National Aeronautics and Space Administration

STOP Modeling in Support of GHAPS Balloon Based Telescope

Brian Catanzaro/CFE Services,
NASA MSFC - Thomas Brooks, Will Johnson, Brian O'Connor
NASA GRC- Robert A. Woodruff (consultant), Ryan Edwards, Evan Racine

November 15, 2017

In Support of Gondola for High Altitude Planetary Science (GHAPS)

Leigh Elrod/NASA MSFC- Optical Telescope Assembly Project Manager
Monica Hoffmann/NASA GRC GHAPS Project Manager

Introduction

GHAPS is a Mission to Launch a Reusable, 1-M Balloon Based Telescope to Address the Needs of Planetary Science

Design Cycles Led by GRC / MSFC Taught Us:

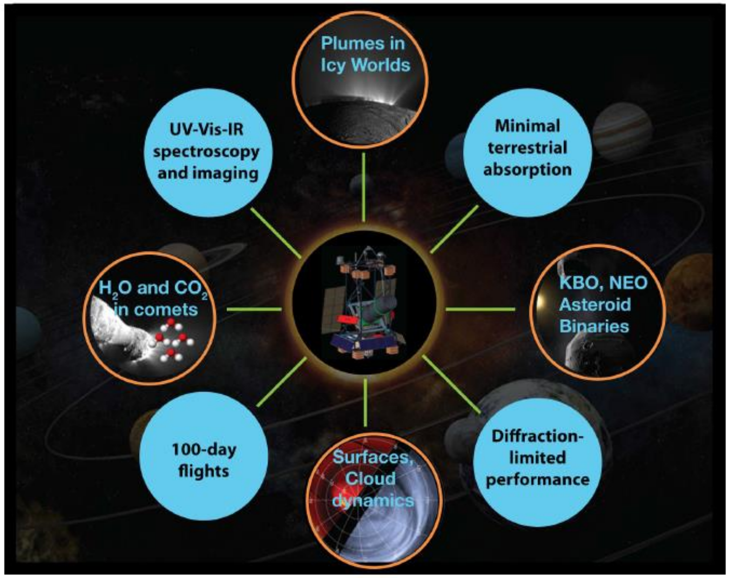
1. Unique Challenges for Balloon Based Optical Telescopes are:
   - Combination of: Wide Thermal Range, Gravity, Lightweight
2. Design / Analysis Indicate that Design Solutions Can Be Found
   - Small Portion of the Overall WFE
3. Stability / Environment Demands Focus Changes on Float
   - Creates Requirements for WFS / WFC
4. Tools for Integrated Analysis
   - Elusive and "Home Grown"

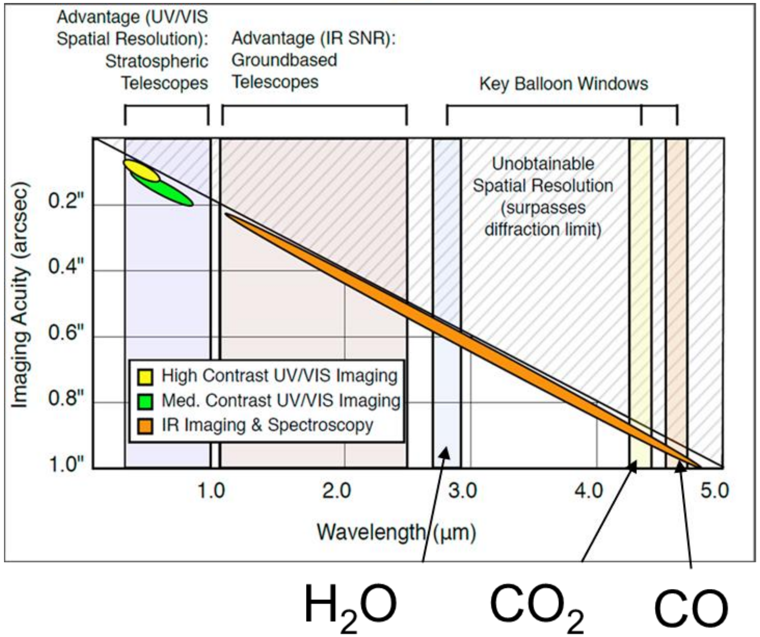
Planetary Science that is Well Suited for Balloon Missions

SCIENCE INSPIRATION

Planetary Science + Balloon Telescopes

- Balloon- based telescopes offer "means of studying planetary bodies at wavelengths inaccessible from the ground" – 2013 Planetary Science Decadal Report
- NASA is currently in the demonstration phase of super-pressure balloons – offering diurnal cycle missions up to 100 days
- Reusable balloon platforms with 100 day missions provide planetary science observations at cadences prohibitive for other assets.
- Path Finding Missions Included: BOPPS and BRRISON
- Workshop Science Target Outputs: Venus, giant planets, icy satellites, and small bodies (e.g. KBO)
- Suggested Observations: Atmospheric composition / dynamics, surface composition, orbital mechanics of small bodies





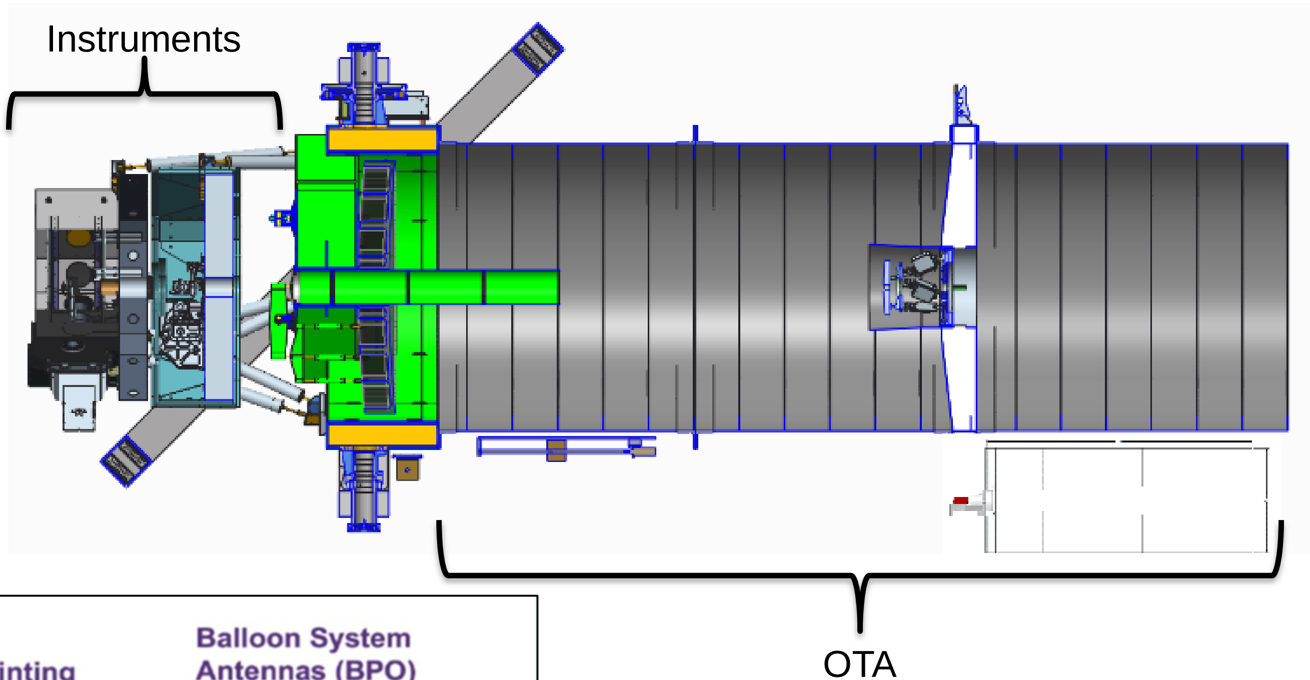
J. Dankovich (et al.) "Planetary Balloon-Based Science Platform Evaluation and Program Implementation" NASA/TM-2016-218870

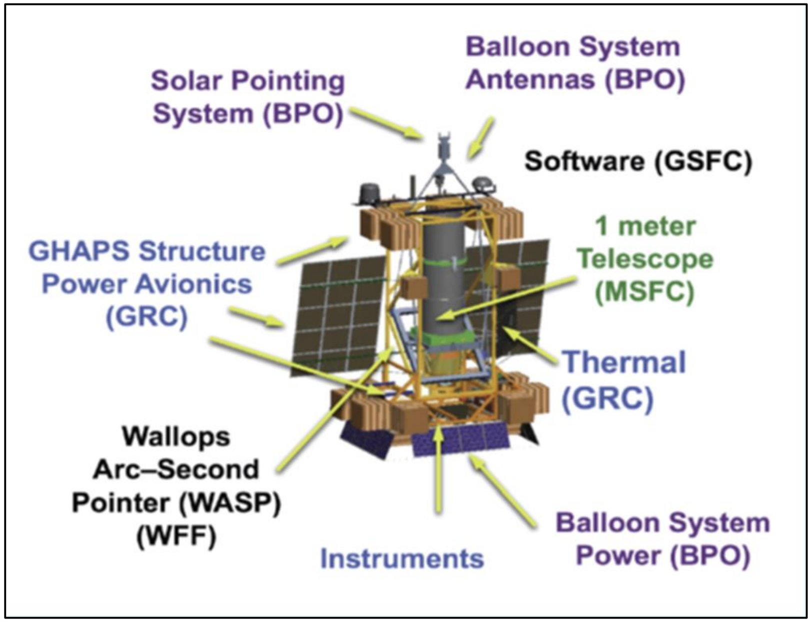
Observatories Features

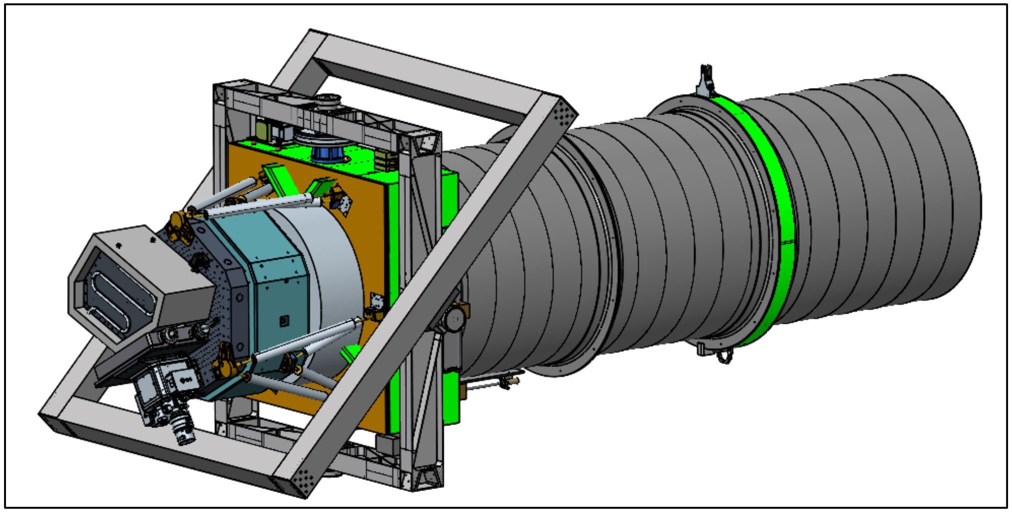
High Spatial Resolution: 0.1 arcsec to 0.2 arcsec
Broadband: UV – IR (300 nm to 5 um)
Small Observing Field of View: 60 arcsec to 100 arcsec

Aperture: **1-m (for Resolution)**
WFE: **Diffraction Limited at 650 nm**
Temperature: **“Cold” for Spectroscopy**
Prescription: **Cassegrain / R-C for Small FoV**
Instruments: **Spectrometer & Imaging**

GHAPS Observatory



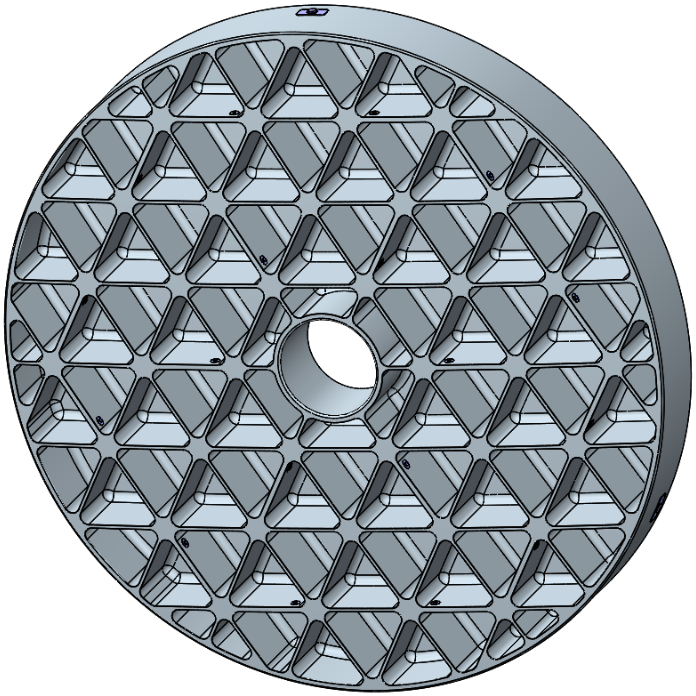




Gravity, Thermal, Mass

UNIQUE DESIGN CHALLENGES

Start with Mass…



- 40 kg in the Facesheet
- Approx. 25% Mass of Solid Mirror

- **Begin with Mass Allocation and Areal Density**
- **Areal Density = 100 kg/sq-m**
  - Mass = 78 kg
  - Area = 0.78 sq-m
- **Why So Heavy?**
  - Gravity and Thermal

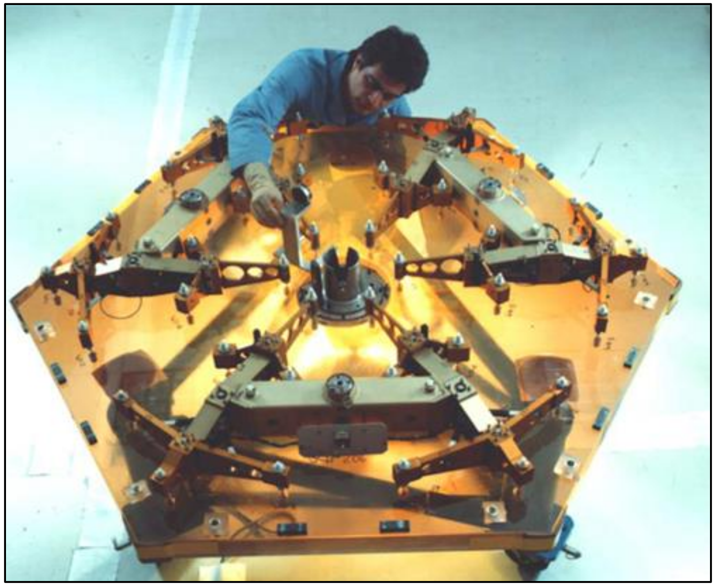
STO Flew with 0.8 m Primary @ 50 kg
Areal Density: 100 kg/sq-m*

* P. Bernasconi, "Balloon-borne telescope for high resolution solar imaging and polarimetry" 2000

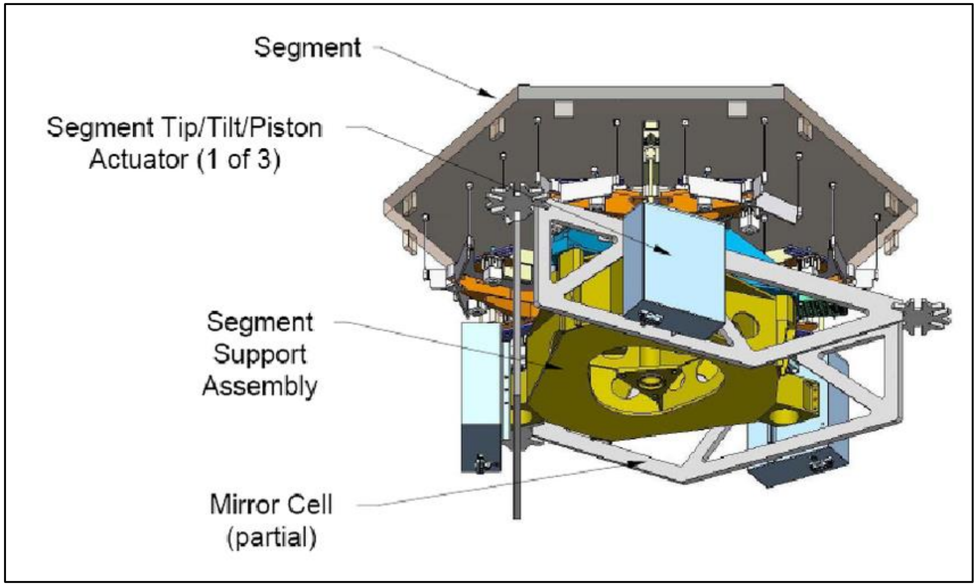
How Do Gravity and Thermal Drive a Solution?

- **Gravity**
  - Elevation Angle Causes Deflection / Surface Errors
  - Requires Extensive Support System Like Ground Based Telescope
    - Whiffle Tree + Tangent Bars

Keck Mirror Support



TMT Mirror Support



Thermal Environment

- **Telescope Sensitivity (OTA WFE Budget = 26.6 nm RMS)**

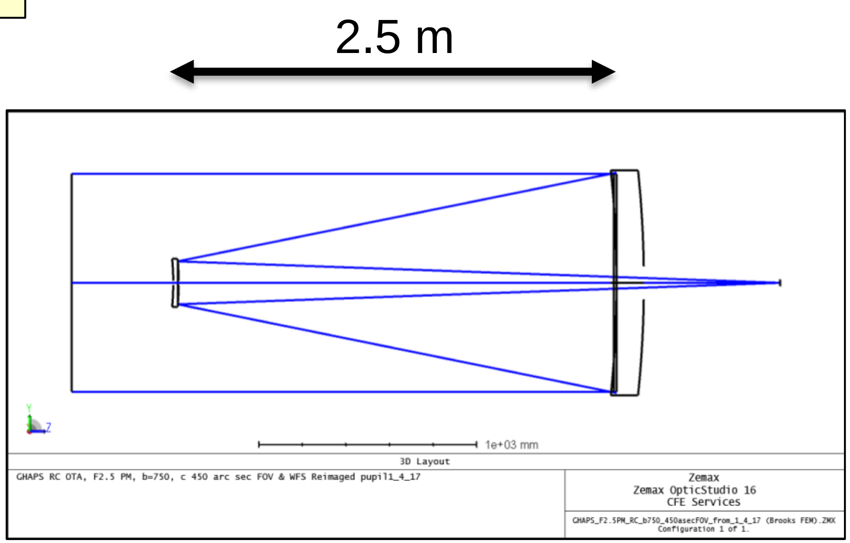
	Focus	**Decenter**	**Tilt**
Sensitivity	5 um / 26.6 nm	> 100 um/ 26.6 nm	> 200 ur / 26.6 nm

- **Environment on Float: + 30 C to -60 C**
  - Athermalize to 5 um / 2.5 m over 90 C

$$\frac{\delta L}{L} = \epsilon = \alpha \cdot \Delta T \rightarrow \alpha = \frac{\epsilon}{\Delta T} = 0.022\ ppm/C$$

1. Very Low Expansion Material
2. Great Athermal Design
3. Low Gradients
4. Good CTE Uniformity

Telescope Needs Focus Control?



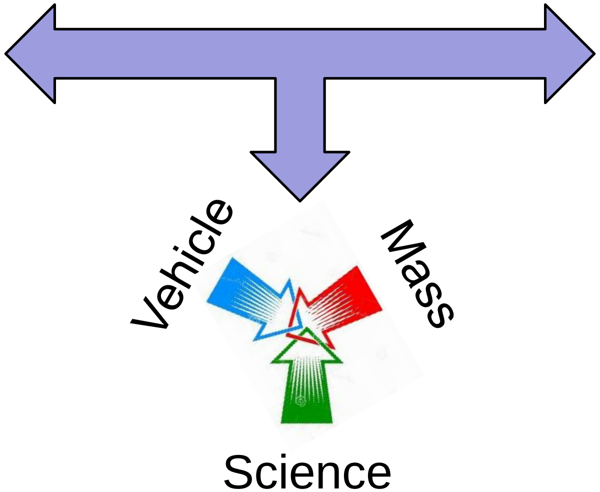
Total Mass Budget

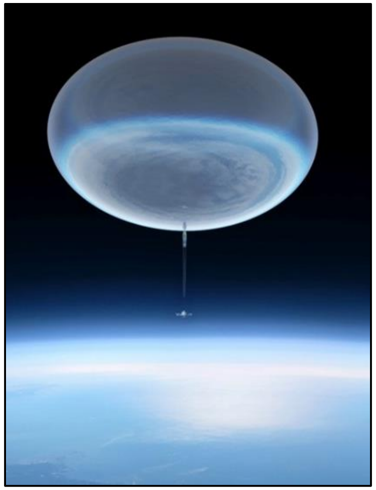
Standard Balloon

- **Mission Duration**
  - 1.5 days to 30 days
- **Lift Capacity**
  - +2900 kg
- **Day / Night Locations**
  - Antarctica = Day @ 10 – 30 d
  - Domestic = Day / Night @ 1.5 d

Super Pressure Balloon

- **Mission Duration**
  - 100 days
- **Lift Capacity**
  - +2500 kg
- **Day / Night Locations**
  - New Zealand @ + 90 d





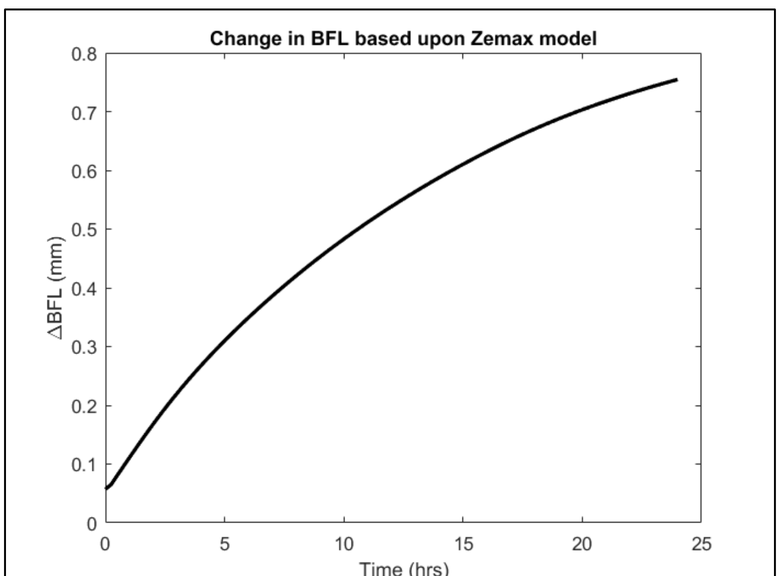
Balloon Type / Site has Impact on: Wavelength, Temperature, Duration

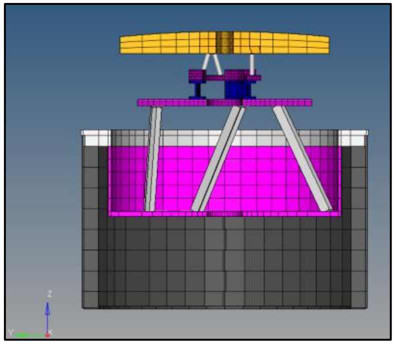
Thermal Stability Demands Changes to Focus on Float Implying WFS / WFC

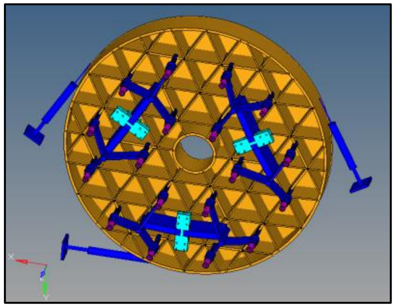
NEED FOR FOCUS / COMA CONTROL

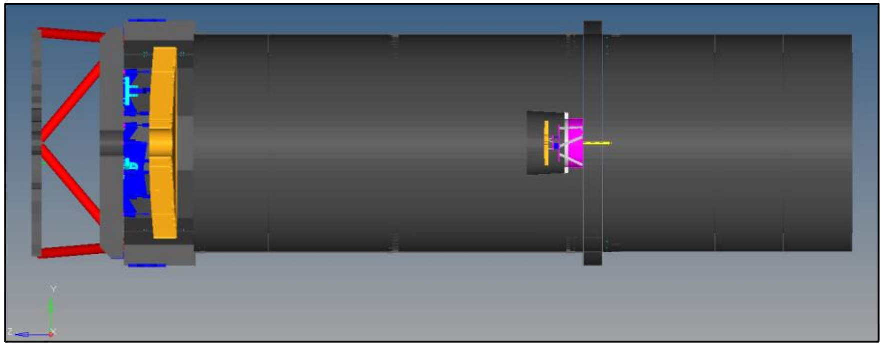
Refocus Still Needed After Complex Athermalization

- **Low Thermal Expansion Materials**
  - Constructed w/Zerodur + CFRC
- **Moderate Thermal Expansion in M1 Support**
  - Whiffle Tree Includes Invar and Titanium
- **High Thermal Expansion in COTS Hexapod**
  - M2 Actuation Includes Aluminum
- **Even With Athermal Design…BFL Changes**
  - ΔBFL / dt = 1 um / hr to 40 um / hr







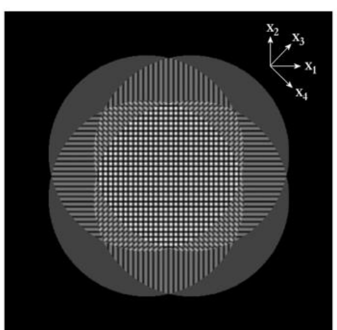


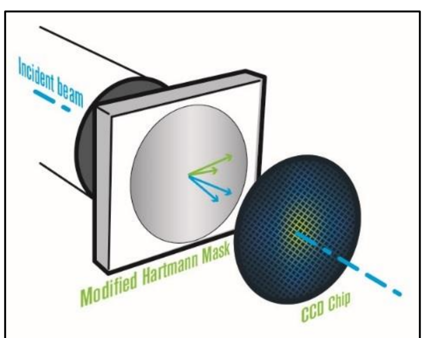
Wavefront Sense / Control

Wavefront Sensing

- Modified COTS Shearing Interferometer (Phasics)
- SCMOS Sensor w/Std Optics

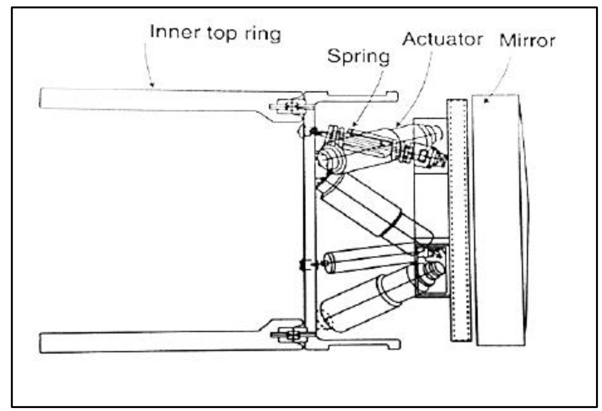
- **Few Sample Points**
  - 40 x 40
  - 20 x 20
- **Repeatability of 5 nm RMS Possible with Magnitude 7 or Less**
  - Driven by Putting Wavefront Over as Few Pixels as Possible

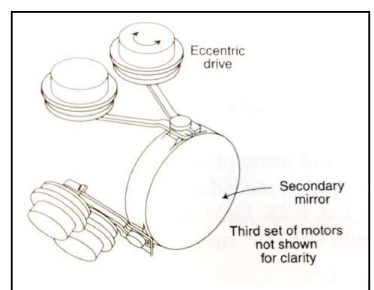




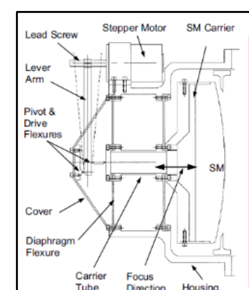
Actuated M2

- **Baseline Solution**
  - Heated 6 DoF (Hexapod)
- **Alternate Solution**
  - Tip / Tilt / Piston Mechanism
  - 3 DoF





HST: (x6) DoF

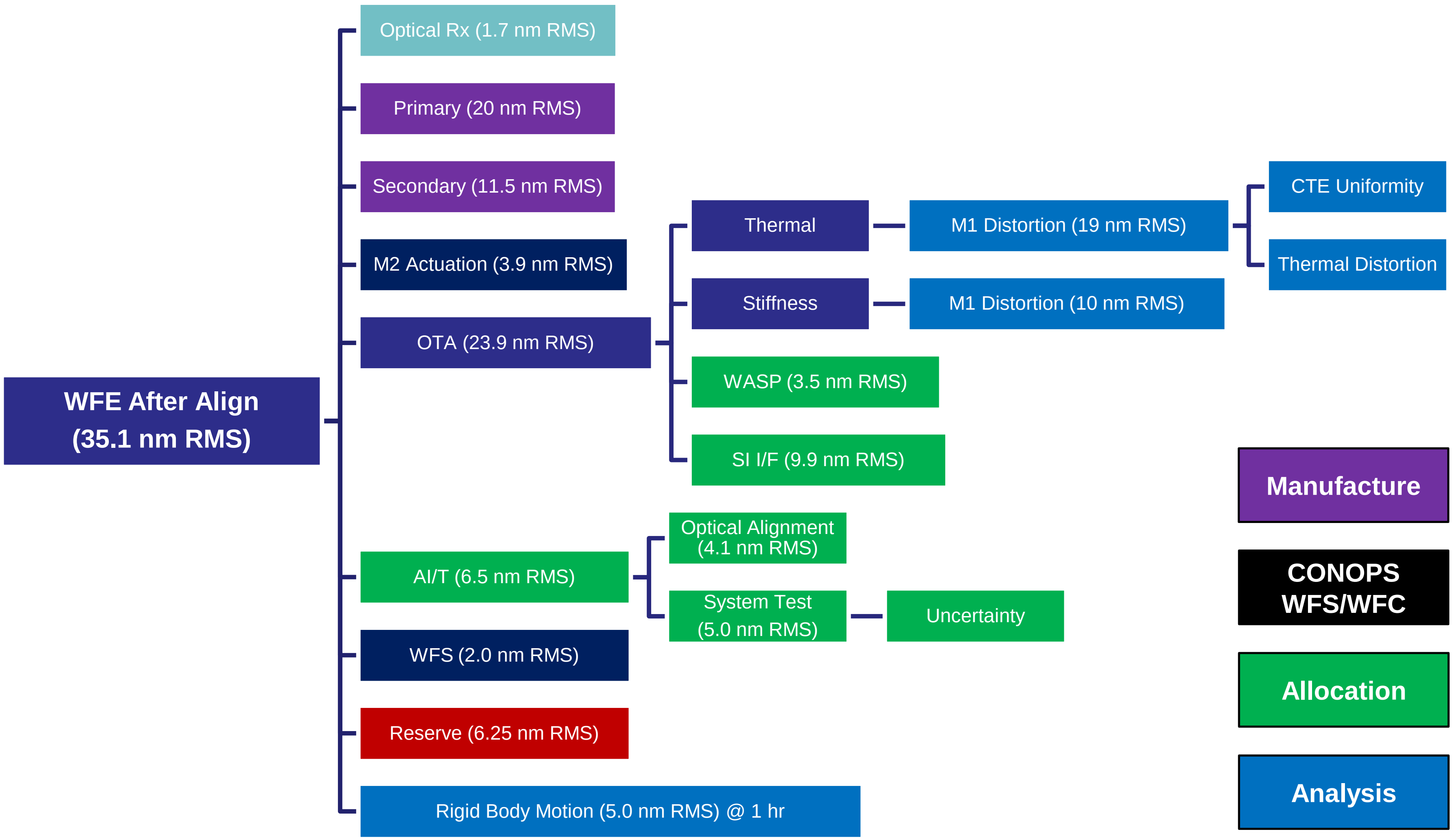


Spitzer: (x1) DoF

WFE Budget Not Dominated by Analysis

DESIGN / ANALYSIS

Telescope WFE Budget



Key Components for STOP Analysis

Thermal

- **CTE Uniformity** / When M1 Cools, CTE Uniformity Affects Surface Figure
- **Thermal Distortion** / Non-Ideal Support Transfers Stress to Mirror at Temperature

Gravity

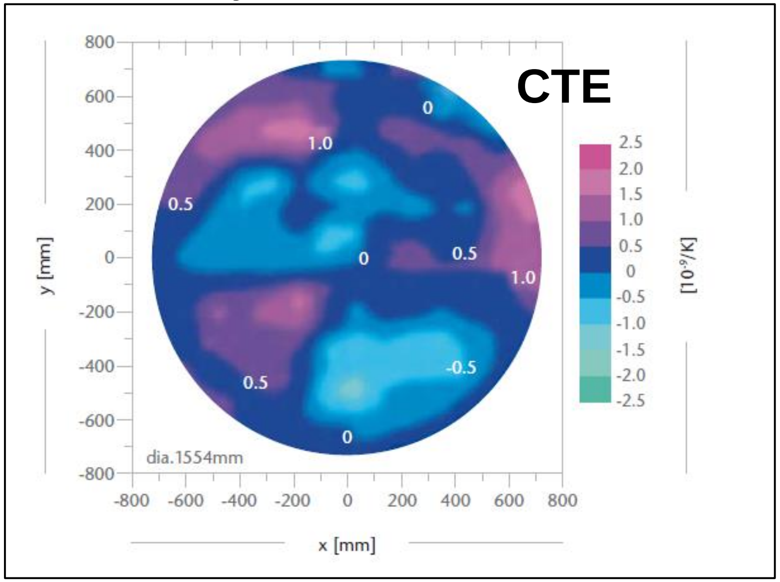
- **Stiffness** / Elevation Changes Result in Mirror Surface Figure Changes

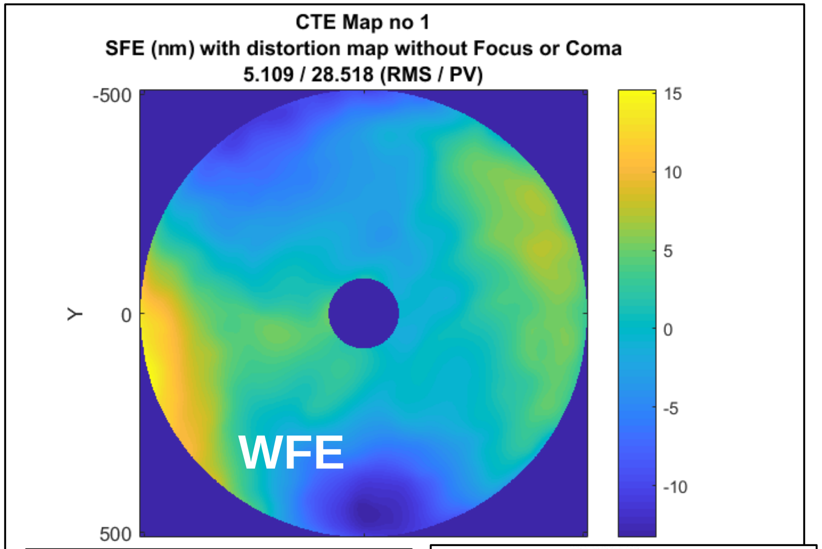
Drift

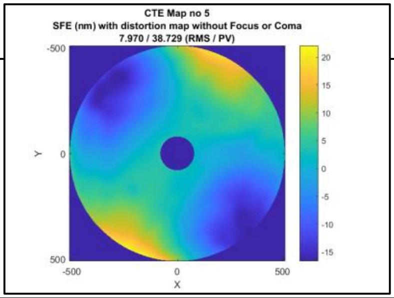
- Thermal Changes Between Refocus / Realign Operations Cause WFE

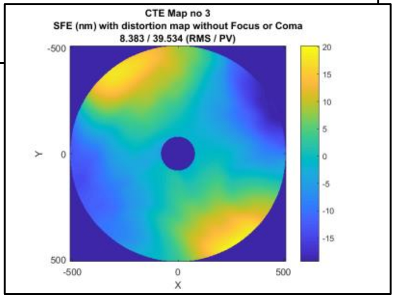
M1 CTE Non-Uniformity

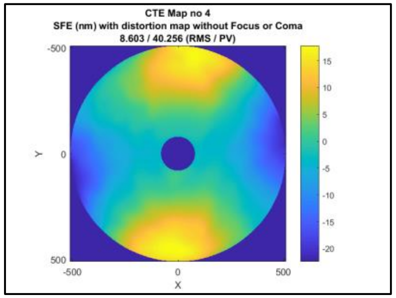
- **Published Example fo Zerodur CTE Distribution**
  - Synthesize Distributions with Similar Spatial Frequencies
- **Run Thermo-Elastic Models on M1**
  - Determine Ensemble WFE from CTE Non-Uniformity
- **WFE = 0.25 nm WFE RMS / deg C**

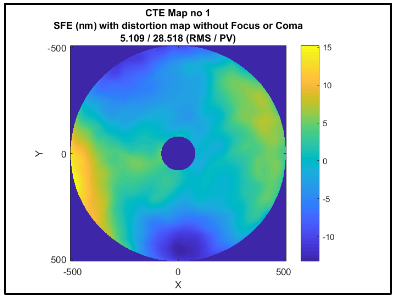






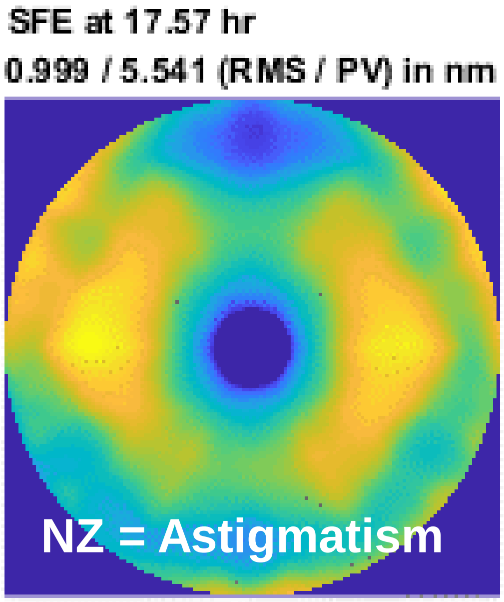


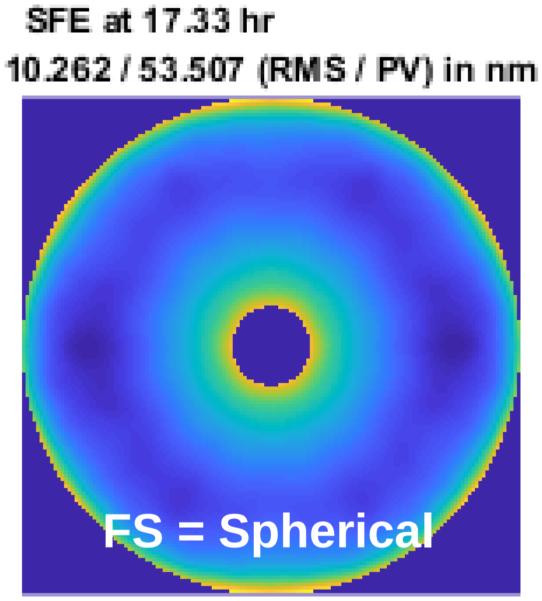




M1 Thermal Gradients

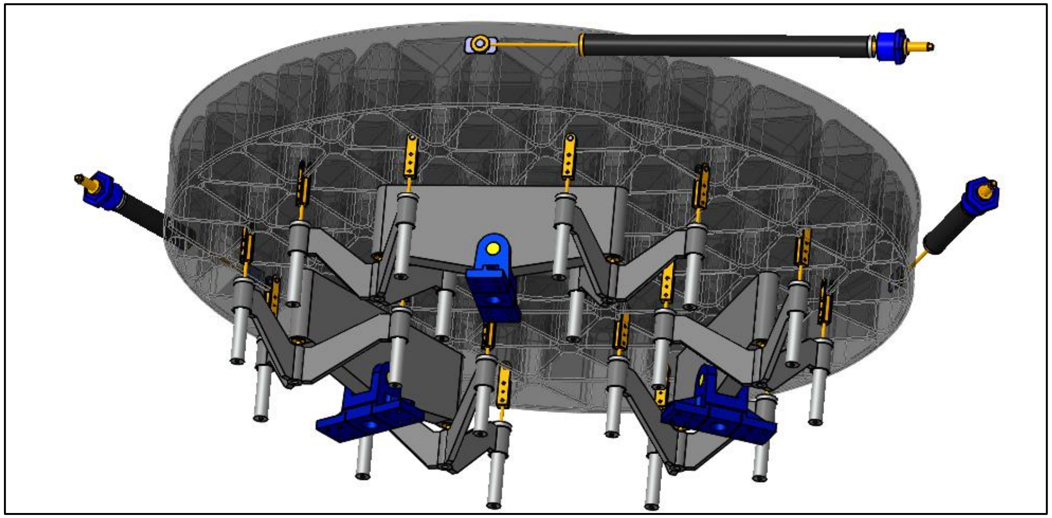
- **Thermal Gradients for Varied by Mission Locations / Flights**
  - Ft Sumner (~1 day)
    - Environment Changes Faster than the Thermal Time Constant
  - New Zealand; Antarctica
    - Quasi-Equilibrium Achieved (~2 days) Prior to Observation

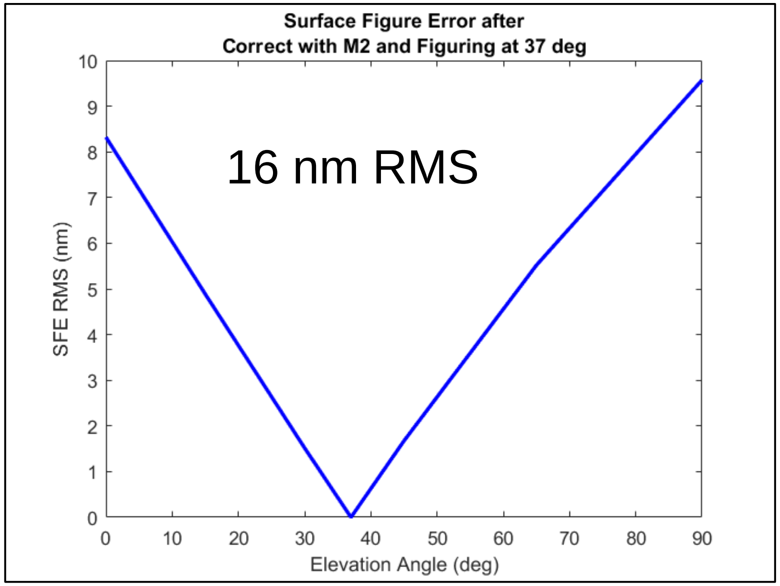


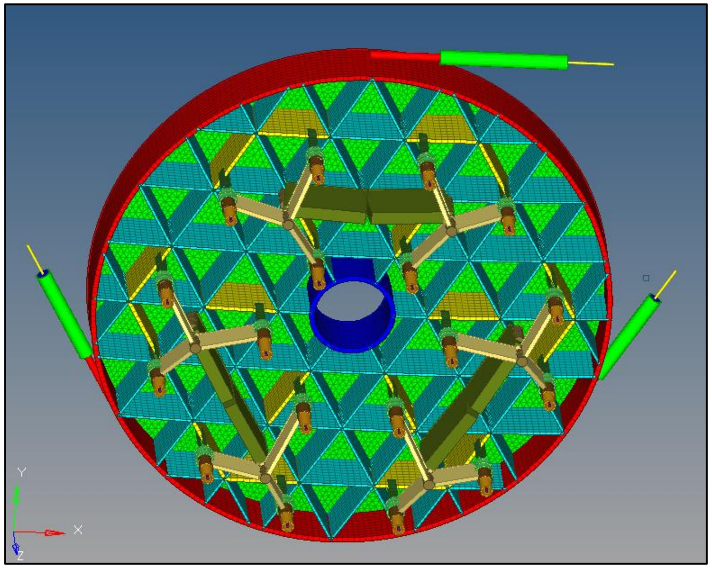


M1 SFE Over Elevation

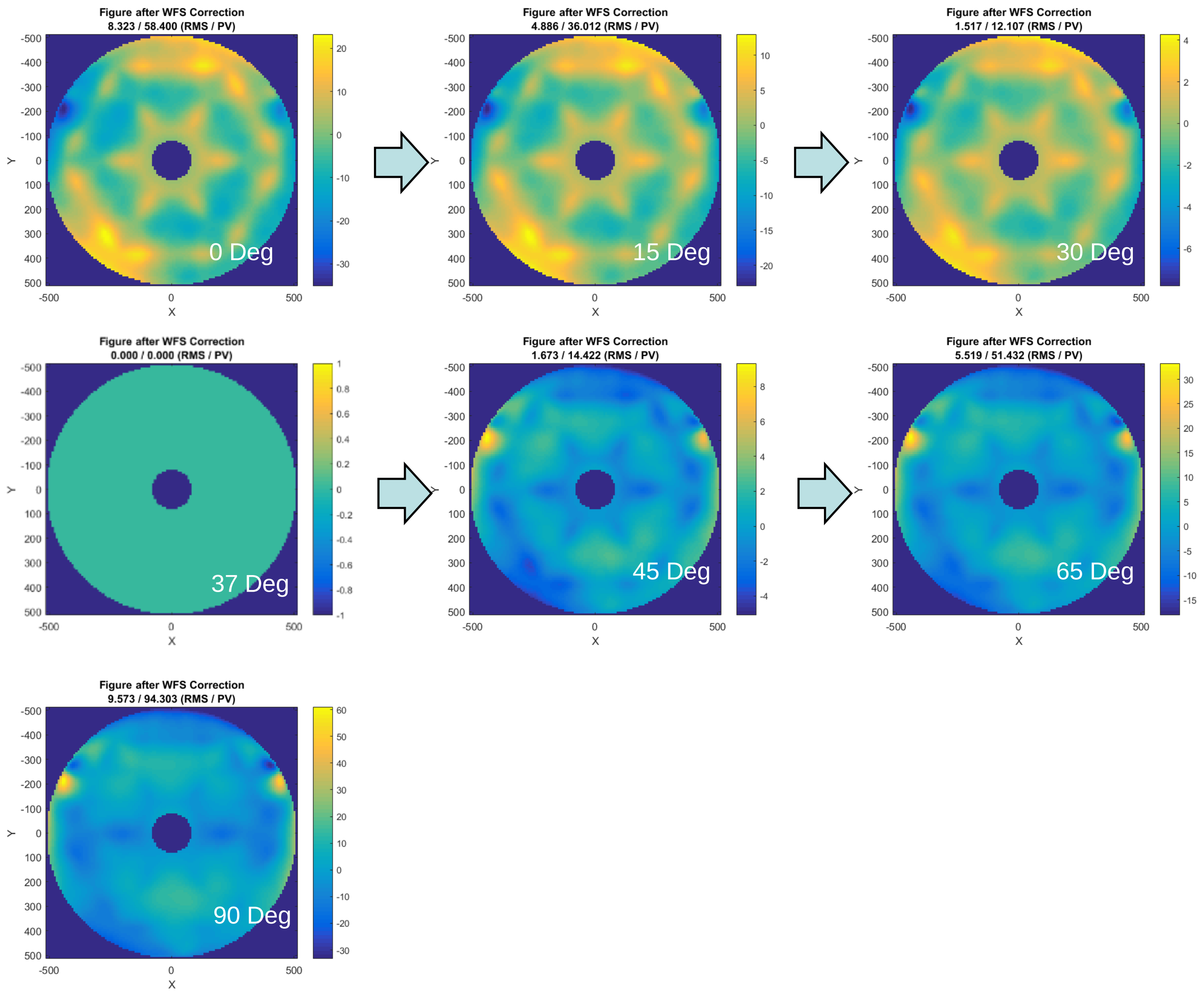
- **Orientation Changes Loads**
- **Polished for 37 deg**
  - Residual Errs at Other Elevations
- **Focus / Coma Assumed Correctable**







Mirror Figured at $\theta_{elevation}$ = 37 Deg



S/W “Glue” and Management

STOP

Architecture to Answer Key Questions

Science Simulation

- Blackbody Radiation
  - Mirror Temperatures
- PSF
  - Image Acuity
- Long Term Stability
  - Long Exposures
  - Impact of Slewing to Refocus

System Model

- Pointing
- Jitter
- PSF
  - WFE
    - Deterministic
    - Stochastic

Scenarios

- Simplified Boundary Conditions
- Design Reference Mission

Tools

- Nastran
- Zemax
- Thermal Desktop
- Matlab / Python
- Visual Studio / C#

Data / Context

- **Models**
  - Nastran
    - Static Model (x3) / Elevation, Thermal
    - Dynamic Model (x2) / +100 modes
  - Thermal Desktop
    - (x2) Configurations
    - (x5) Scenarios
    - (x100) Transient Temperature Outputs for Nastran Model
  - Optical Model (x1)

Deterministic and Stochastic Scenarios

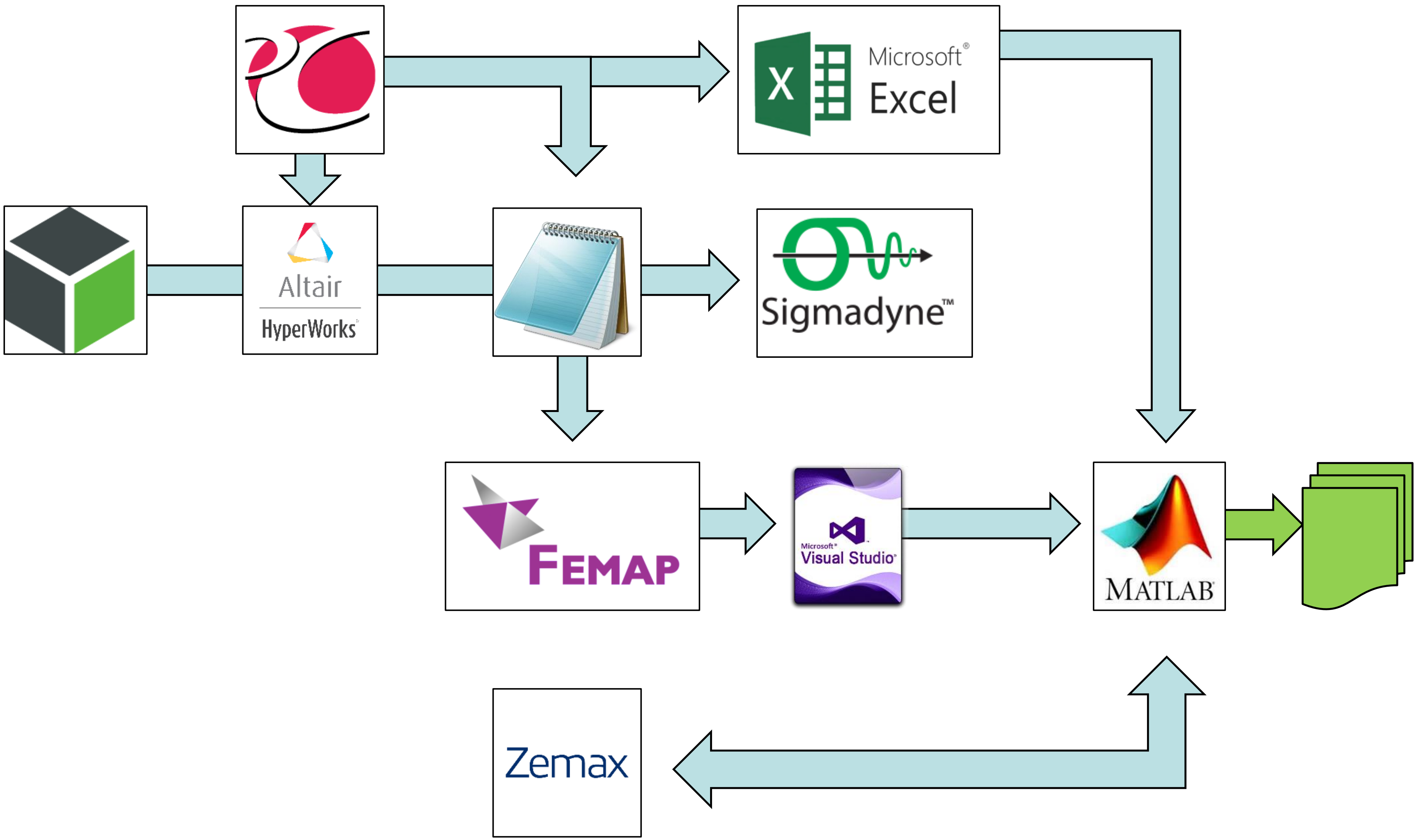
Robust Process to Support Iteration

10's – 100's Files

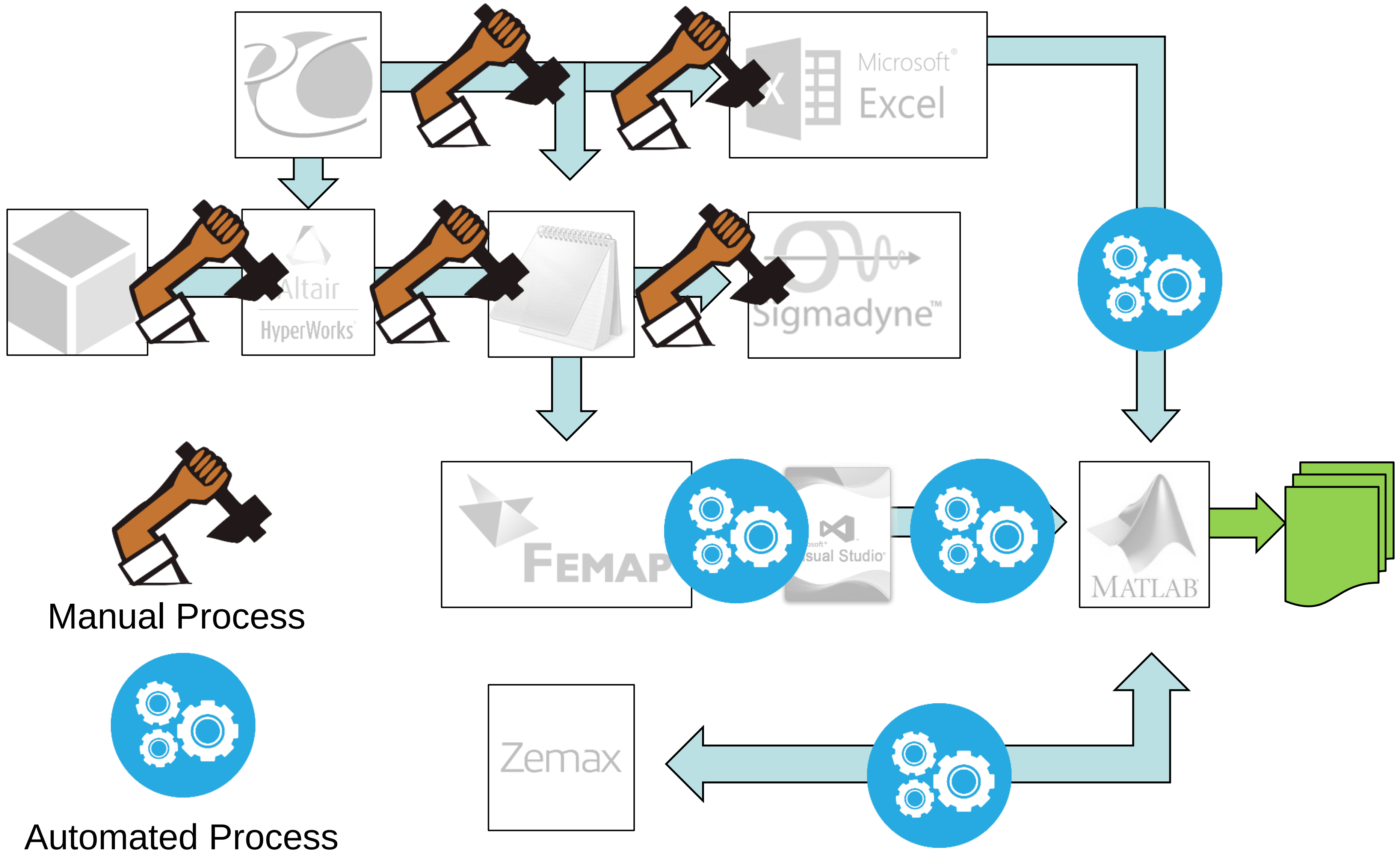
Top Level Outputs Not Supported by S/W

A Lot of Point-Click

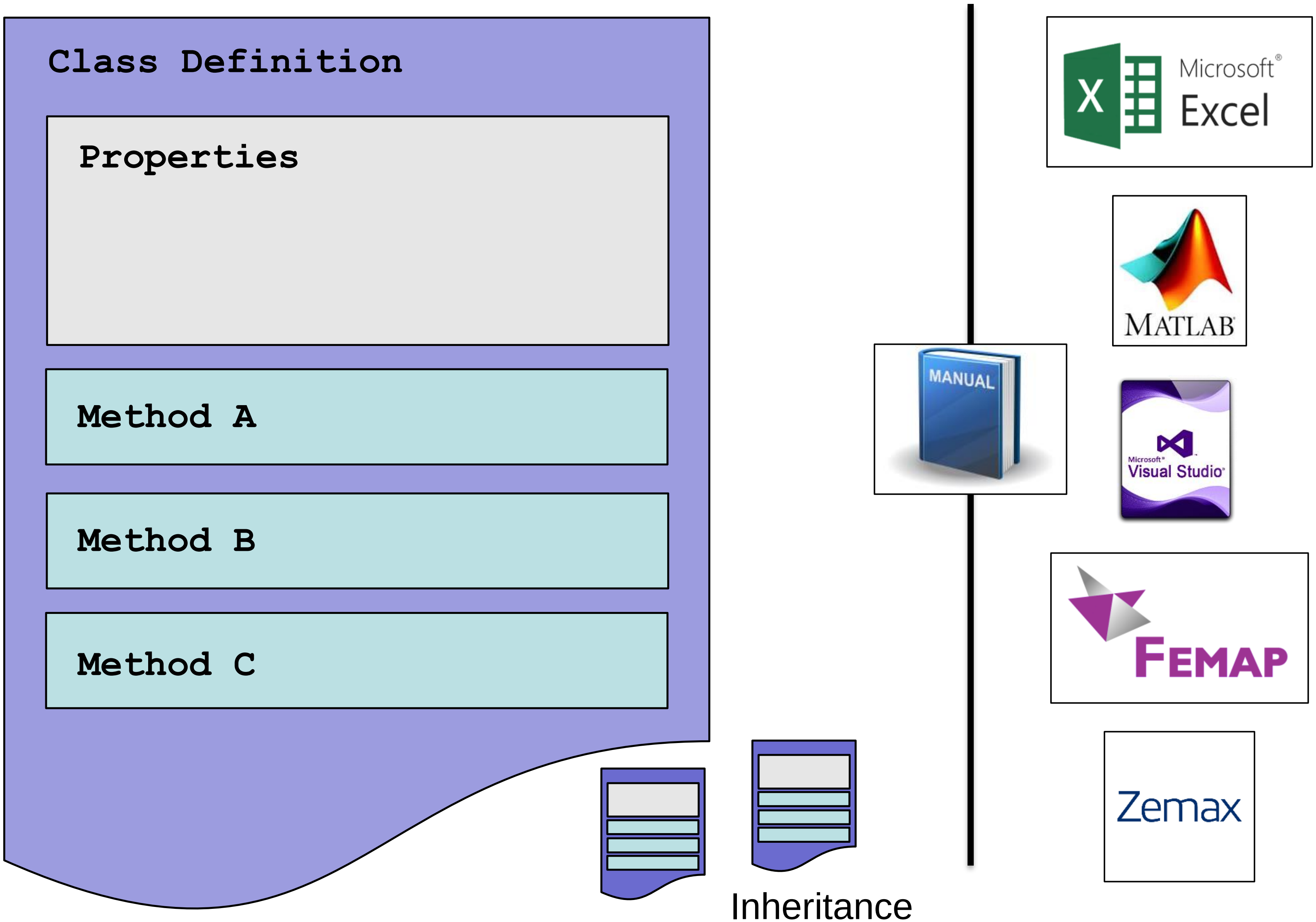
Hierarchical Object Oriented S/W with API Interface



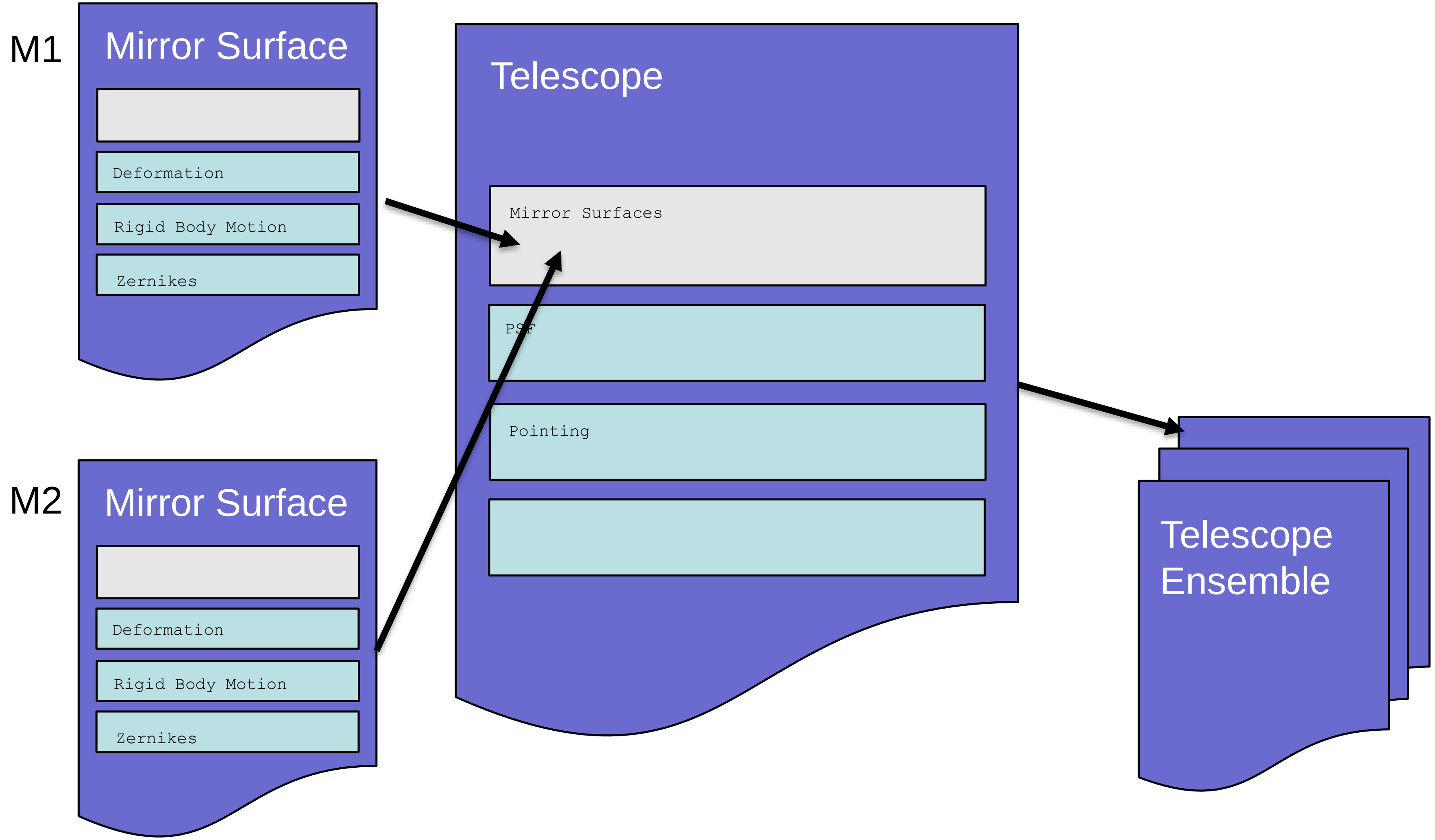
Hierarchical Object Oriented S/W with API Interface



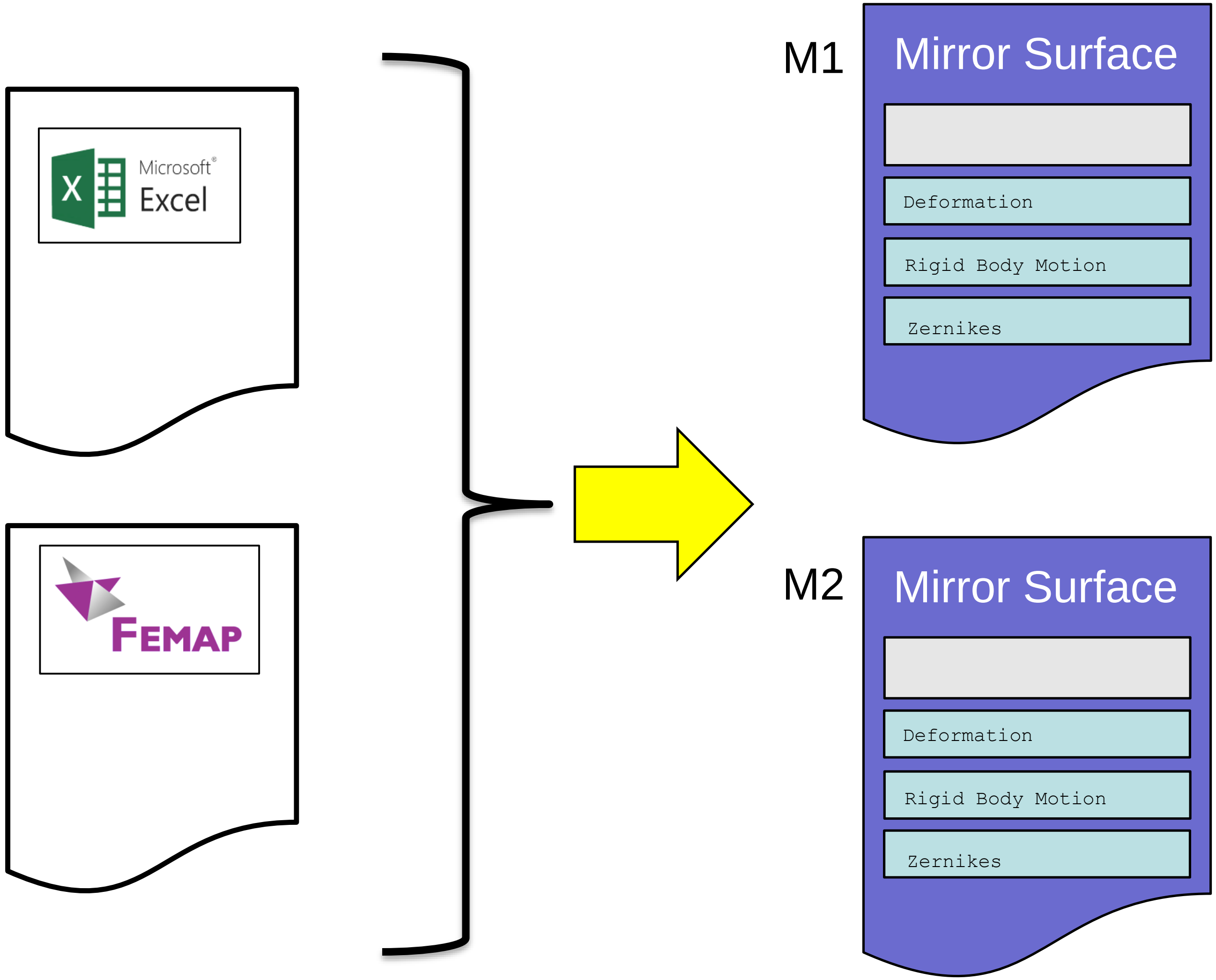
Automation through OOP with API



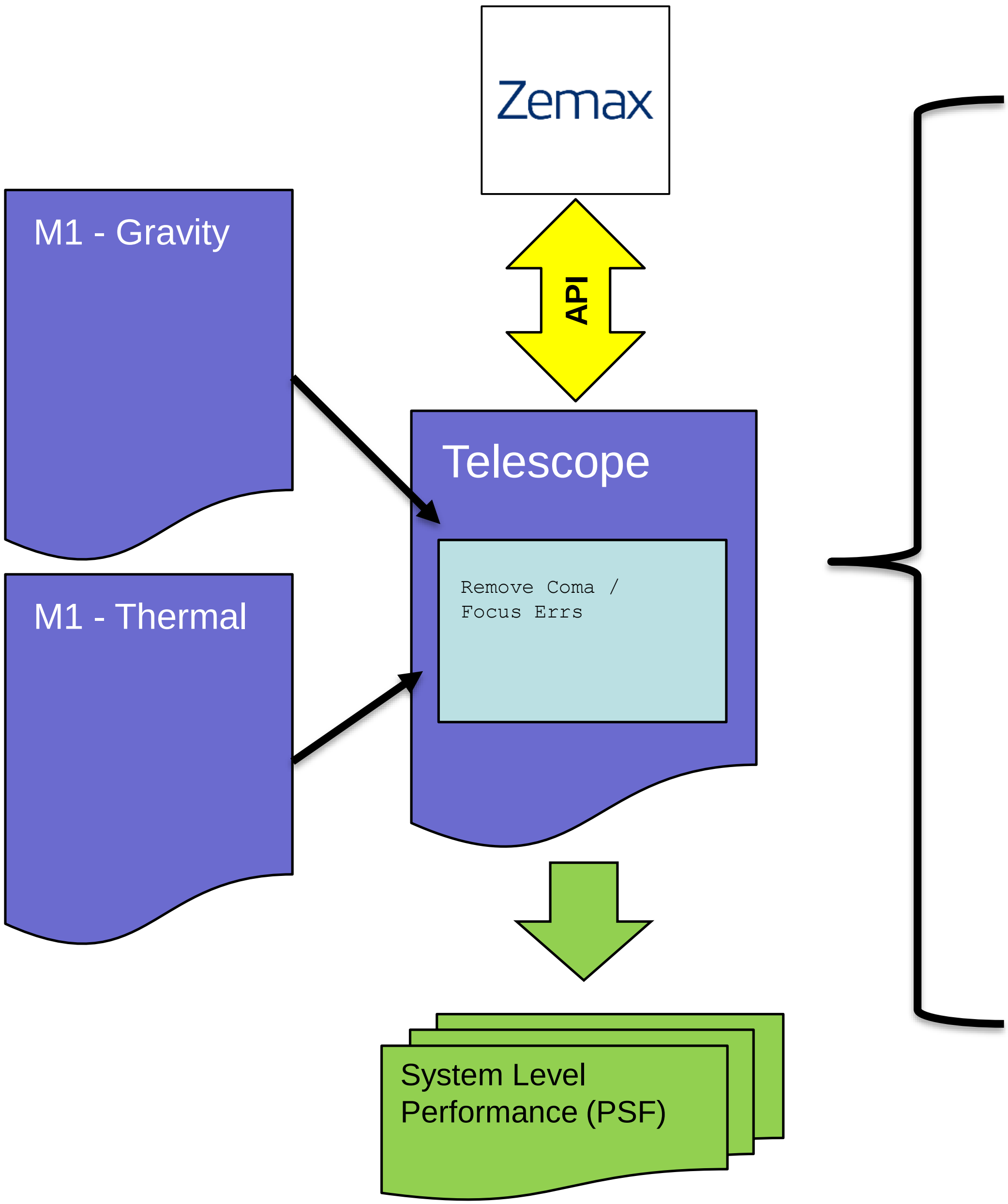
Classes to GHAPS / STOP

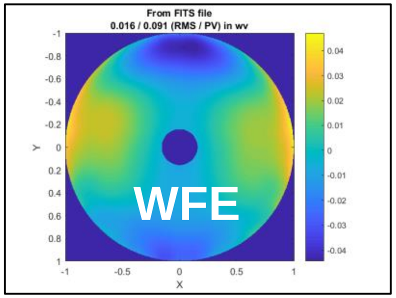


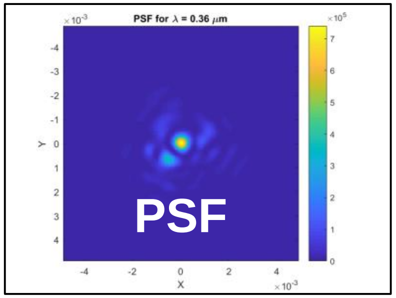
Objects Interact with Data to Import and Analyze

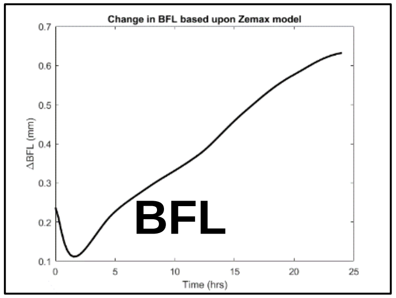


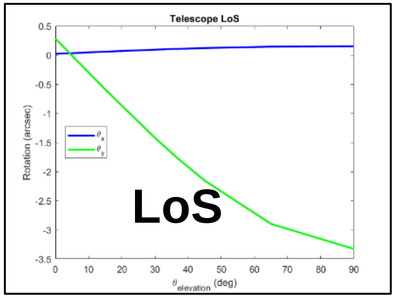
Telescope Object Analyzes w/API to Get System Level Answers



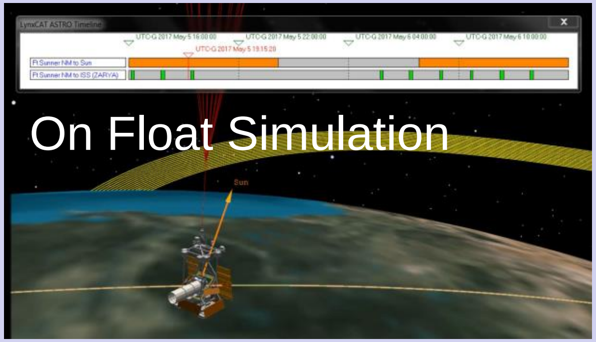


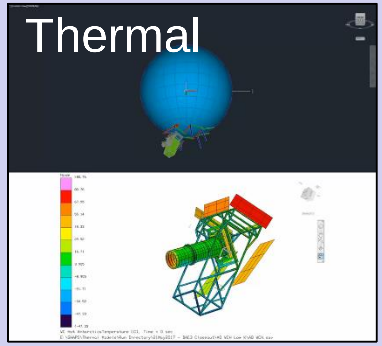


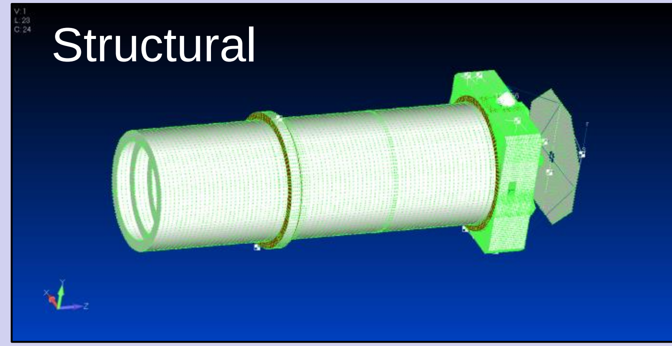


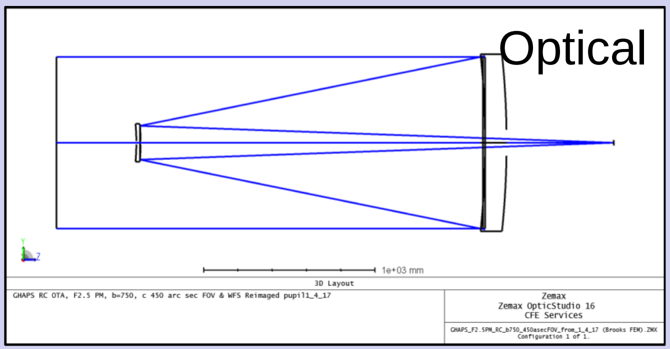


Design Reference Mission to Science Eval





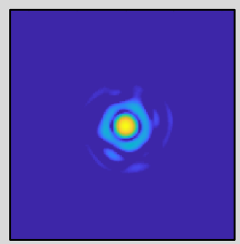


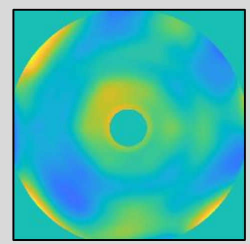


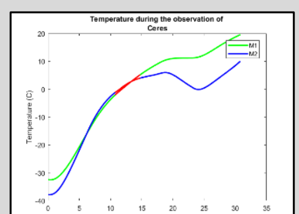
Antarctica

Ft. Sumner

New Zealand







(x3) Missions
(x9) Targets Each

- **For Structure**

  PSF, Mirror Temperatures

- **For Science**

  SNR for Spectroscopy, Integration Time, Detection Rate for KBO, Evaluation of Image Quality

What Did This Enable?

- **Verification**
  - Verification through API and Cross Correlation with Different S/W
- **Automatic Export of Data to Scientists**
  - FITS Files for WFE and PSF to Verify Science Instrument Sims
- **Rapid Assessment of New Scenarios**
  - (x3) Flights; (x100) Thermal Conditions; (x2) Thermal Configurations; (x7) Elevations
- **Evaluation for CONOPS**
  - WFS / WFC: Range of Travel; Need for Corrections; Drift on Float
  - Jitter / Pointing: FSM in Instrument; Fine Steering in Instrument
- **Science Instrument Interface**
  - Pointing of Telescope vs. Pointing of Science Instrument
  - Opto-Mechanical Interface to Bench; Requirements for Call
- **Monte Carlo Simulation**
  - Incorporate Stochastic Errors in M1 Fabrication (100's of Cases)
  - Identify Sensitivities, Requirements
  - Feedback to Scientists on Consequences of Requirements

Final Notes

- **Planetary Science Still Has a Need for an Observatory**
  - Decadal Science Questions Remain Unanswered with Existing Assets
- **Balloon Based Telescope Platform**
  - Addresses Many Science Question
- **Design Solutions Can Be Found**
  - Challenging Environment Addressed with GHAPS as One Solution
- **STOP Analysis Still a Complex Endeavor**
  - Requires Several Disciplines Working Together
  - Software Tools not Widely Available

Acknowledgements: B. Arnold (MSFC), E. Bolydreva (Phasics), B. Jones (ret. MSFC), J. Juergens (GRC), M. Lewis (GRC), C. Russell (MSFC), D. Schrage (GRC), B. Tornabene (GRC), E. Young (SwRI)