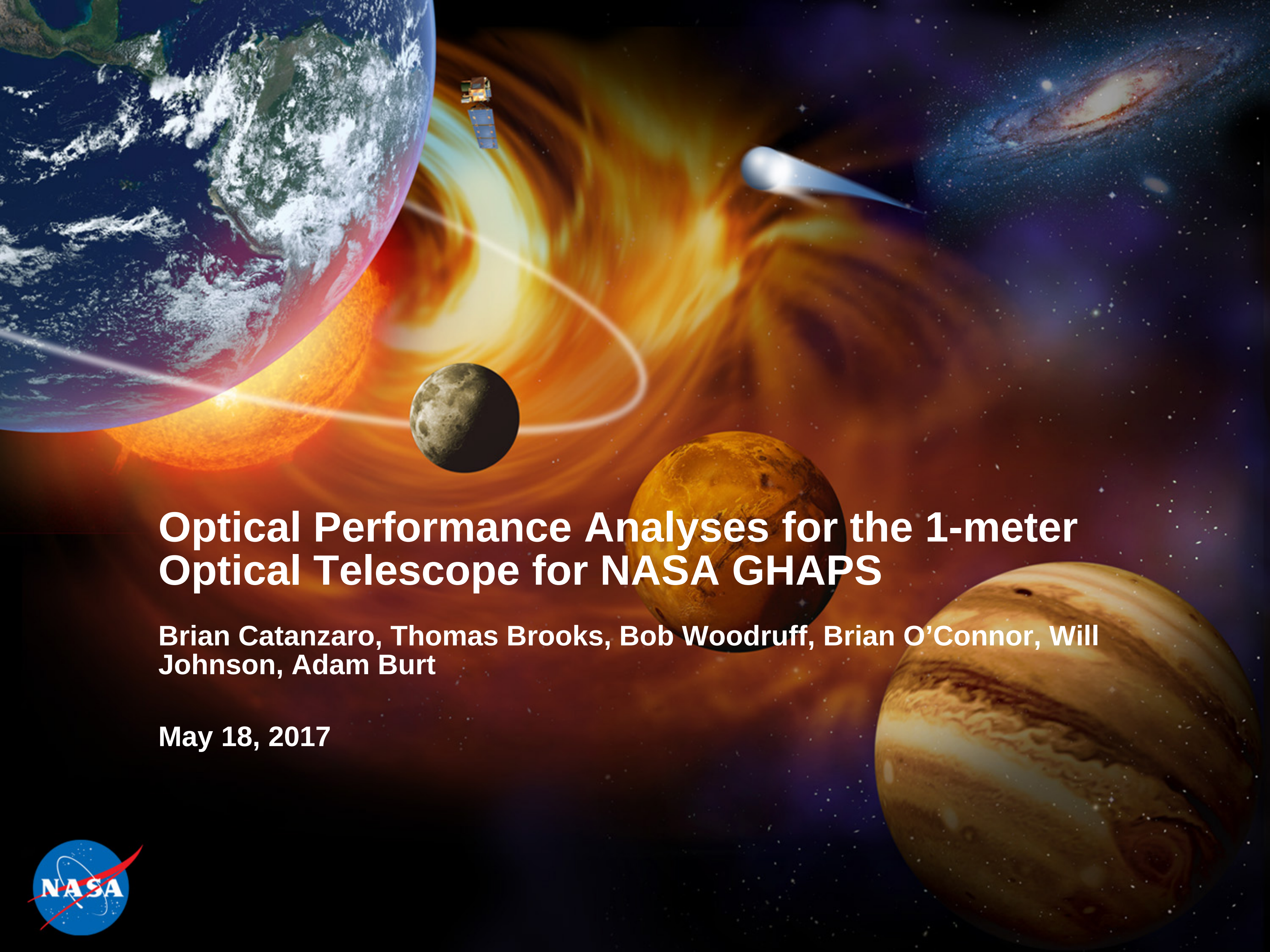


Optical Performance Analyses for the 1-meter Optical Telescope for NASA GHAPS

Brian Catanzaro, Thomas Brooks, Bob Woodruff, Brian O’Connor, Will Johnson, Adam Burt

May 18, 2017

GHAPS

Gondola for High-Altitude Planetary Science

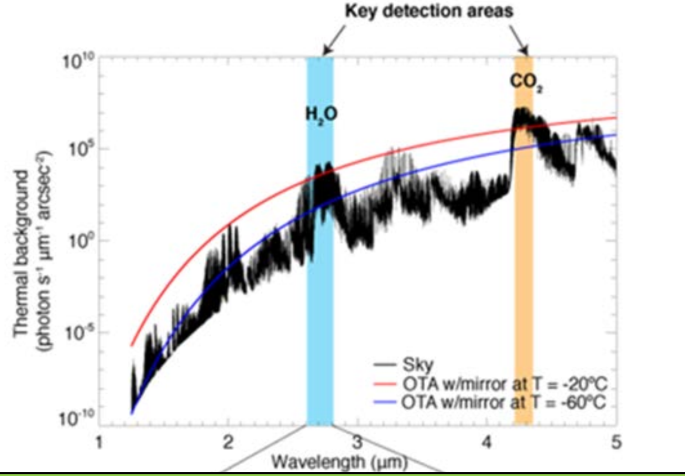
- **Definition**
  - Planetary Science Observatory
  - Stratospheric Balloon Platform
  - Shared / Competed Resource available for Exchanging Instruments
- **History**
  - Build Off of Experiences on BRRISON and BOPPS

- **GHAPS Goals**
  - Support Science Outlined in Planetary Science Decadal Survey
    - NRC 2011
  - Access to Wavelengths Inaccessible from
    - Ground-Based and Airborne Facilities
  - Observe Science of Extended Periods of Time
  - High Spatial Resolution at UV / Visible
  - High Spectral Resolution at UV to IR

GHAPS Science Capability

- **GHAPS is a first generation platform optimized for multiple long duration flights and for planetary science**
- **IR observation design supports detection of water and carbon dioxide.**
- **Long duration flights enable temporal science not practically possible any other way**
  - Study Jupiter storms, Venus clouds and super rotation, methane or water cycles on Mars or Moon, volcanic tracking, atmospheric SO2, Volatiles/organics (in comets, asteroids and Mercury), and more.
- **GHAPS is expected to evolve over time with science demands**

IR observation signal to noise



GHAPS will provide a re-usable platform for decadal class planetary science.

GHAPS Overview

GHAPS is a Class D, GLPR 7120.5.10A Silver Project

- **Develop a Re-useable Balloon Platform to meet Planetary Science Goals and Objectives as outlined in Decadal Survey**
- **1 meter Optical Telescope Assembly (OTA) with Sub-arc-second pointing capability**
- **Designed for a minimum of 5 flights from**
  Balloon Program Office (BPO) launch loca
- **Designed for mission durations up to 100**
- **Planetary Science Observations 300-5000**
- **Low cost refurbishment (1 yr) between fli**
- **The first flight is planned for Fort Sumner**
  Mexico in the fall of 2020
- **The objective of the first flight is to demo**
  performance and conduct science observ
- **A competitive process will be used to select investigators and the GHAPS Instrument Suite**

GHAPS Gondola & Payload

Solar Pointing

Balloon System

Arc - Second Pointer (WASP) (WFF)

Instruments

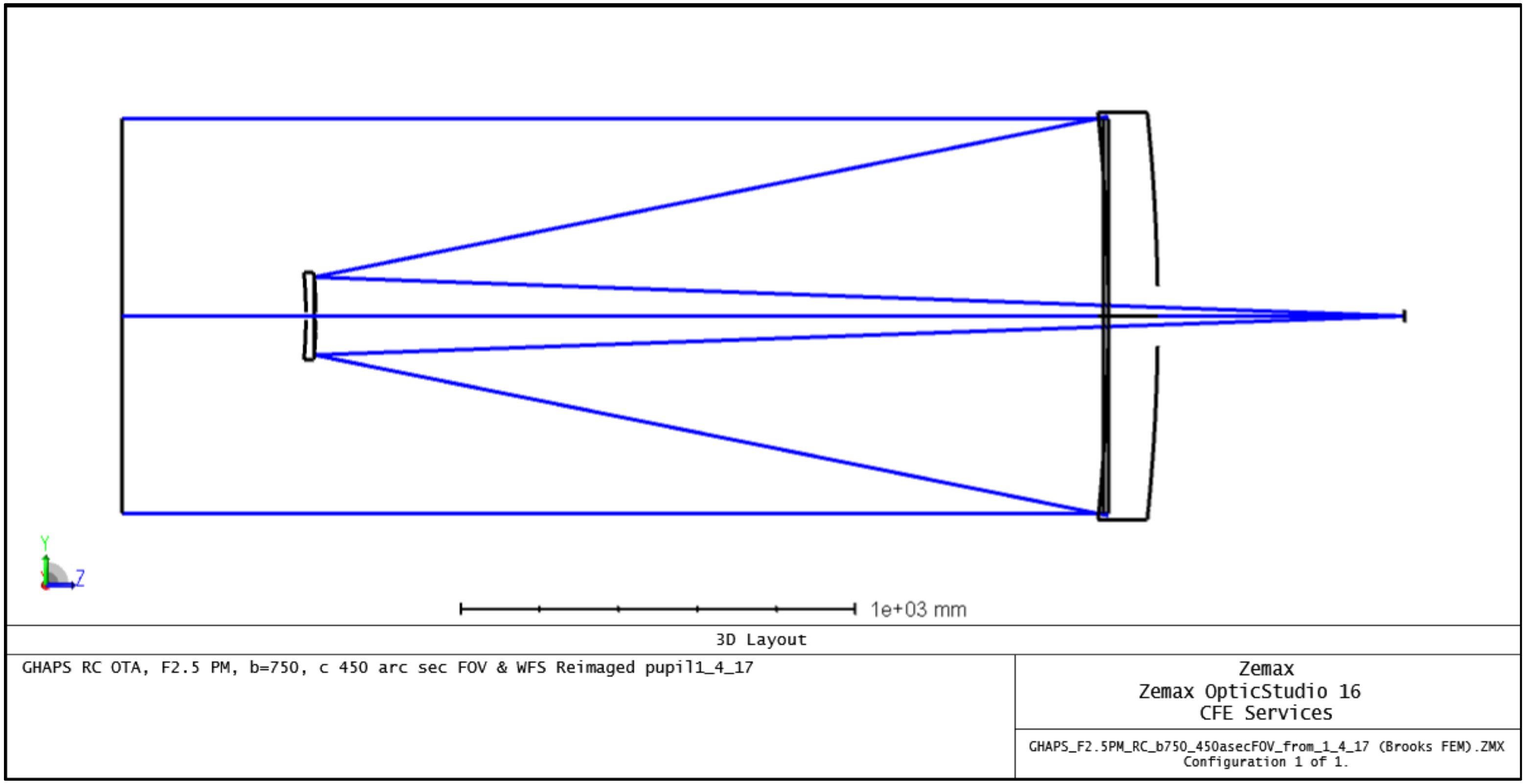
Balloon System Power (BPO)

Summary of Optical Requirements

- **Aperture: 1-m**
- **Optical Quality**
  - Strehl > 80% @ 500 nm
  - FHWM < 0.12 arc-sec = (x1) Airy Radius @ 500 nm
  - WFE > 26.6 nm RMS @ 500 nm
- **FoV: > 1 arc-min Dia. @ Diffraction Limit**
  - Total FoV > 450 arc-sec [+7.5 arc-min]
- **Pointing**
  - Pointing Bias < 1 arc-sec @ 10 min
  - Jitter < 0.062 arc-sec
- **Wavebands**
  - UV / Vis (Supported by Resolution) = 300 nm to 1000 nm
  - IR (Supported by Low Emissivity) = 1 um to 5 um

OTA Design

- **Two Mirror / Ritchey-Chretien**
  - F/14, D = 1 m, BFL = 0.75 m
- **Moveable Secondary Mirror**
  - Hexapod to Correct Aberrations on Float from Gravity / Thermal
  - Controlled by Wavefront Sensor



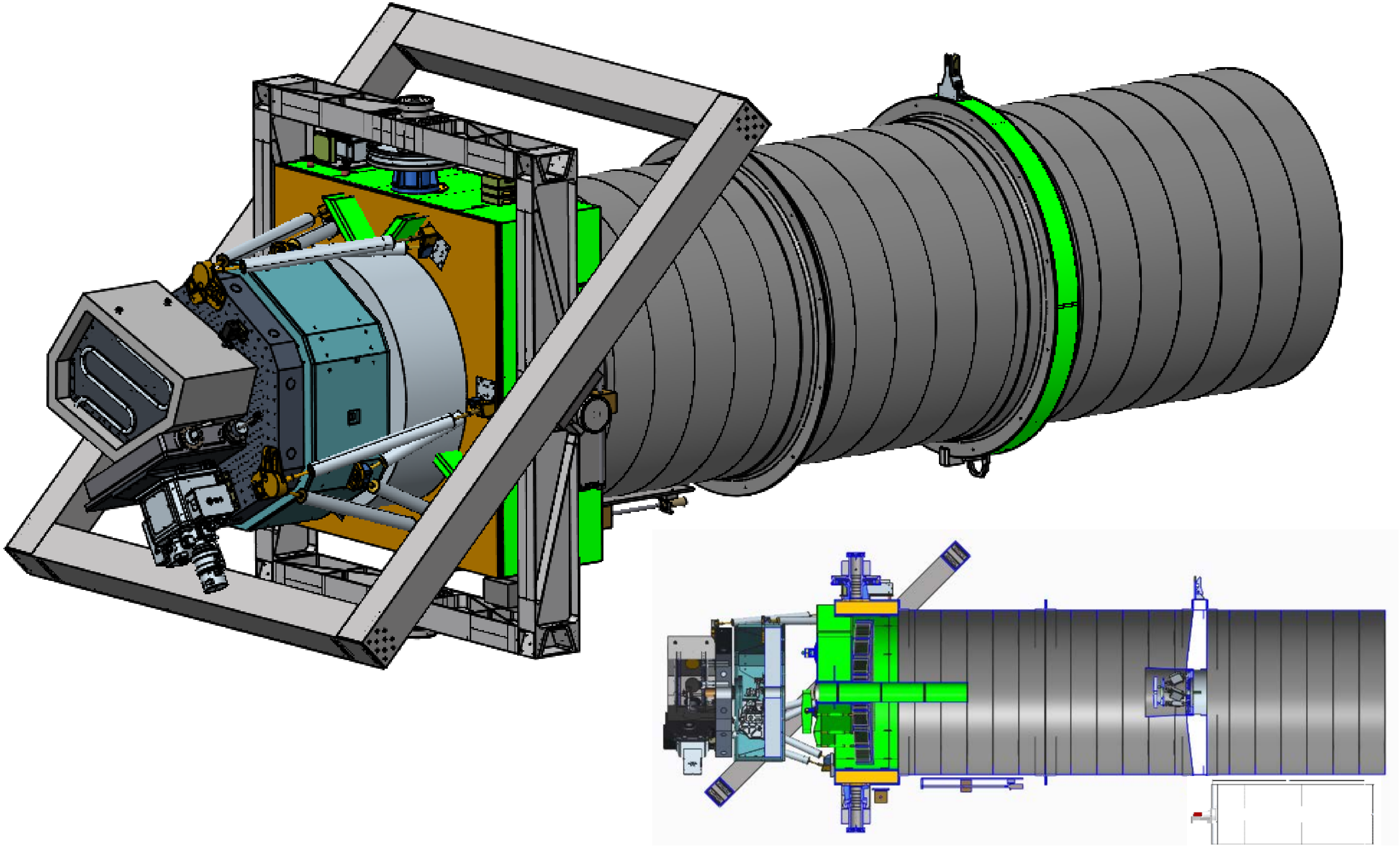
3D Layout

GHAPS RC OTA, F2.5 PM, b=750, c 450 arc sec FOV & WFS Reimaged pupil1_4_17

Zemax
Zemax OpticStudio 16
CFE Services

GHAPS_F2.5PM_RC_b750_450asecFOV_from_1_4_17 (Brooks FEM).ZMX
Configuration 1 of 1.

OTA Design



Structural, Thermal, Optical Performance

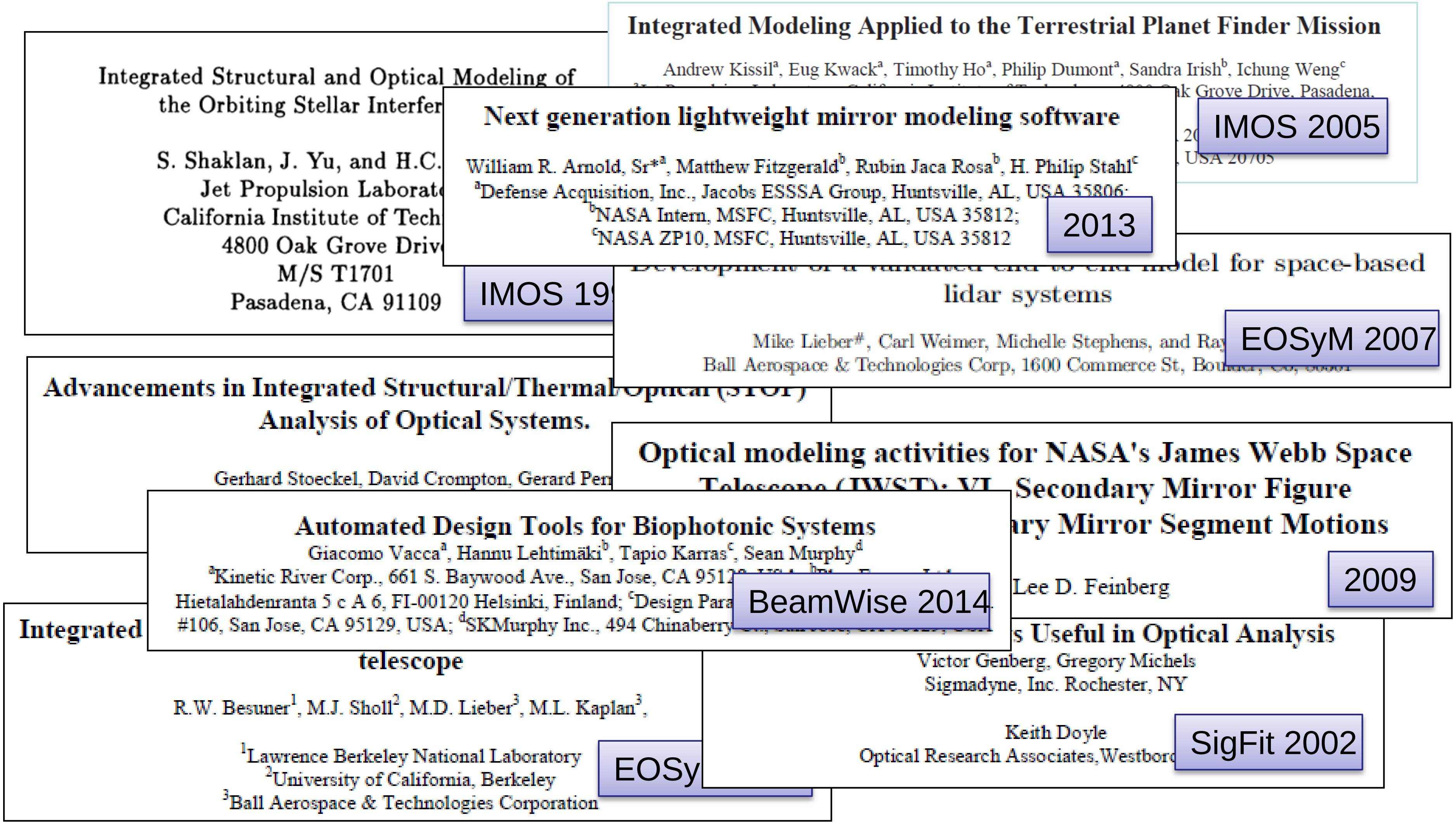
STOP ANALYSIS

STOP Analysis / Definition

- **Structural Thermal Optical Performance**
- **Optical Systems are Sensitive to Misalignment**
  - Displacements < 50 microns
  - Rotations < 5 arc-sec
- **Subtle Changes in Conditions can Impact Performance**
  - Stiffness
    - Elevation Changes in Gravity Field
    - Vibration from Instruments, Reaction Wheels, Pointing System
  - Thermo-Elastic Deformation
    - Thermal Soak / Variety of Materials, Differential CTE
    - Thermal Gradient / On-Float Environment, Solar, Earth-shine, …

How is All This Incorporated into Design and Operations?

Long, Rich Heritage in Integrated Modeling



Integrated Modeling Applied to the Terrestrial Planet Finder Mission

Andrew Kissil[a], Eug Kwack[a], Timothy Ho[a], Philip Dumont[a], Sandra Irish[b], Ichung Weng[c]
k Grove Drive, Pasadena,
, 20
USA 20705

IMOS 2005

Integrated Structural and Optical Modeling of
the Orbiting Stellar Interfer

S. Shaklan, J. Yu, and H.C.
Jet Propulsion Laborat
California Institute of Tech
4800 Oak Grove Driv
M/S T1701
Pasadena, CA 91109

IMOS 19

Next generation lightweight mirror modeling software

William R. Arnold, Sr*[a], Matthew Fitzgerald[b], Rubin Jaca Rosa[b], H. Philip Stahl[c]
[a]Defense Acquisition, Inc., Jacobs ESSSA Group, Huntsville, AL, USA 35806;
[b]NASA Intern, MSFC, Huntsville, AL, USA 35812;
[c]NASA ZP10, MSFC, Huntsville, AL, USA 35812

2013

del for space-based
lidar systems

Mike Lieber#, Carl Weimer, Michelle Stephens, and Ray
Ball Aerospace & Technologies Corp, 1600 Commerce St, Bou

EOSyM 2007

Advancements in Integrated Structural/Thermal/Optical (STOP)
Analysis of Optical Systems.

Gerhard Stoeckel, David Crompton, Gerard Per

Optical modeling activities for NASA's James Webb Space
Telescope (JWST): VI. Secondary Mirror Figure
ary Mirror Segment Motions

Lee D. Feinberg

2009

Automated Design Tools for Biophotonic Systems

Giacomo Vacca[a], Hannu Lehtimäki[b], Tapio Karras[c], Sean Murphy[d]
[a]Kinetic River Corp., 661 S. Baywood Ave., San Jose, CA 9512
Hietalahdenranta 5 c A 6, FI-00120 Helsinki, Finland; [c]Design Para
#106, San Jose, CA 95129, USA; [d]SKMurphy Inc., 494 Chinaberry

BeamWise 2014

Integrated
telescope

R.W. Besuner[1], M.J. Sholl[2], M.D. Lieber[3], M.L. Kaplan[3],

[1]Lawrence Berkeley National Laboratory
[2]University of California, Berkeley
[3]Ball Aerospace & Technologies Corporation

EOSy

s Useful in Optical Analysis

Victor Genberg, Gregory Michels
Sigmadyne, Inc. Rochester, NY

Keith Doyle
Optical Research Associates, Westbor

SigFit 2002

STOP Analysis Tools for GHAPS

Thermal Desktop

- On-Float Thermal Model
- Temperature Maps
- Unique Mesh

Nastran / Femap

- Static
  - Deflections over Elevation
  - Mirror Sag
- Dynamic
  - Modes
- Thermo-Elastic
  - Thermal Soak
    - Rigid Body
    - Mirror Deformation
  - Thermal Gradients
    - Rigid Body
- Unique Mesh

Zemax

- Model Fidelity
  - Linearization
  - Ray Trace
- Wavefront Error
  - Zernike Coefficients / WFE Map / PSF
- Line of Sight
  - Spot Diagram / Centroid

Python

- Dynamics Model
- Frequency Response Function
- Time Series Jitter

Matlab

- Extracting Data
- Combining Datasets
- Top Level Analyses

Cases Presented

- **Gravity**
  - Misalignment Due to Elevation
    - WFE / Mirror Deformation, Rigid Body Motion of Mirrors
    - LoS / Rigid Body Motion of Mirrors and Instruments
  - Polishing Conditions
  - AI/T Conditions
- **Temperature**
  - Soak
    - Rigid Body Motion
    - WFE / CTE non-uniformity in Primary Mirror Substrate
- **Dynamics**
  - Lessons from Integrated Model (FRF)
  - WASP Disturbances / LoS

Wavefront Error

- **Several “Offsets” or Re-Calibration Points**
  - Wavefront can be Nulled When Re-aligned with M2
  - Wavefront can be Polished Into Orientation when M1 is Built
- **Wavefront Error Linearity and Separability**
  - WFE is Small
  - Approximation of Linearity Checked for this Design
    - Aberrations can be (Almost) Arbtrarily Added (Subtracted)
    - Not Necessarily RSS’d
    - Misalignment, Thermal Soak, Gradient, Re-Calibration
  - WFE Conveniently Separated
    - Tip / Tilt: Line of Sight which is Calibrated
    - Focus / Coma: Aberrations Removed by M2 Alignment
    - Low Order (remaining) Zernikes (up to 36)
    - High Order Residuals (fine features)

Gravity

- **Balancing Stiffness**
  - Goal in Design
  - Mirrors will Move… They Must Move Together!
- **Impact on Operation over Elevation**
  - Does Mirror Deformation Affect WFE?
  - How Much Does Rigid Body Motion Affect
    - WFE? LoS?
  - How Often Would M2 Need to Be Adjusted
- **Impact on Primary Mirror Testing**
  - Why Polish M1 Facing Up? Sideways? At ?? Degrees?

Computational Process wo/Zemax

Collect Nodes from Each Load Case

- Individually for Each Mirror
- Individually for Each Load Case

Fit Rigid Body Movement

- Translation
- Rotation

Compute Zernike Coefficients

- Use Linearization and Sensitivities

Compute Aberrated WFE

Compute RMS WFE

Computational Process w/Zemax

Collect Nodes from Each Load Case

- Individually for Each Mirror
- Individually for Each Load Case

Fit Rigid Body Movement

- Translation
- Rotation

Displace / Rotate Model

- Use Matlab + Zemax ZOS-API

Retrieve Zernikes

Compute RMS WFE

Linearization / Matlab, Zemax
FEA / Nastran, FEMAP
Rigid Body Analysis / Nastran, Matlab
Full WFE Analysis / Matlab, Zemax

DETAILS

How Sensitive is the Optical Performance to Motion?

Taylor Series / Partial Derivatives / Jacobian

LINEAR SENSITIVITY MODEL

Mathematical Model

- **Same Concept as a Taylor Series**
  - Perturb the Model with Each DoF
  - Record the Variation in the WFE
  - Ignore Cross Terms

$$W = \sum_{i=1}^{36} C_i \times Z_i(x, y)$$

← Zernike Expansion

$$C_i\left(\delta x, \delta y, \delta z; \delta\theta_x, \delta\theta_y \delta\theta_z\right) \approx \delta x \times \frac{\partial C_i}{\partial x} + \delta y \times \frac{\partial C_i}{\partial y} + \cdots$$

← Taylor Series

$$\delta u \times \partial v \times \frac{\partial^2 C_i}{\partial u \partial v} \ll \delta u \times \frac{\partial C_i}{\partial u}$$

← Ignore Higher Order Terms

Jacobian Matrix Model:
C is a Dependent Variable Vector (F)
DoF's are Independent Variable Vectors (x)

$$J = \begin{bmatrix} \frac{\partial F_1}{\partial x_1} & \cdots & \frac{\partial F_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial F_m}{\partial x_1} & \cdots & \frac{\partial F_m}{\partial x_n} \end{bmatrix}.$$

Extract Values from Zemax Model

- Use Matlab to Interrogate Optical Model
- Perturb a Degree of Freedom (DoF)
- Collect Zernike Coefficients
- Map Coefficients to WFE
- Record RMS vs. DoF

Degrees of Freedom for Sensitivities

M2 Despace

- Move M2 along the Optical Axis

M2 Translation

- Move Along X Axis
- Move Along Y Axis

M2 Rotation

- Rotate About X Axis
- Rotate About Y Axis

M1 Translation

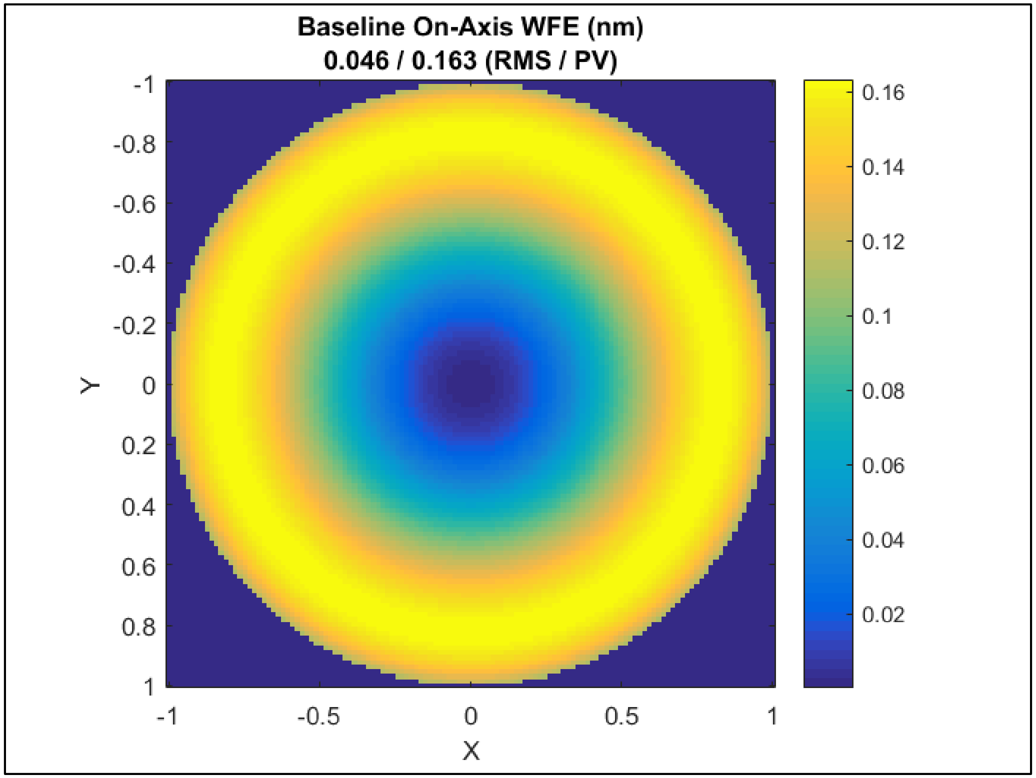
- Move Along X Axis
- Move Along Y Axis

M1 Rotation

- Rotate About X Axis
- Rotate About Y Axis

1. All Results are in Coordinate System of Optical Model
2. All Results Appear Linear over the Range of Interest
3. Cross Terms were <u>Not</u> Evaluated
4. Zernikes are *Not* Orthogonal Over Annulus…Ignored this for Now

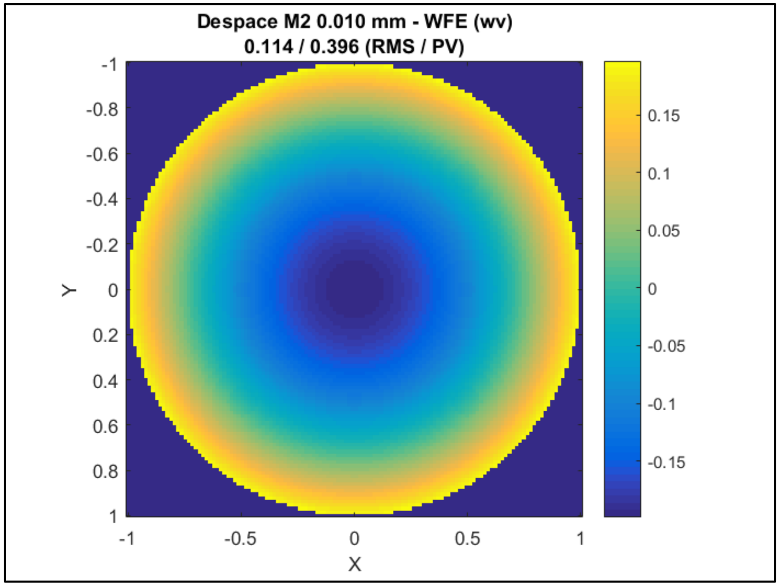
On-Axis Performance

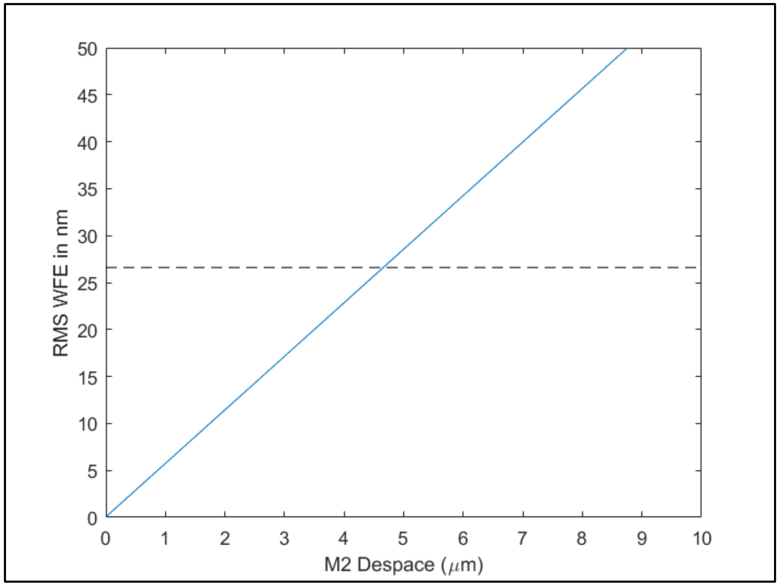


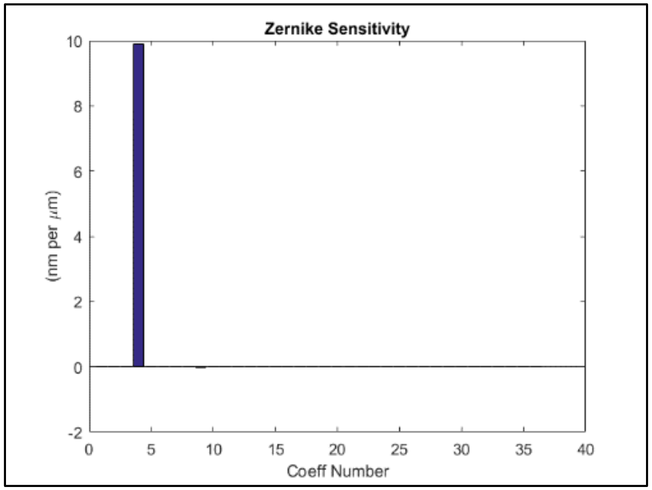
- **Collect Zernikes**
- **Map WFE Over the “Unit Circle”**
  - Unit Circle: Normalized to Radius = 1 at Edge of Pupil
  - Ignore Central Obscuration for Now…

Despace: Moving M2 Along Z

- **Range: 0 to 10 um**

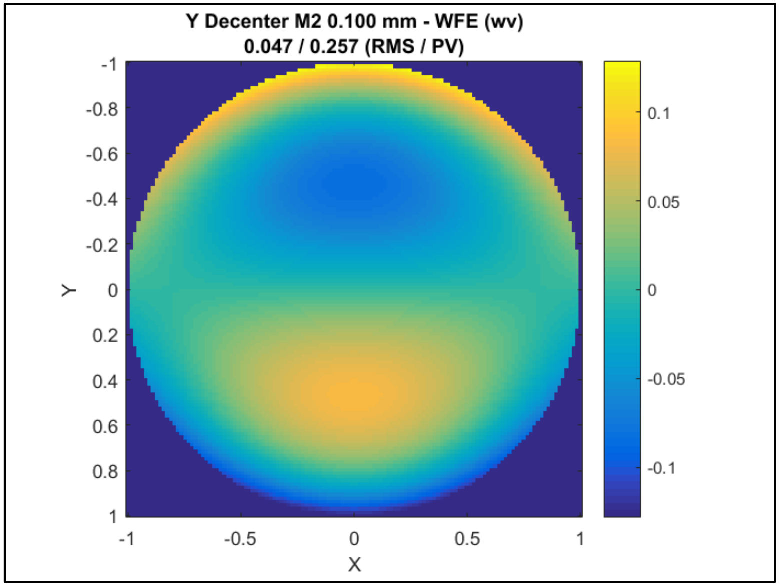


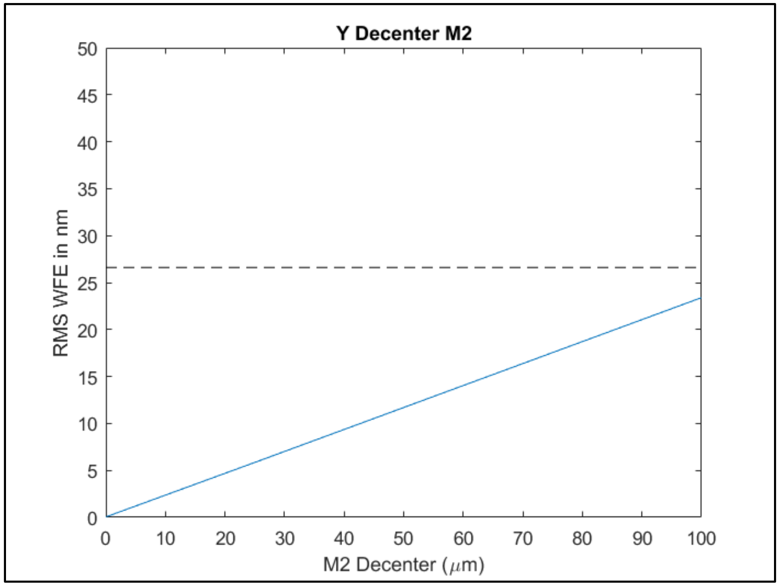


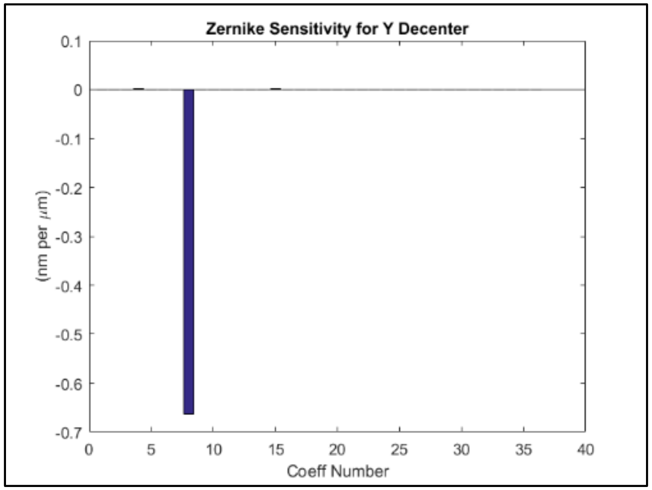


Decenter: Moving M2 Along Y

- **Range: 0 to 100 um**

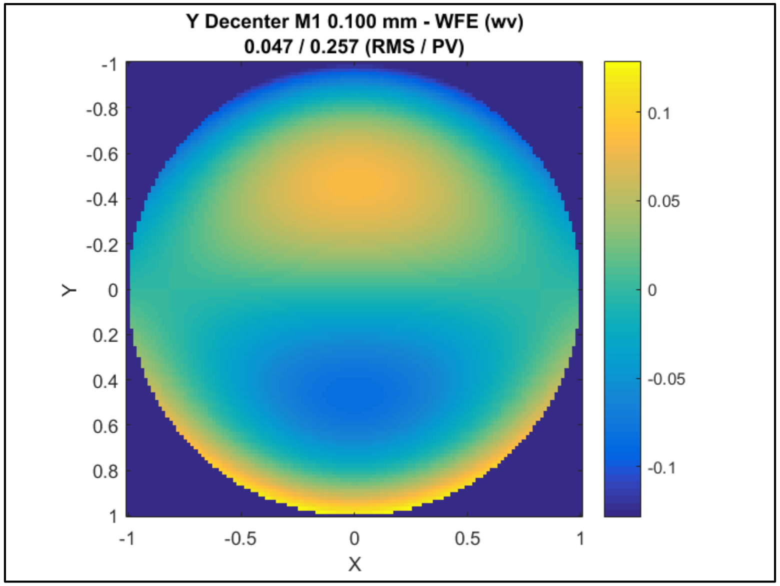


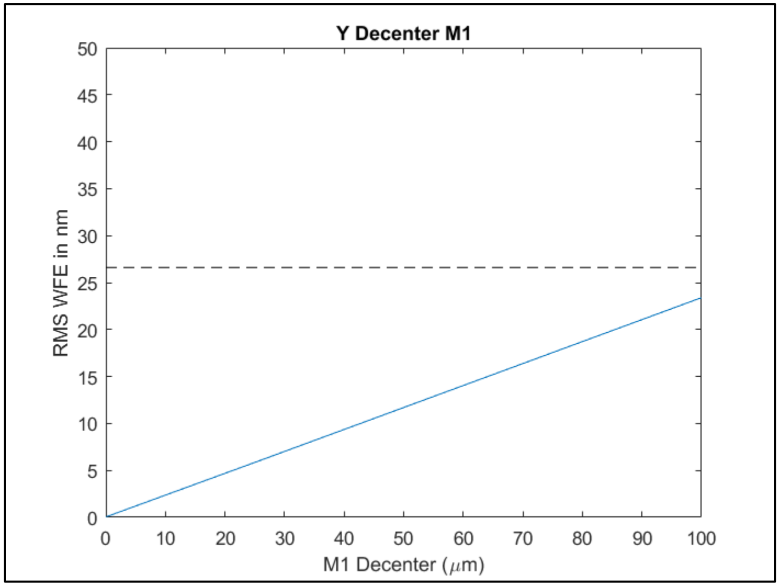


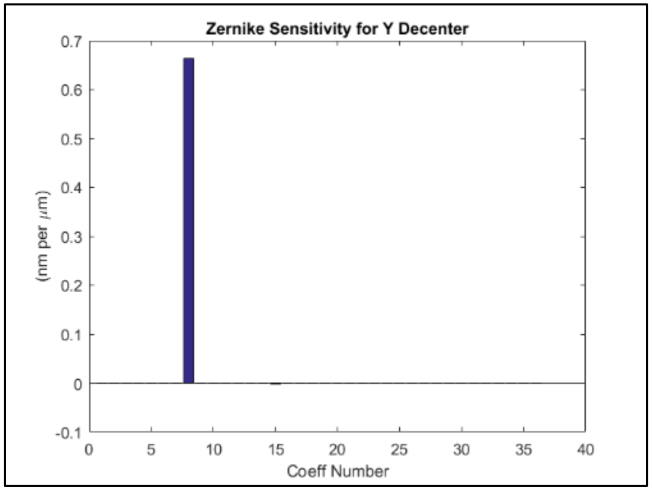


Decenter: Moving M1 Along Y

- **Range: 0 to 100 um**







Line of Sight

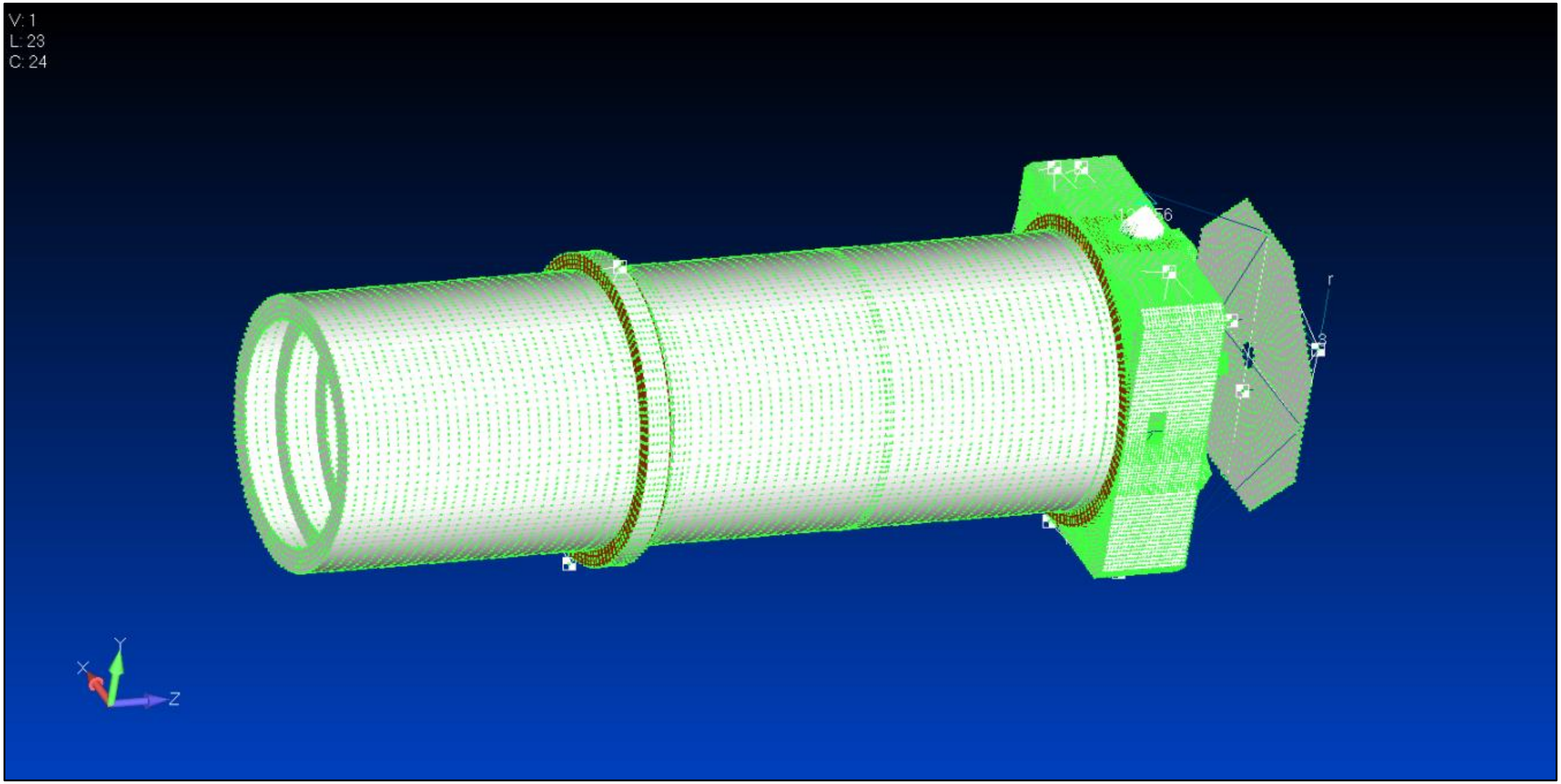
- **Add Feature to Zemax Model**
  - Coordinate Break to Represent Instrument Deck
- **Rigid Body Motion of the Instrument Deck**
  - Translates Around Center of Deck
  - Rotates Around Center of Deck
- **Follow Spot After Instrument Deck**
  - Spot Location vs. Elevation

$$\boxed{\vec{\theta}(\theta_{elev}) \equiv \begin{pmatrix} \theta_x(\theta_{elev}) \\ \theta_x(\theta_{elev}) \end{pmatrix} \approx \begin{pmatrix} x(\theta_{elev}) \\ y(\theta_{elev}) \end{pmatrix} \times \frac{1}{f}}$$

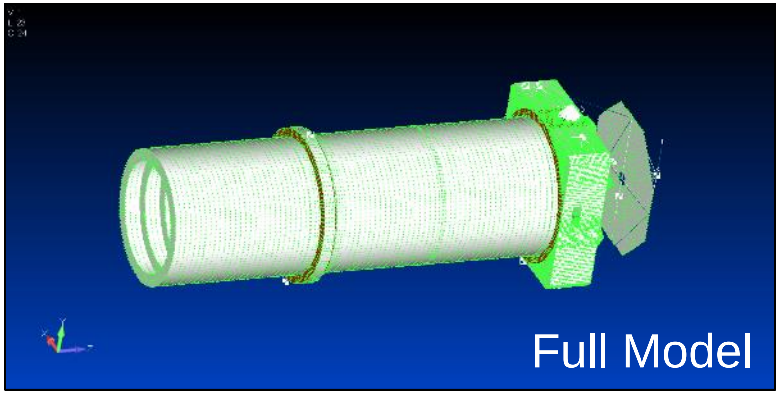
Nastran Linear Model

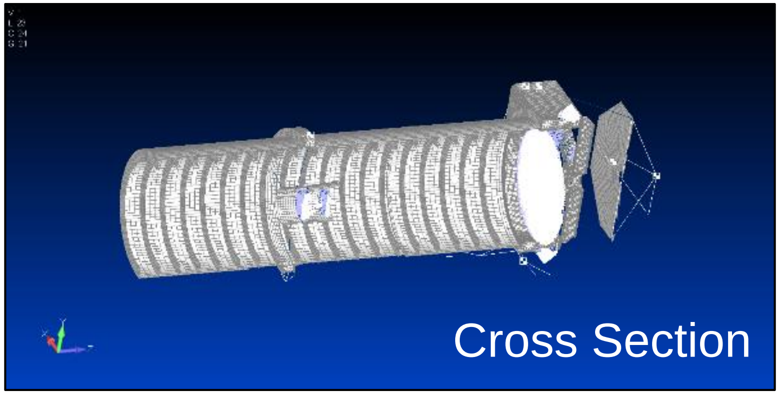
STRUCTURAL MODEL

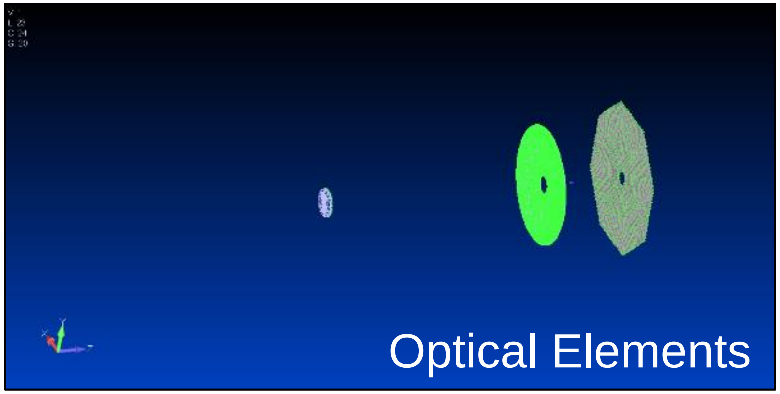
Model Viewed in Femap

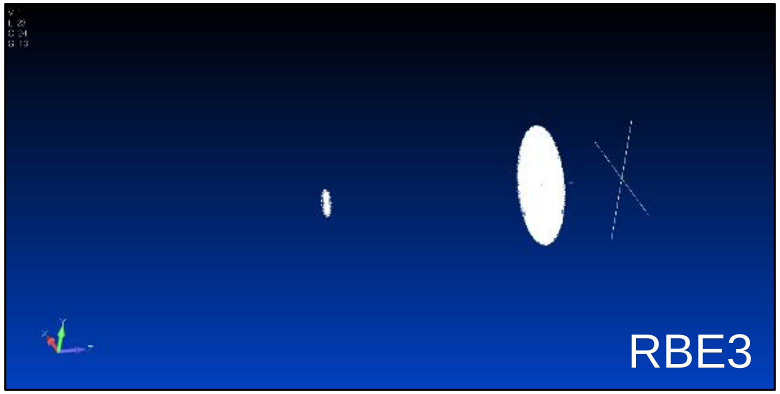


FEM Views


Full Model


Cross Section


Optical Elements


RBE3

Combining Load Sets

- **FEA without Load = 0-G (in space!?)**
  - Performance over Elevation = Difference Between Various Load Cases
- **Load Cases**
  - Horizon (θ_{Elev} = 0), Zenith (θ_{Elev} = 90)
  - Various Elevations: θ_{Elev} = {15, 30, 37, 45, 65}
- **Interpretation**
  - Assume Telescope is Aligned at Horizon
  - Assume Model is Linear
  - Deformation is Relative to the Horizon (1G-Y) Load Case

$$\boxed{\left\{u_{deformed}\right\} = \left\{u_{node}\right\} + \left\{\delta u_{load}\right\}}$$

$$\boxed{\left\{u_{Zenith}\right\} = \left\{u_{1G-Z}\right\} - \left\{u_{1G-Y}\right\}}$$ Relative to Horizon Load Case

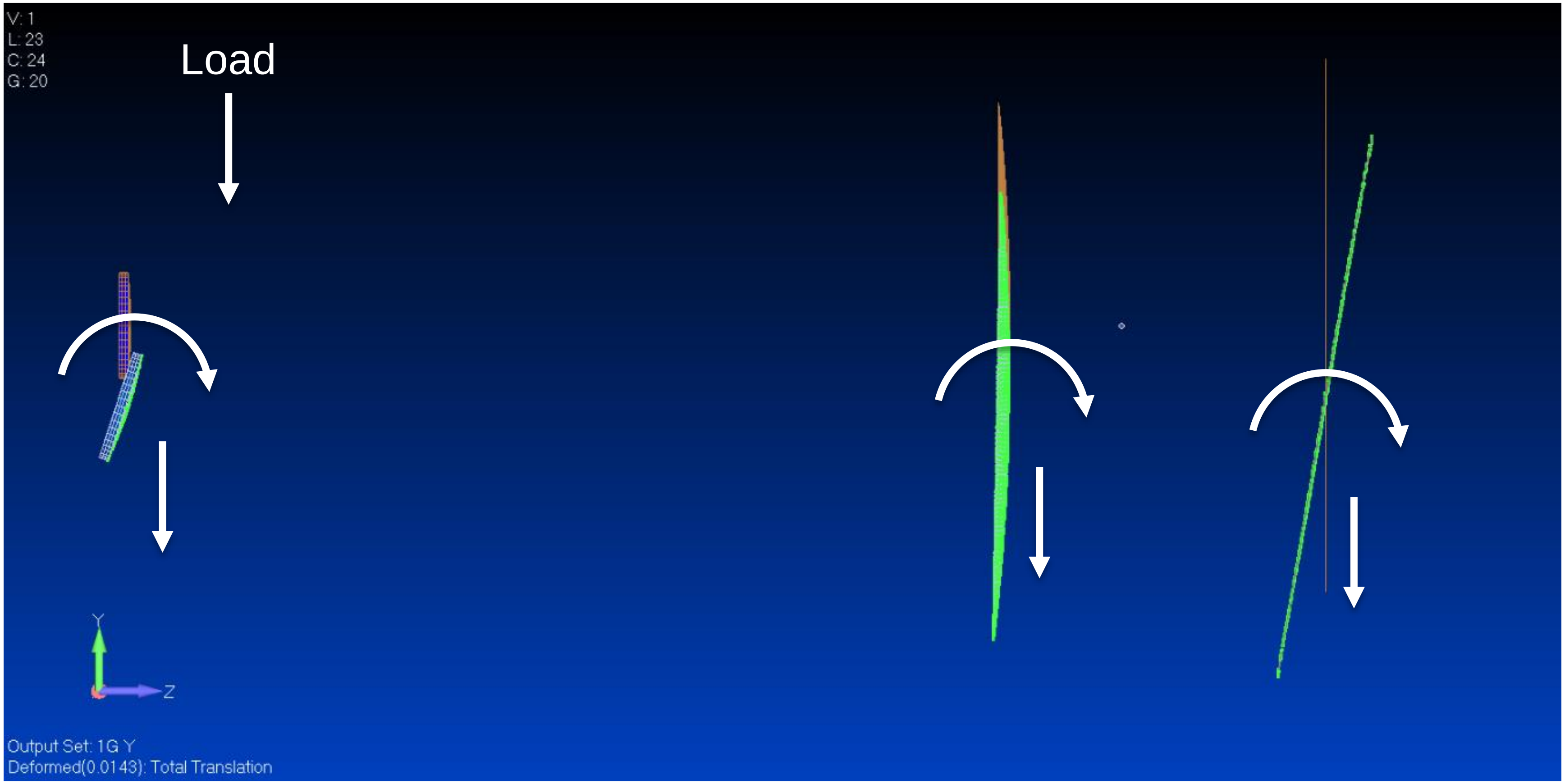
$$\boxed{\left\{u(\theta_{elev})\right\} = \left\{u\left(\vec{F}(\theta_{elev})\right)\right\} - \left\{u\left(\vec{F}(\theta_{elev} = 0)\right)\right\}}$$

Rigid Body Motion

STRUCTURAL MODEL

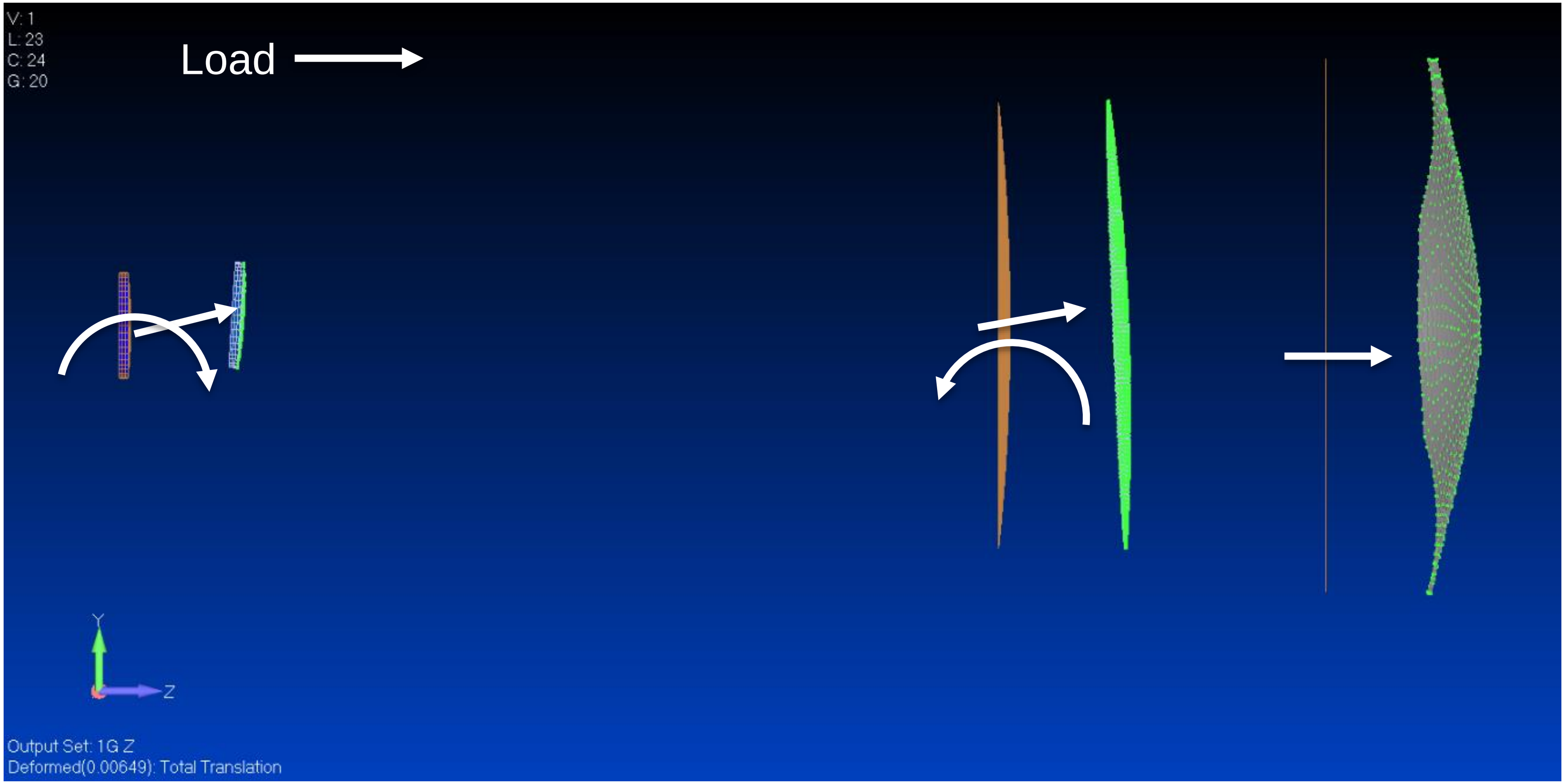
Pointing At Horizon

- **Deformation from 0-G**



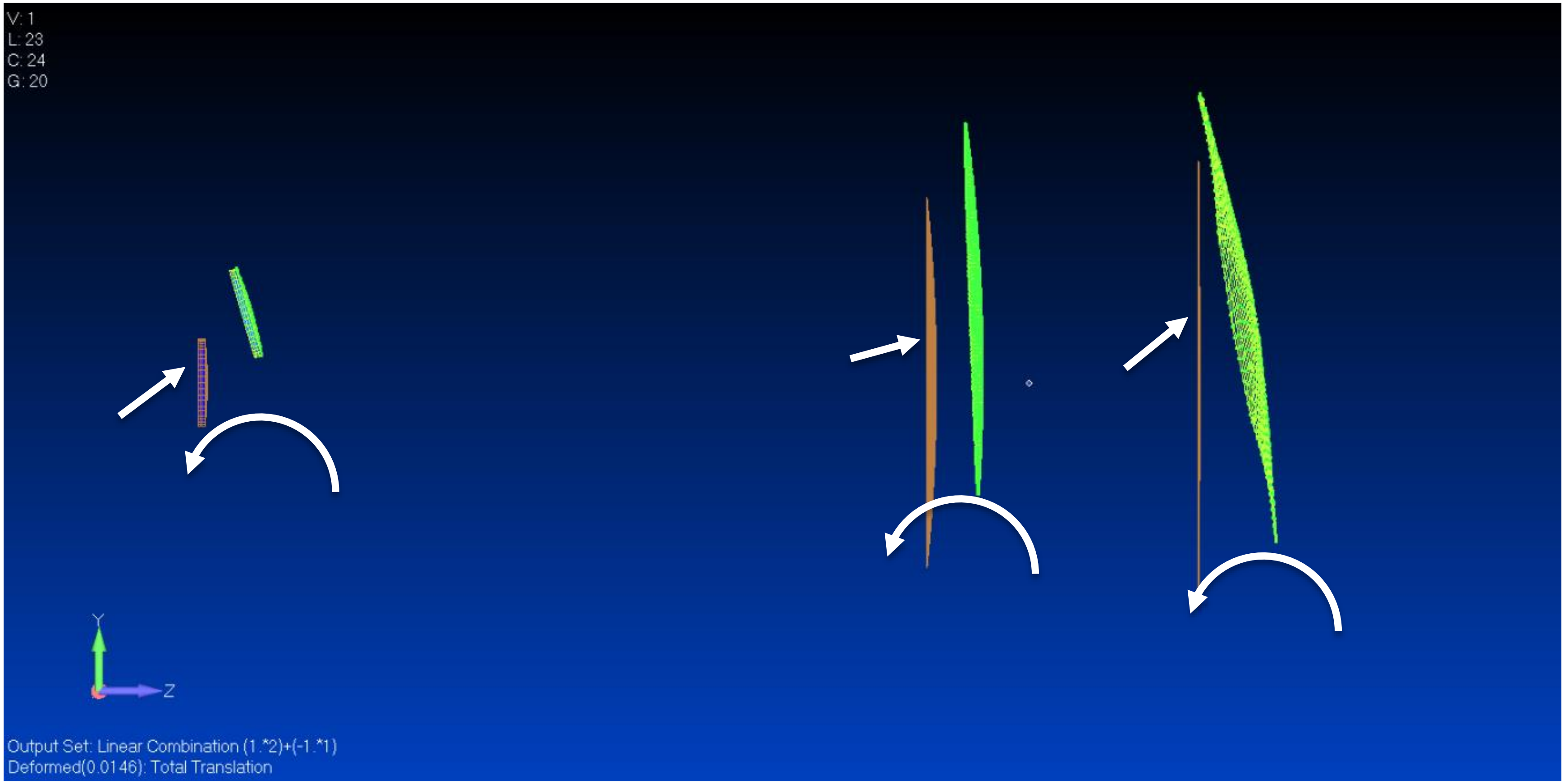
Pointing At Zenith

- **Deformation from 0-G**



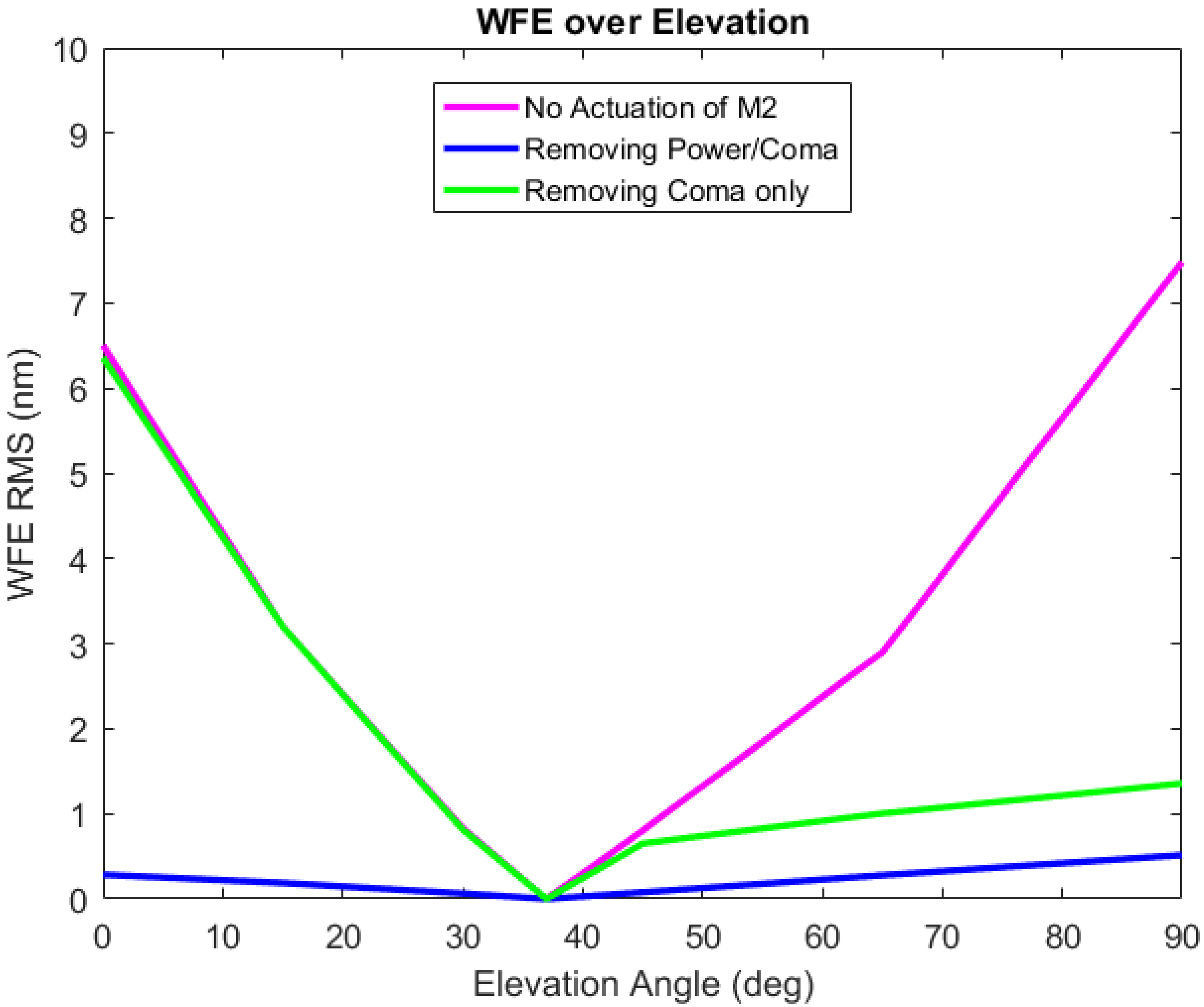
What Does the Difference Look Like?

- **Deformation at Zenith Relative to Horizon**



Output Set: Linear Combination (1.*2)+(-1.*1)
Deformed(0.0146): Total Translation

WFE over Elevation (Aligned at 37 deg)



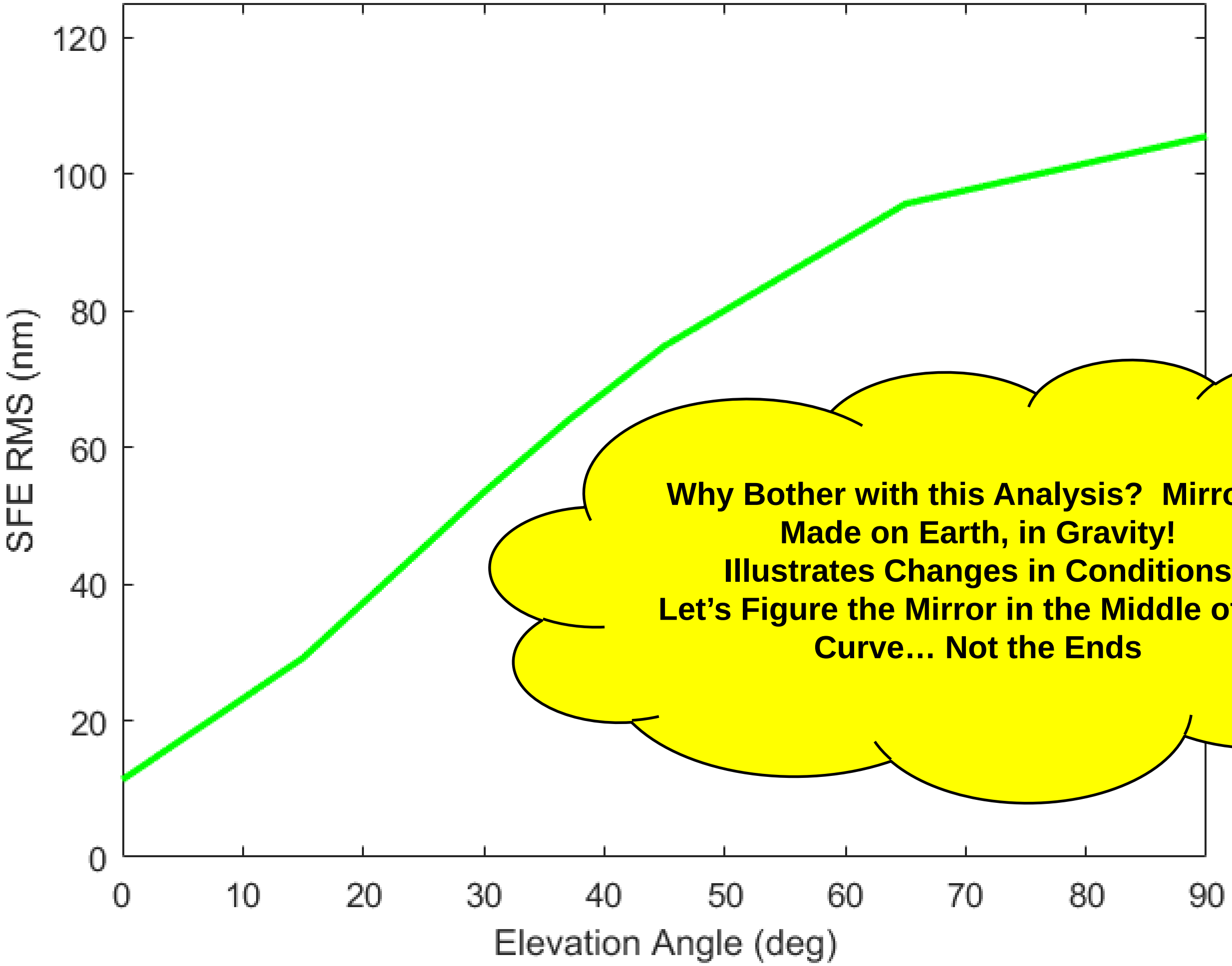
Primary Mirror Deformation

STRUCTURAL MODEL

Mirrors are Not Infinitely Stiff

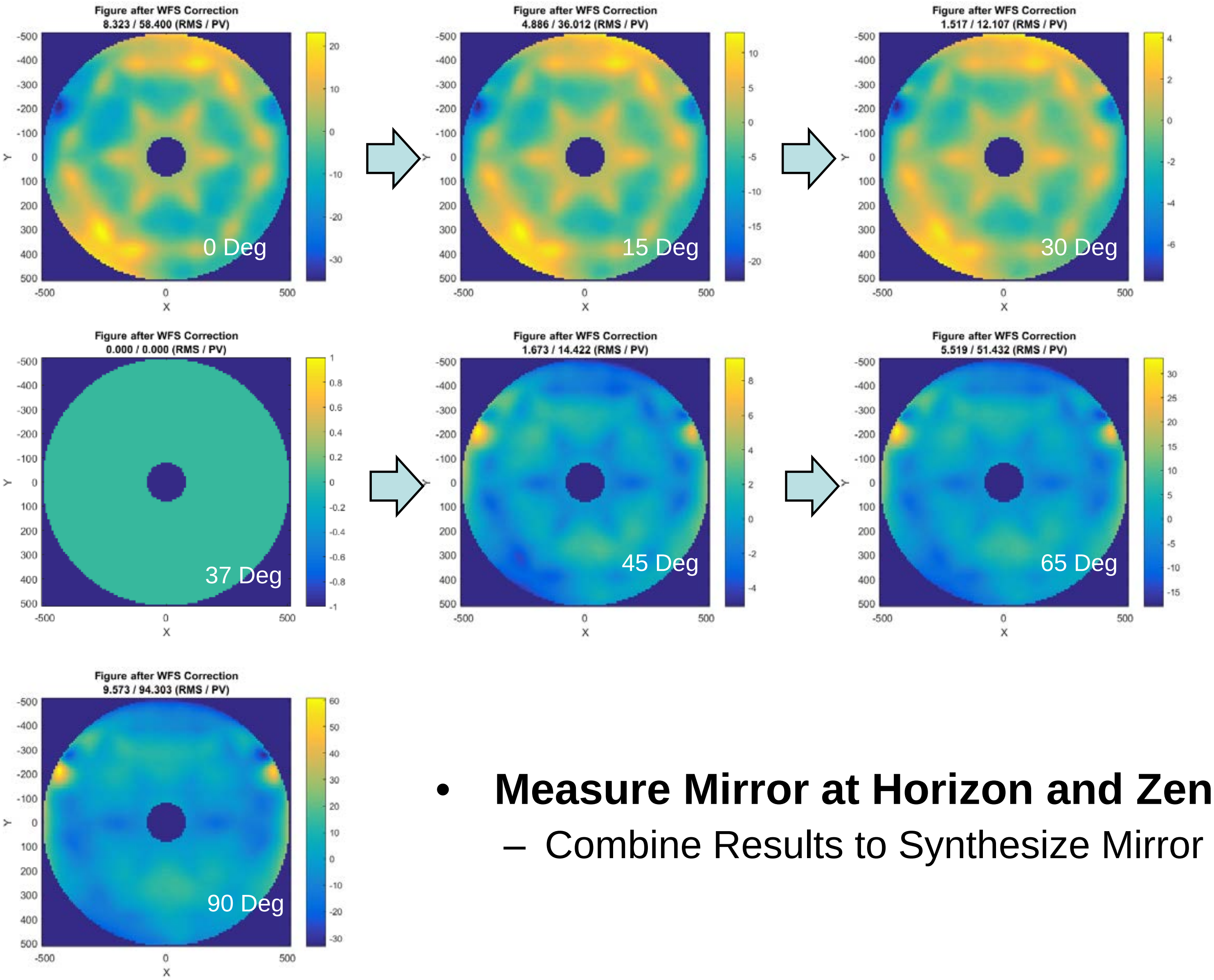
- **Solid Mirrors Deflect when Elevation Angle Changes**
  - So Do Lightweight Mirrors
- **Key Questions**
  - Does the Change Over All Elevations Meet Budget?
  - Can Mirror be Figured (Polished) with a “Bias” to Ensure Budget is Met at the Extremes?

Surface Figure Error if Made in 0-G



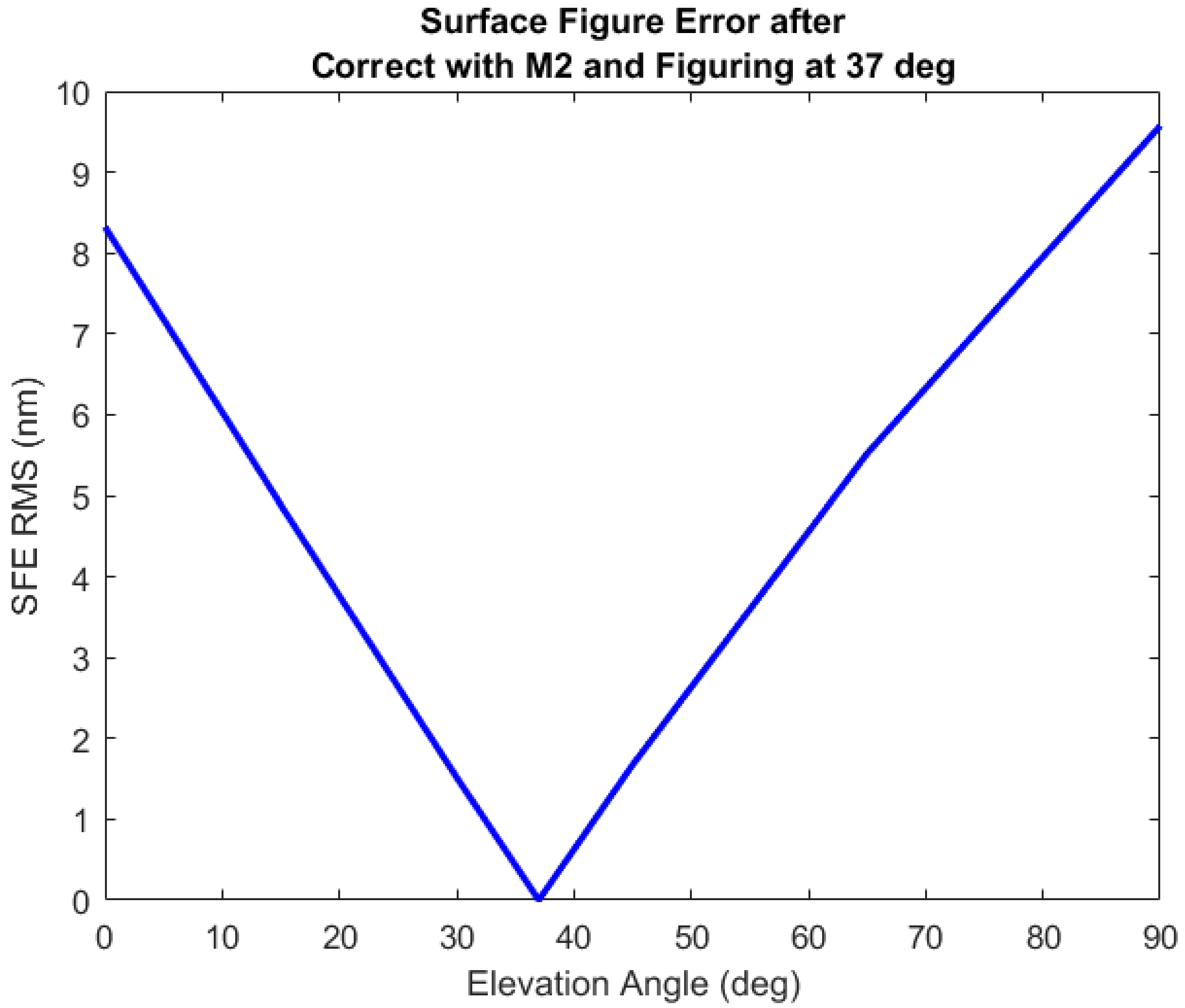
Why Bother with this Analysis? Mirror is Made on Earth, in Gravity!
Illustrates Changes in Conditions
Let’s Figure the Mirror in the Middle of the Curve… Not the Ends

Mirror Figured at 37 Deg



- **Measure Mirror at Horizon and Zenith**
  - Combine Results to Synthesize Mirror at 37 Deg

Surface Figure Error – Meets Budget Allocation

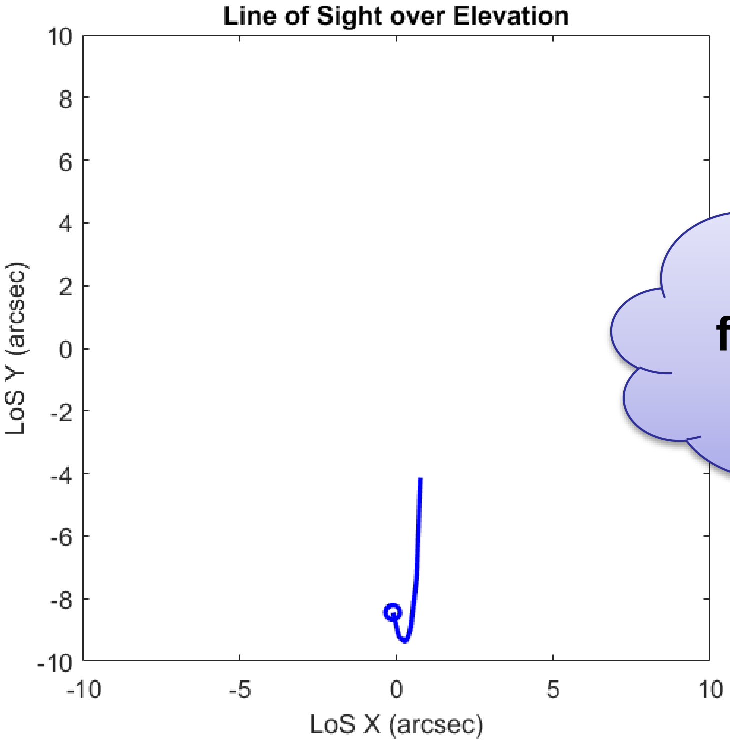


Line of Sight

STRUCTURAL MODEL

Line of Sight / Changes with Elevation

- **Raw Motions are Large**
  - 5 to 50 um and 0 to 200 urad
- **Relative Motions are Small**
  - Balancing Stiffness Keeps M1, M2 Aligned… the Sag Together
- **Compute LoS from Spot Diagram**
- **Easily Withing Range of Guidance System**



Trajectory from 0 Deg to 90 Deg

Thermo-Elastic Results from Thermal Soak

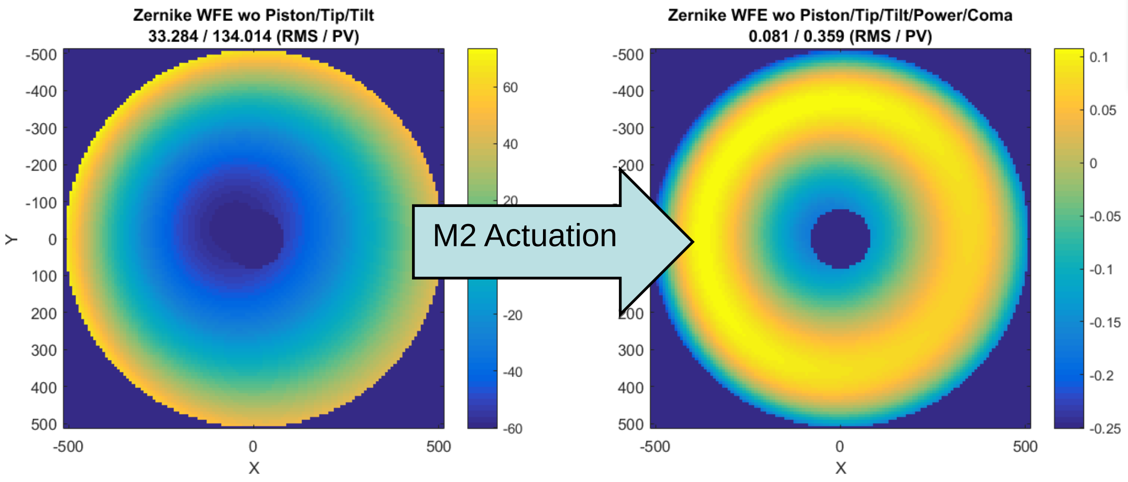
STRUCTURAL MODEL

Temperature

- **Impact of Soak**
  - Does Soak Deform M1 in a Manner that is Not Correctable with Alignment?
  - What is the Required Capture Range for a Wavefront Sensor from Ground to Float?
- **Same Process**
  - Apply Thermal Soak Conditions
  - Recover Mirror / Instrument Motion
  - Apply to Optical Model
  - Recover WFE

WFE < 34 nm RMS
Easily within Capture Range

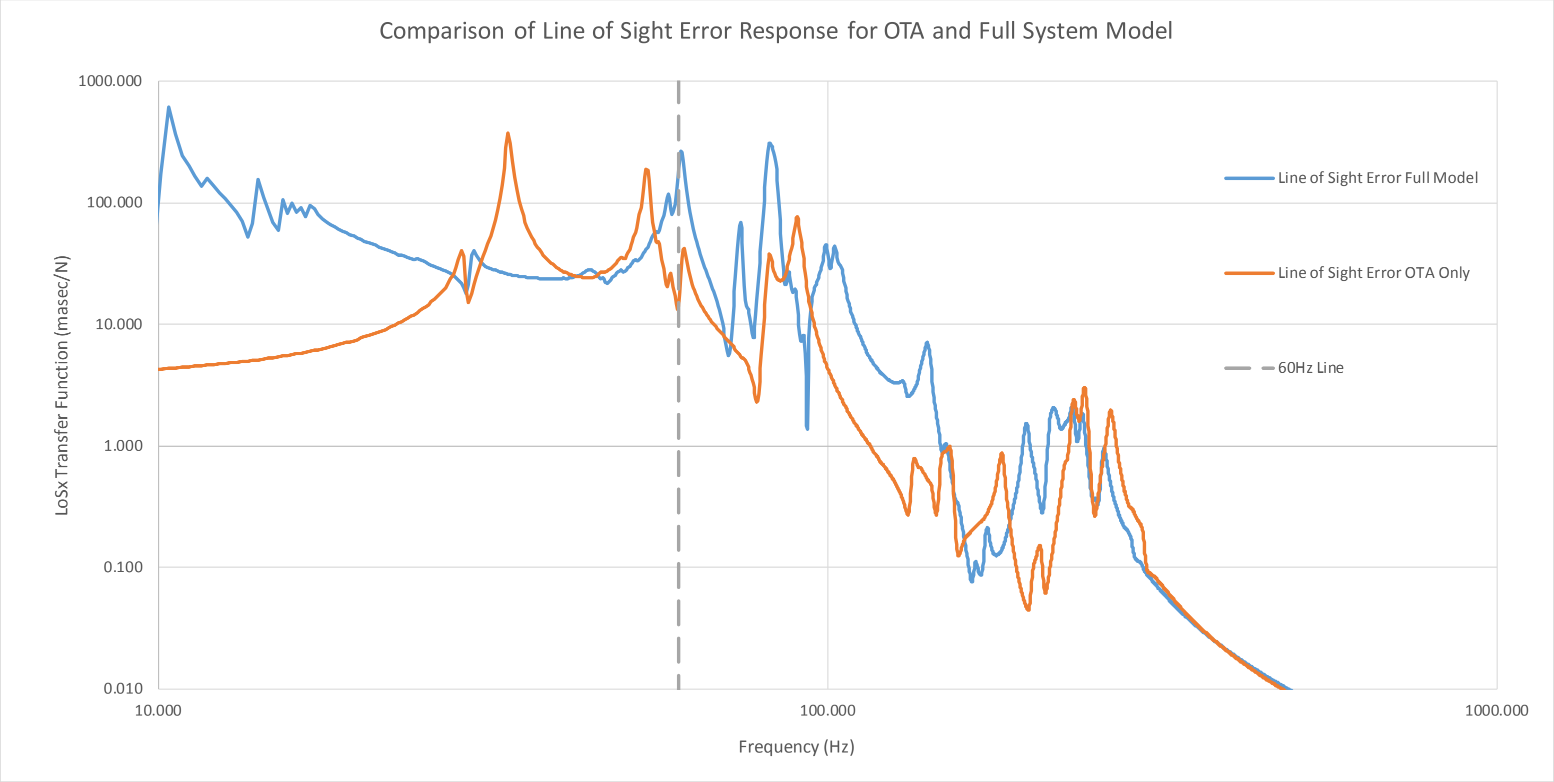
Residual after Correction
$\text{WFE}_{\text{residual}}$ < 1 nm RMS



Modes to Jitter

DYNAMICS MODEL

Integrated vs. OTA Model



- **LoS Transfer Function = LoS from Disturbance vs. Frequency**
- **Used to Evaluate Cryo-Cooler Disturbance (60 Hz)**
- **Note Shift in Response of OTA vs. Integrated Model**

Lesson Learned: When Possible, Use Integrated Model

Line of Sight / WASP Distrubance

- **What is the Jitter (Fast Motion of PSF) when Observing Science?**
  - Take WASP Disturbance
  - Apply to Integrated Model
  - Capture M1, M2, Instrument Motion
  - Convert to Line of Sight
- **Jitter < 5 milli-arc-sec**

Summary

- **Described Rigorous STOP Analysis Process**
  - Integrated Inputs from (x4) Models into System Performance
- **Supports WFE and LoS Budgets**
  - See B. Woodruff’s Poster