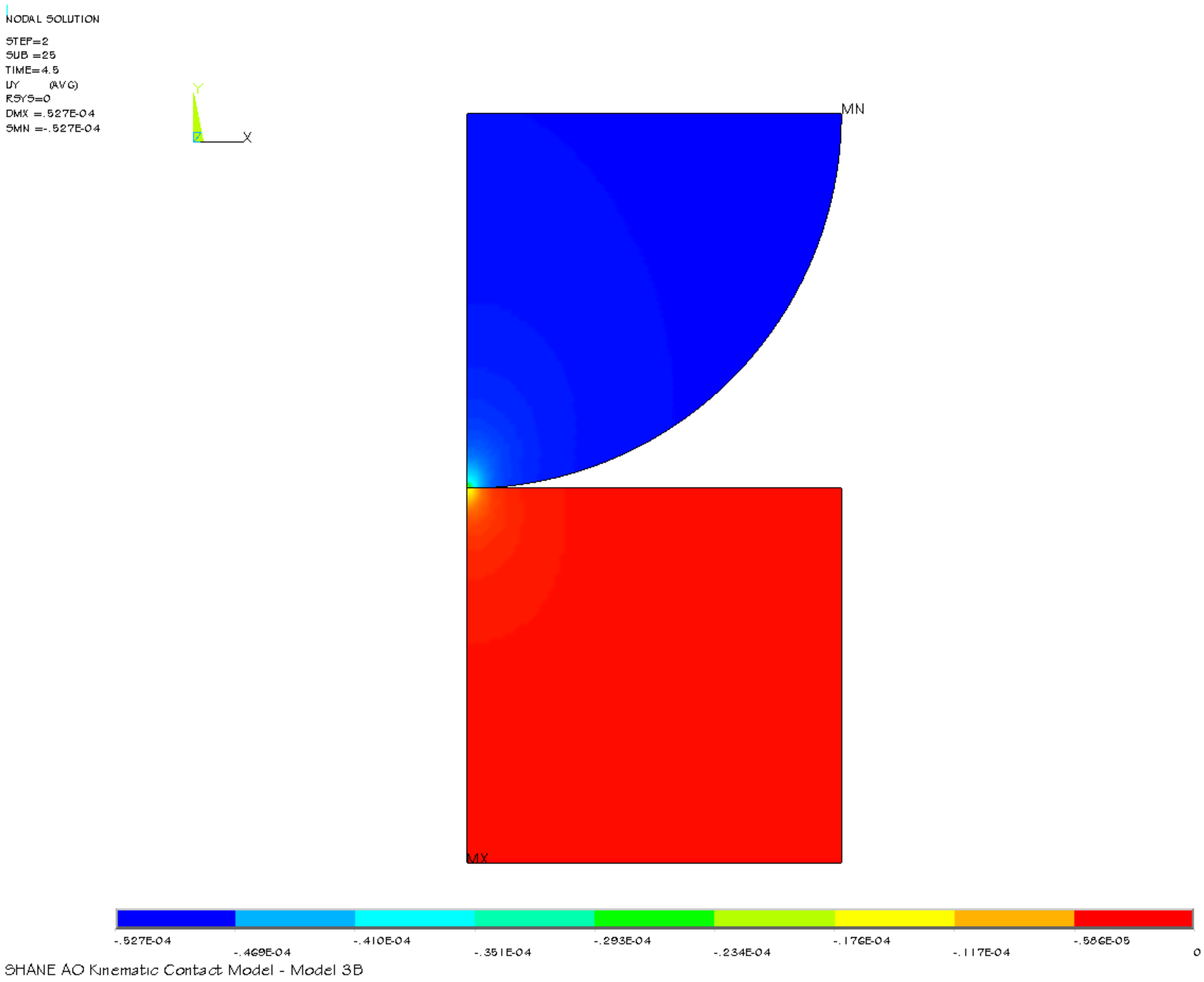
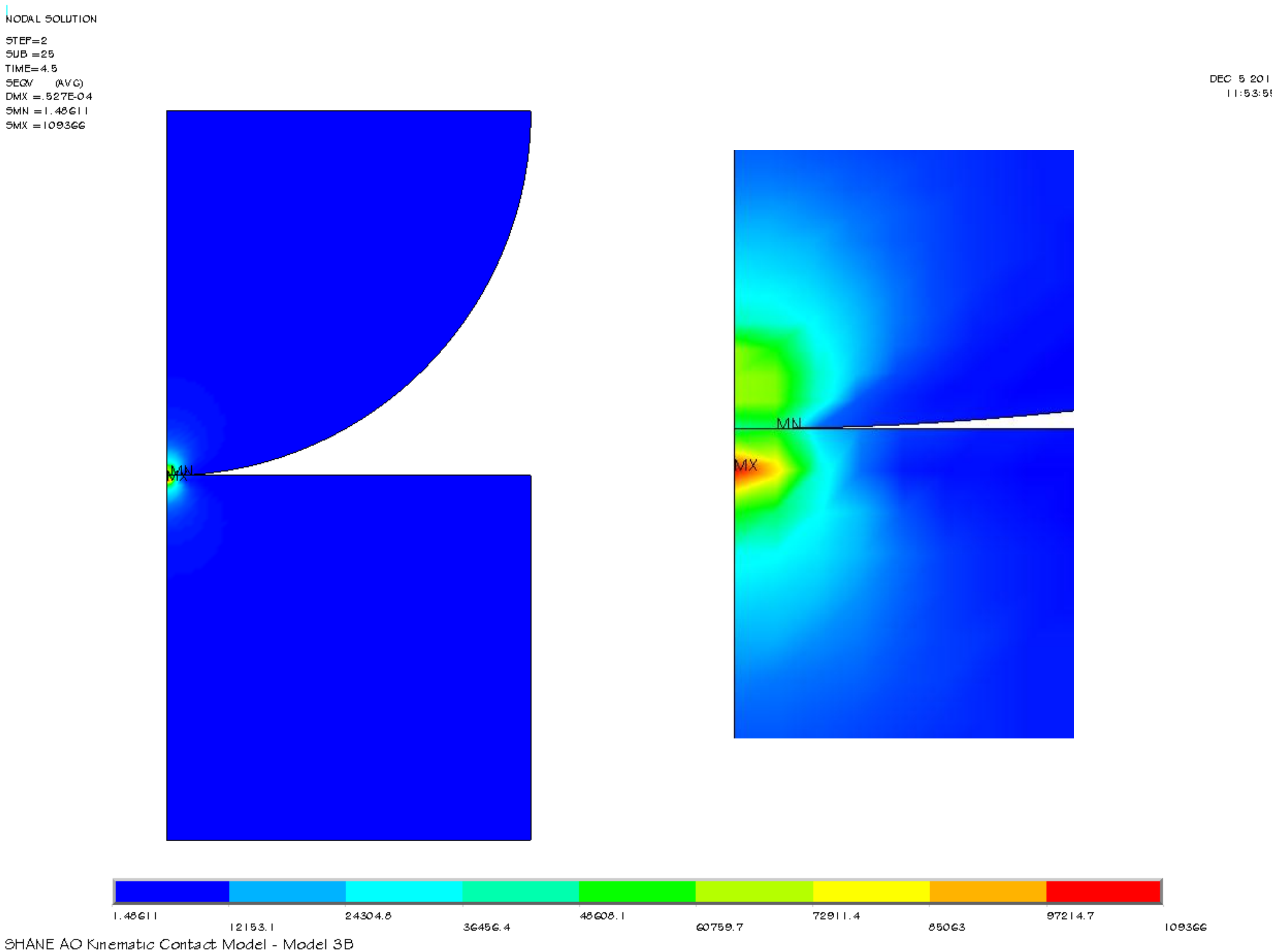


Sapphire Base – 20 N Stress



Sapphire Base – 30 N Deflections

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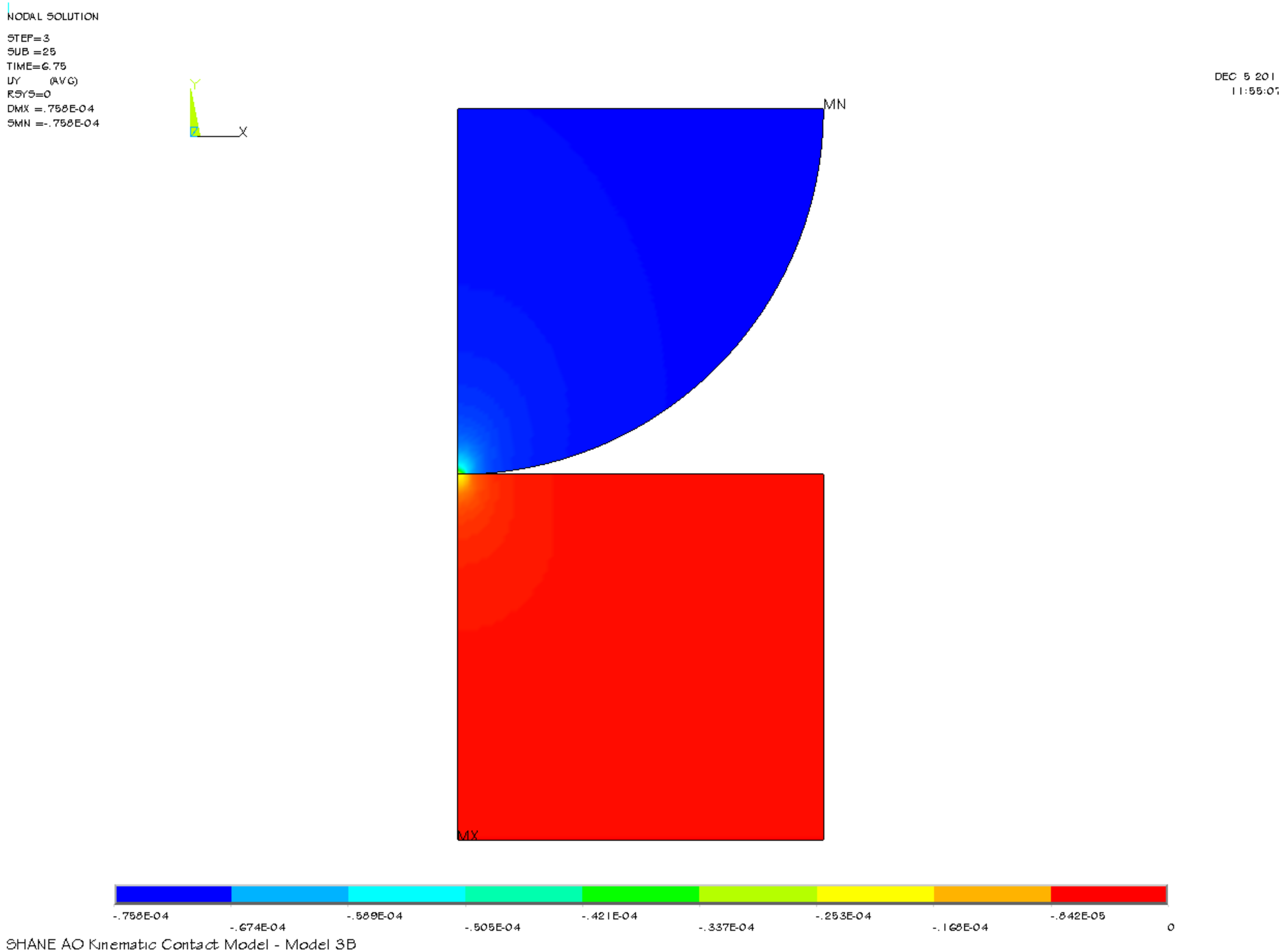
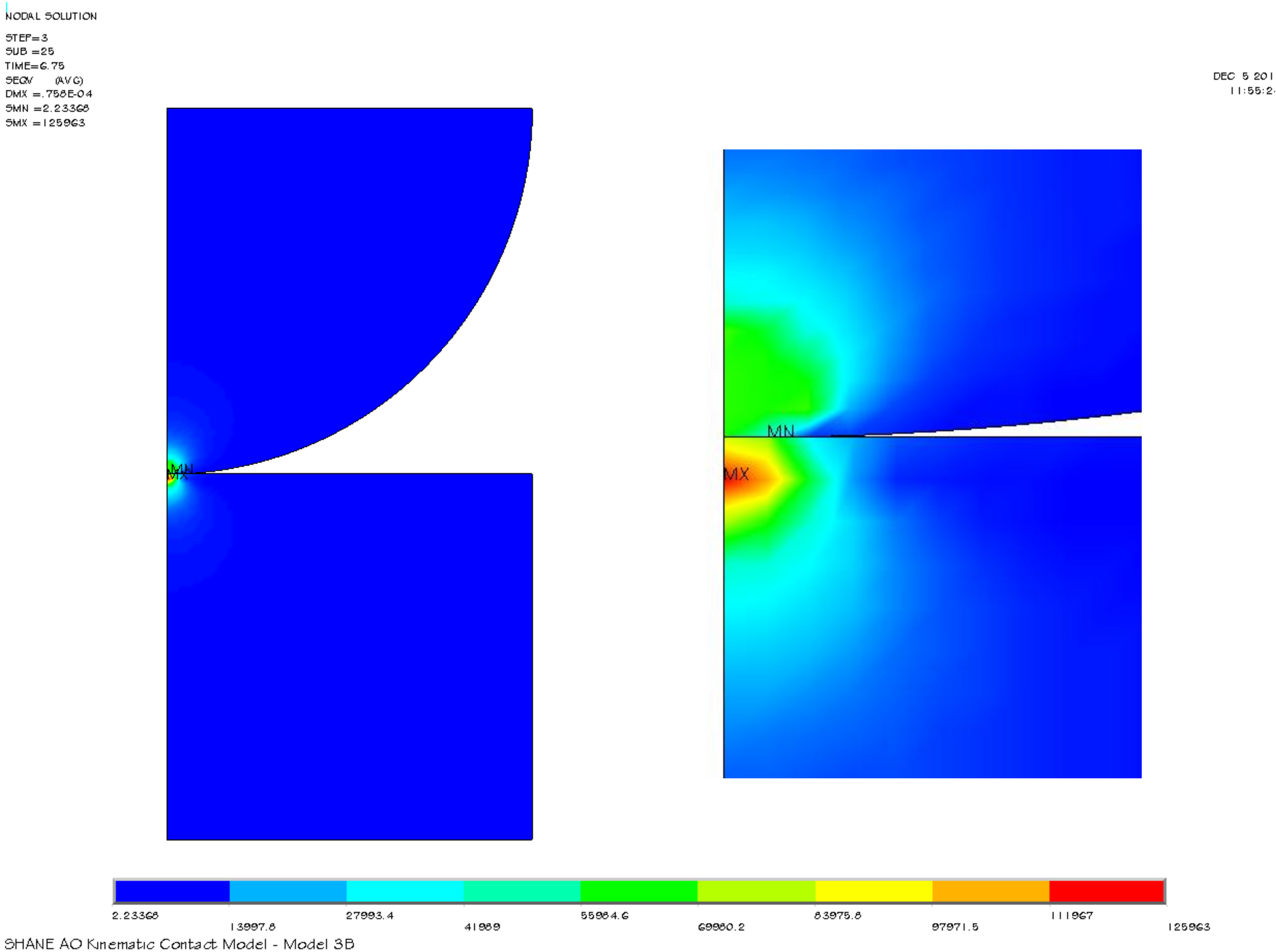


Sapphire Base – 30 N Stress



Woofer Assembly Design

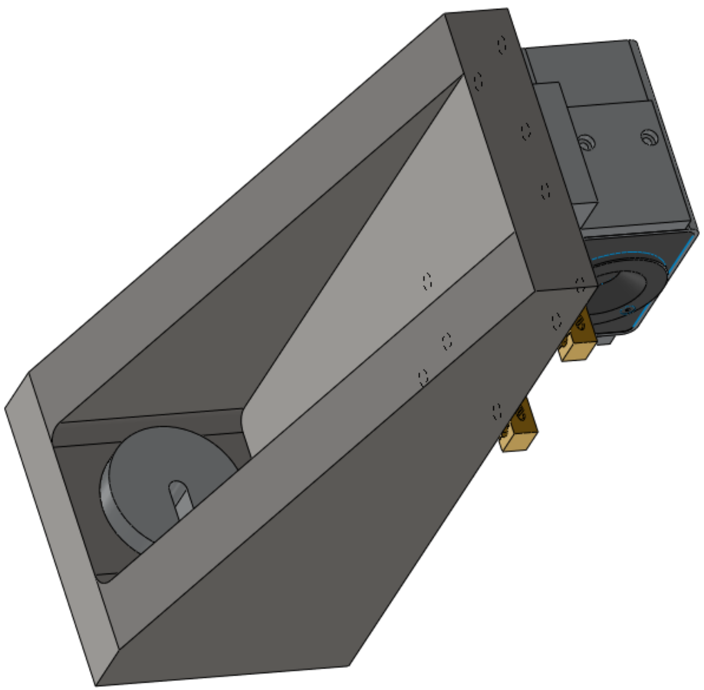
Presentation Agenda:

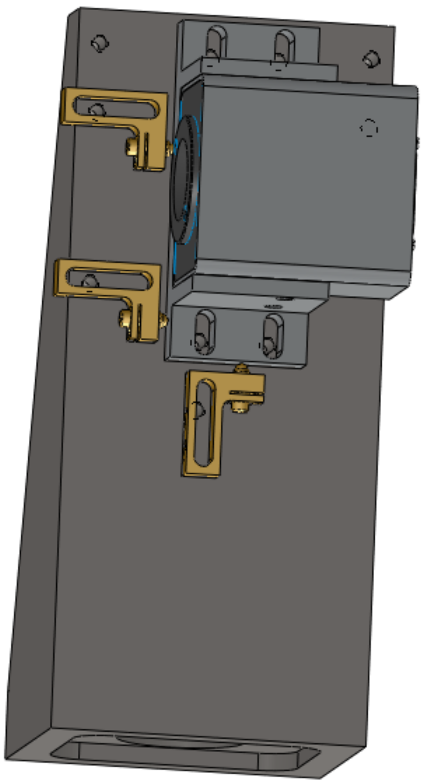
- Overview and Requirements
- Positioning resolution
- Deflection analysis: FEA
- Summary

Woofer Assembly Design

Overview/Requirements:

- •All positioning will be achieved with nudgers
    - •Need to position x, y, and z to within 10 microns of ideal
    - •Need to position to within 10 arcsec of ideal
- •Deflection Goals:
    - •Less than 1 micron displacement for any gravity vector orientation
    - •Less than 2 arcseconds angular displacement for any gravity vector orientation





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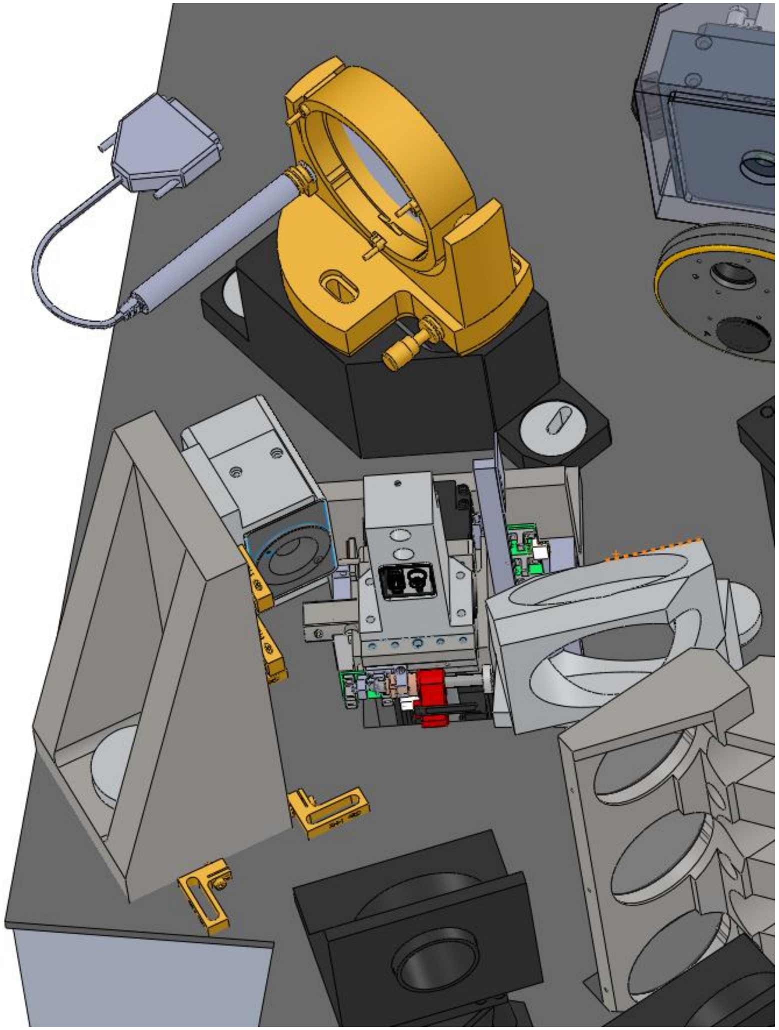
Integrated in AO assembly:



Woofer Assembly Design

Objective:

1. Assess maximum angular and linear deflection of MEMs due to 90 and 180 degree change in gravity vector

Assumptions and Conditions:

1. All parts are screwed down to each other and properly torqued
2. Gravity vector changes from telescope at horizon orientation to opposite horizon orientation
3. No base support deflection
4. Optical table does not deflect
5. Mount bracket made of 304 SS
6. Woofer mount plate is made of 6061 T6 Aluminum
7. Woofer is modeled as piece of solid 6061 with the same mass as the woofer (0.44Kg)

Woofer Assembly Design

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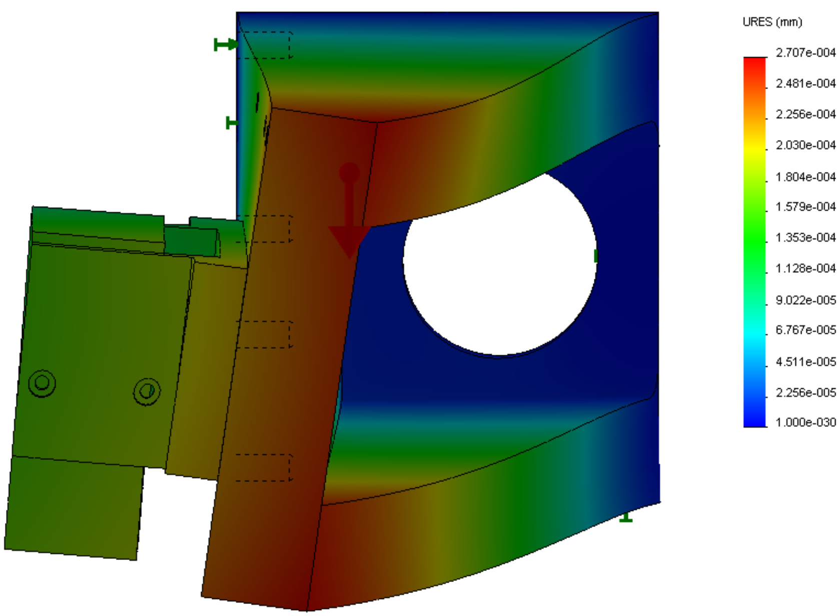
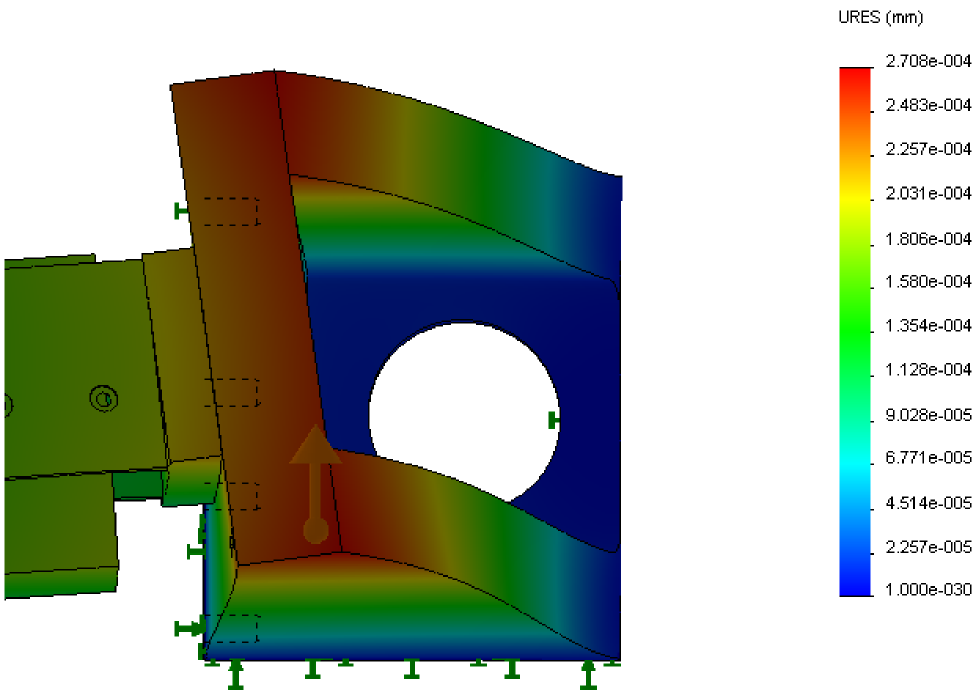
Extremes of Gravity Vector in X
DM net Linear deflection: 0.3 microns
Angular deflection: approx. 0.4 arcsec





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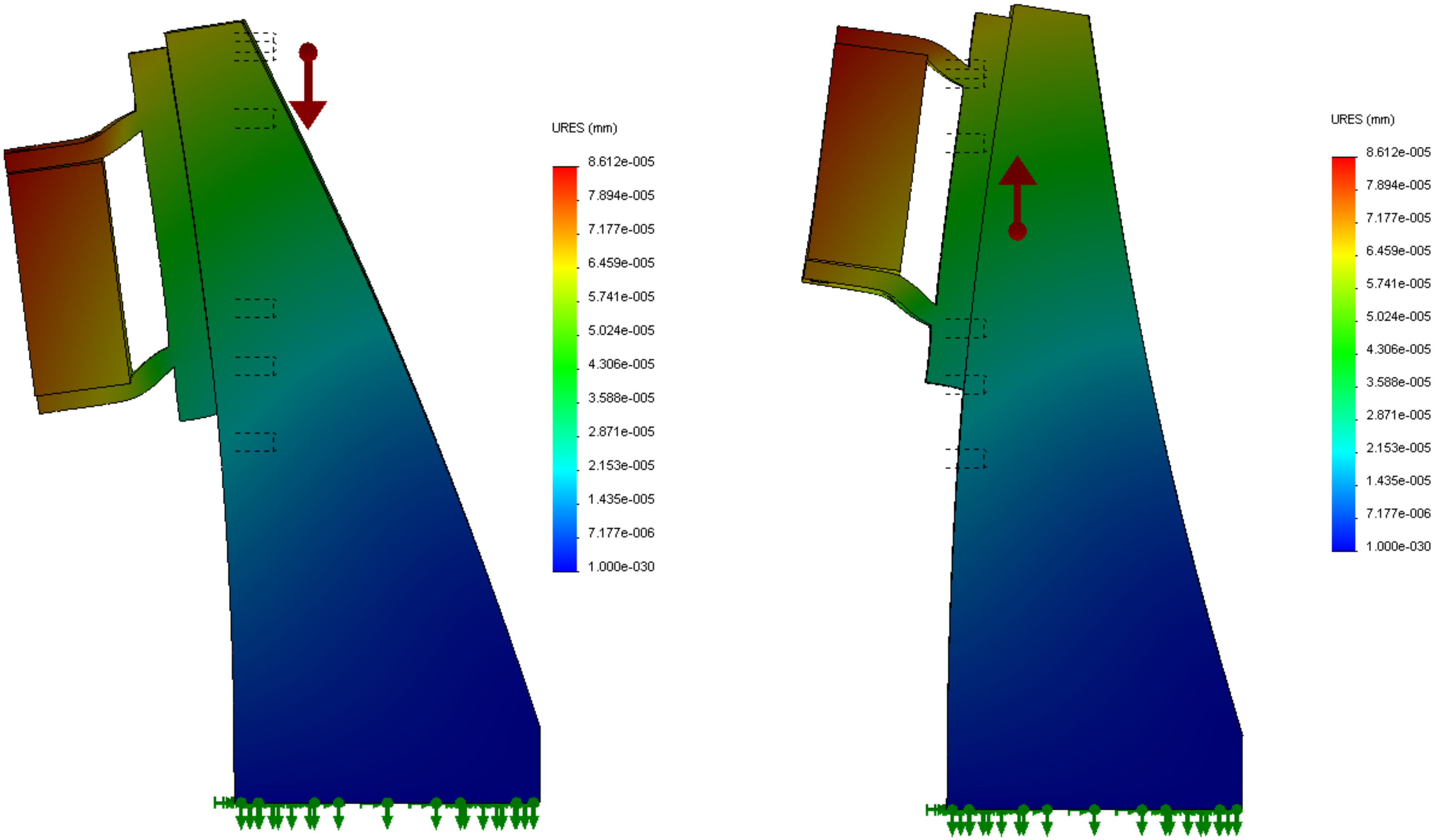
Extremes of Gravity Vector in Y
DM net Linear deflection: 0.17 microns
Angular deflection: approx. 0.2 arcsec



Woofer Assembly Design

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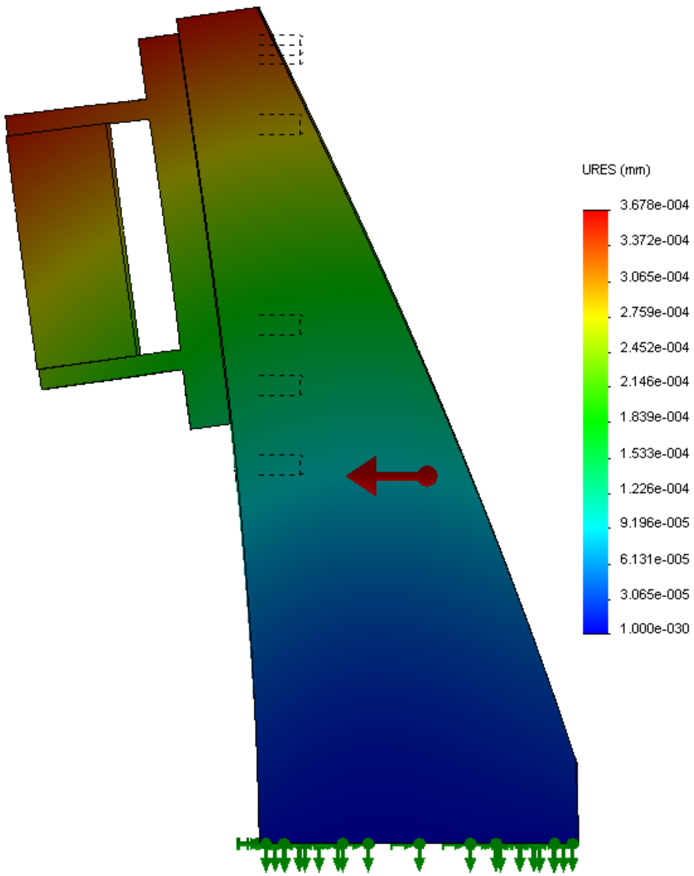
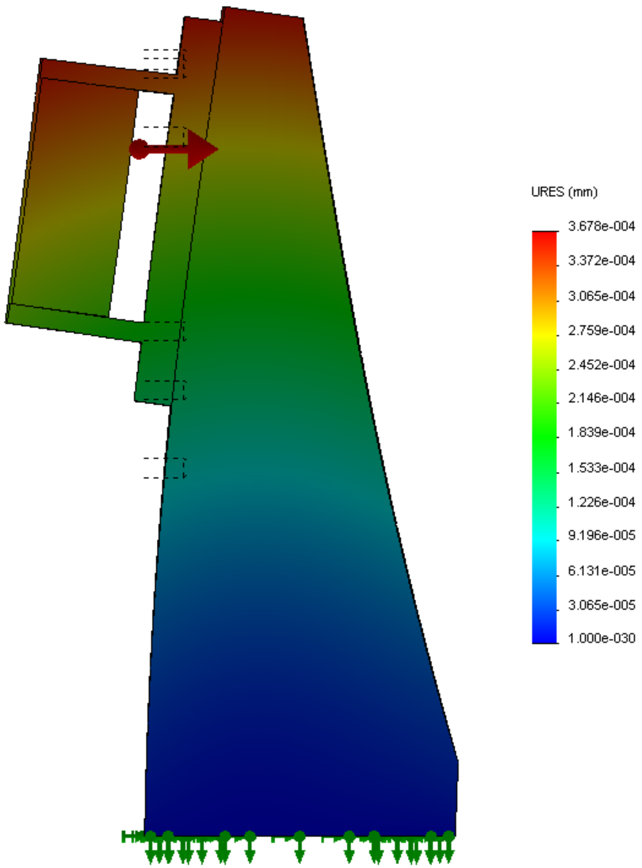
Extremes of Gravity Vector in Z
DM net Linear deflection: 0.6 microns
Angular deflection: approx. 0.72 arcsec





Woofer Assembly Design

Conclusion Remarks:

- **Nudgers need resolution down to 10 microns**
  - **Can definitely be achieved with differential micrometers and likely with 80+ tpi standard nudger screw**

- **Shim stock requirements**
  - **Will need shim stock resolution of 2.5 microns (.0001")**
  - **Can achieve using 0.0005" (silver)mylar and 0.00075" (gold)mylar**
  - **0.0005" is our thinnest size**

- **Gravitational Deflection is smaller than specified allowances**
  - **Very stable mounting bracket**
  - **Fairly easy without translation or rotation requirements**

Mechanical Design

Reviewer Q&A
and Discussion

Principal Items Remaining

- Wavefront sensor assembly placement on AO bench
- Final iteration with bench vendor
- Electronics final positioning

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Wrap-up

- 1:00 Intro
  - Charge to the reviewers
  - Top level requirements
  - Science and science camera
- 1:30 Optical design
- 2:15 Mechanical design
- 4:15 Reviewer closed session
- 4:40 Feedback