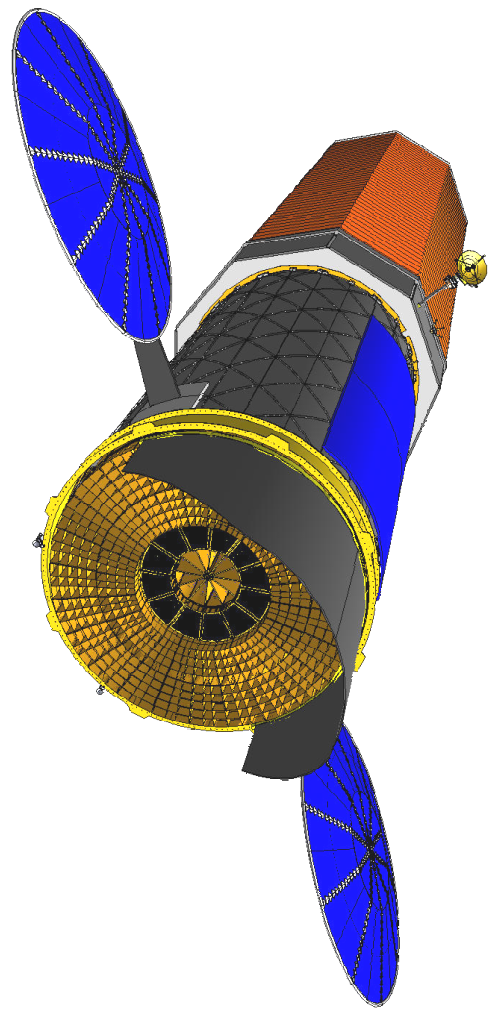
Design and Analysis of the International X-Ray Observatory (IXO) Flight Mirror Assembly (FMA)

12/07/2009

Ryan McClelland (SGT Inc.), Tim Carnahan (NASA/GSFC), Mike Choi (NASA/GSFC), David Robinson (NASA/GSFC), Timo Saha (NASA/GSFC)

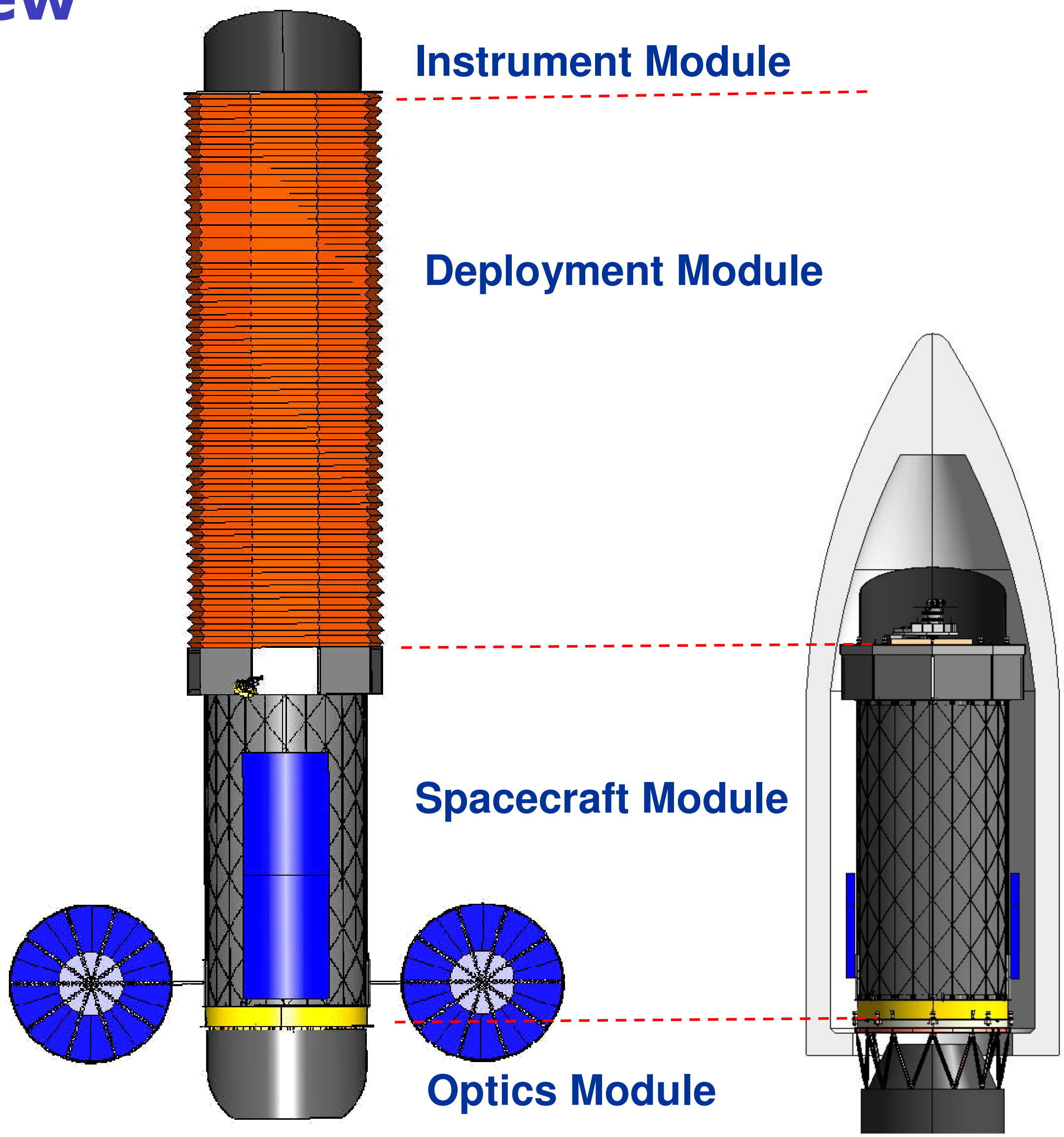
FMA Design and Analysis - Outline

- **Objective**
  - Overview of FMA baseline design
  - Summarize recent analysis results
- **Presentation Outline**
  - IXO Mission Overview
  - FMA Design Overview
  - Module Design Overview
  - End-to End Analysis of Suspension Mount
  - Mirror Structural Analysis and Testing
  - Preliminary STOP Analysis
  - Thermal Design and Analysis



IXO Mission Overview

- Collaboration between NASA, ESA, and JAXA
- The observatory is deployed to achieve 20 m focal length
- 3.4m FMA OD
- Observatory Mass ~6600 kg (including 30% contingency)
- Launch on an Atlas V 551 or Ariane V
- Direct launch into an 800,000 km semi-major axis L2 orbit

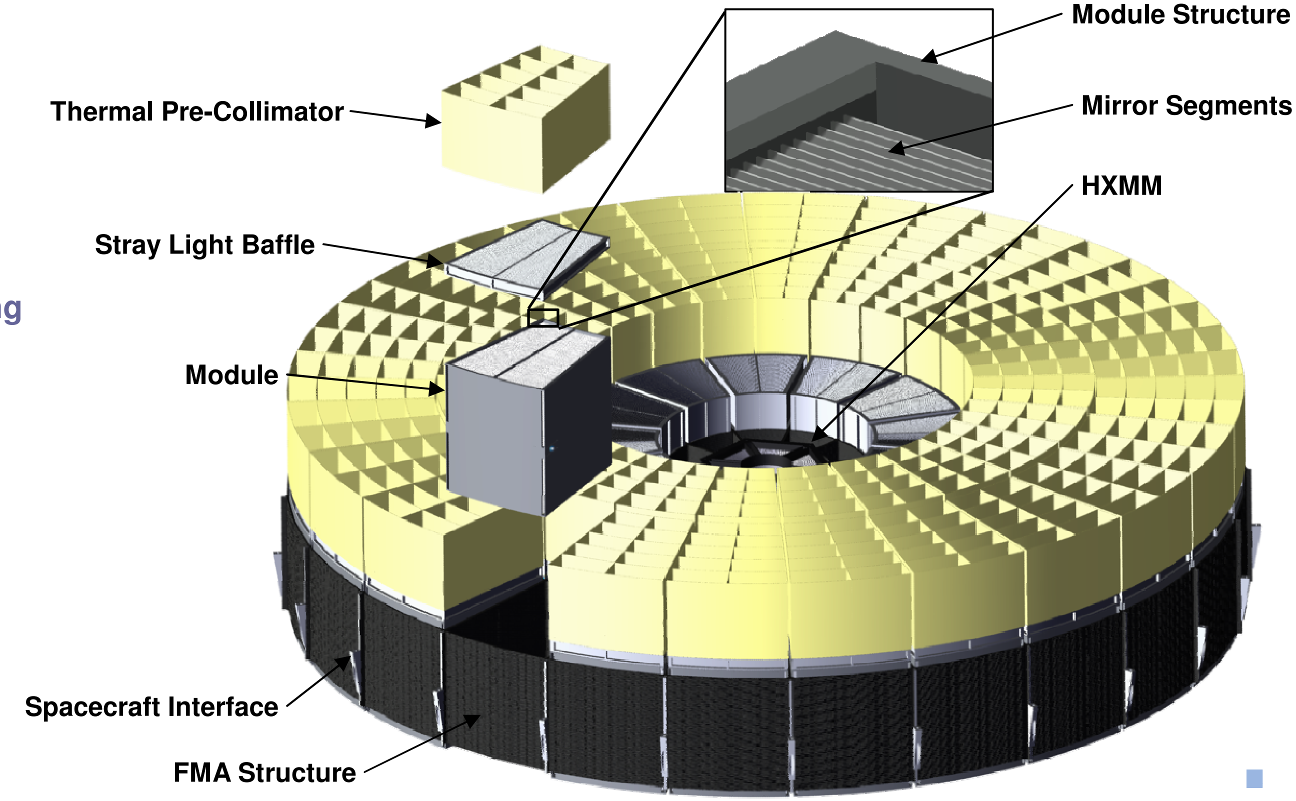


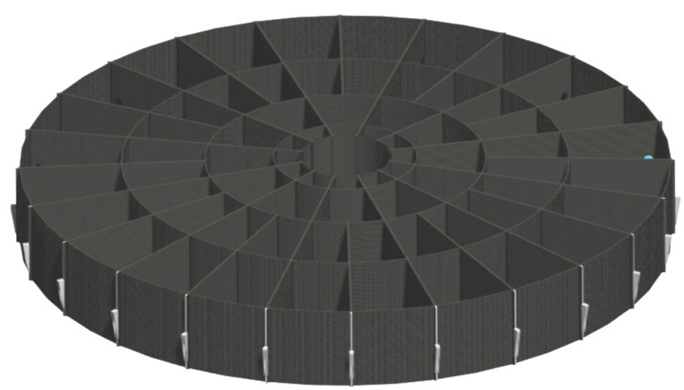
Deployed IXO Configuration

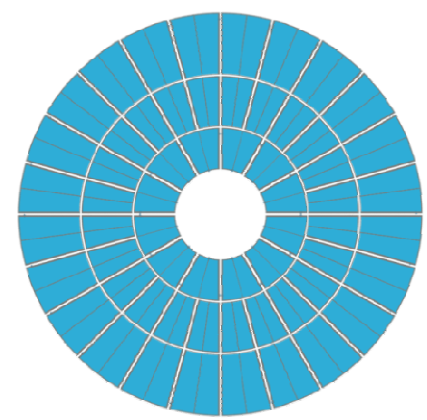
Stowed IXO Configuration

FMA Overview

- Primary Structure
  - Composite carrier for modules
  - Attaches to Spacecraft adapter ring via 24 mounting feet
- 60 SXT modules
  - 12/24/24 layout
  - Kinematically mounted to primary structure
  - Each carries 200-300 glass segments
- HXMM at FMA center
  - Built using existing technology, perhaps similar to NuSTAR
- FMA "just engineering"
  - Standard materials and practices
  - All tech development in Module creation
  - OAP or suspension mount

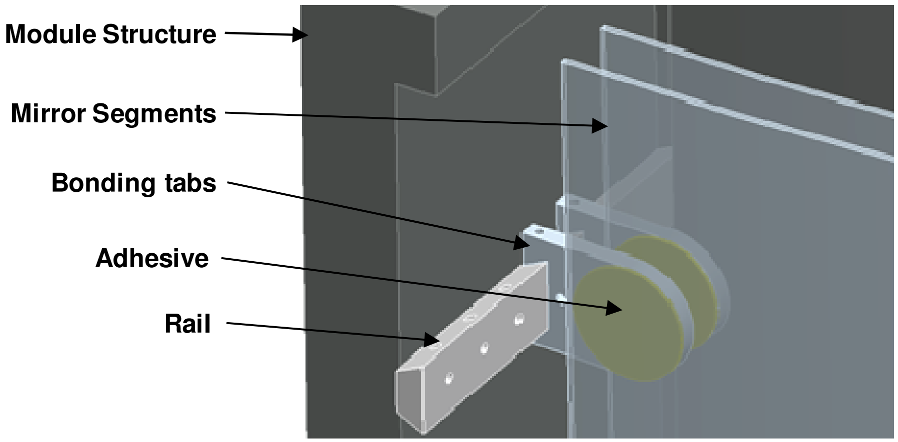


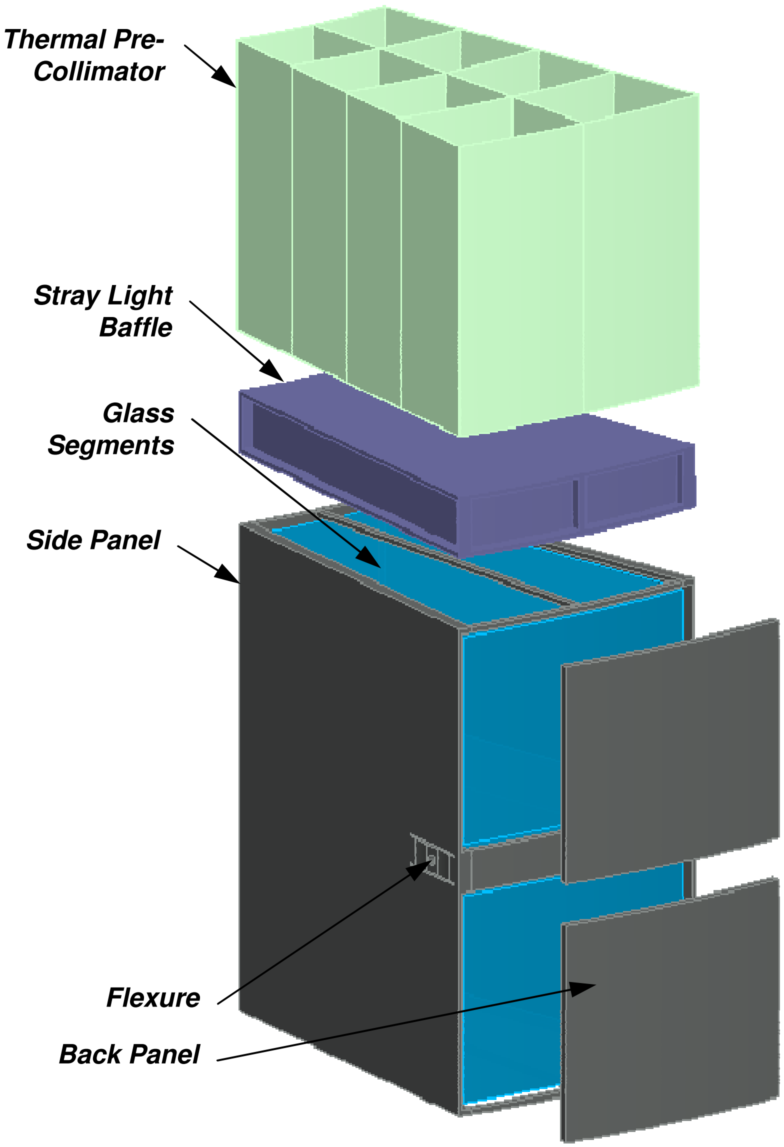




Module Design

- Primary structure
  - Panels on four sides on modules
  - Also protect glass segments from FOD etc.
- Tabs and rails
  - Transfer load from mirrors to primary structure
- Stray light baffle
  - Block single bounce x-rays
  - Heated to control module temperature
- Thermal pre-collimator
  - Limits view of mirrors to space
- Kinematic flexure mounts
  - System of flexures decoupling module deformation from FMA primary structure deformation



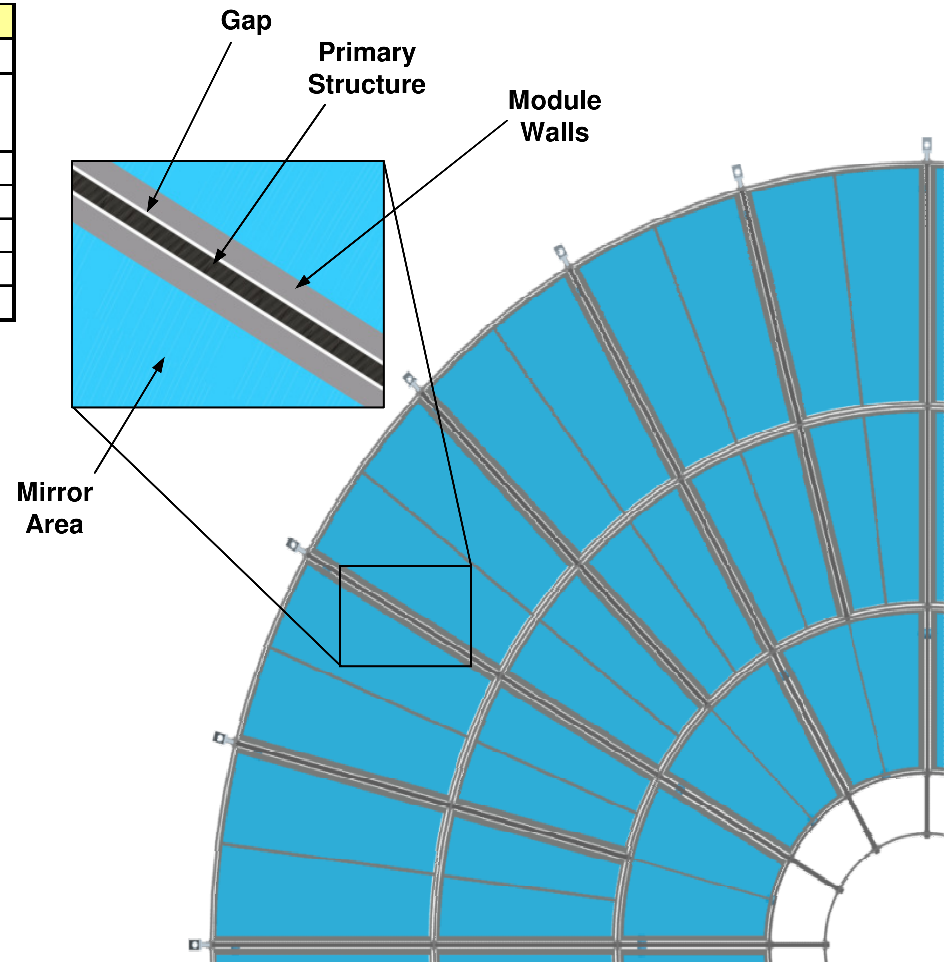


FMA Requirements and Performance

- **FMA design meets requirements to the extent we can currently analyze**

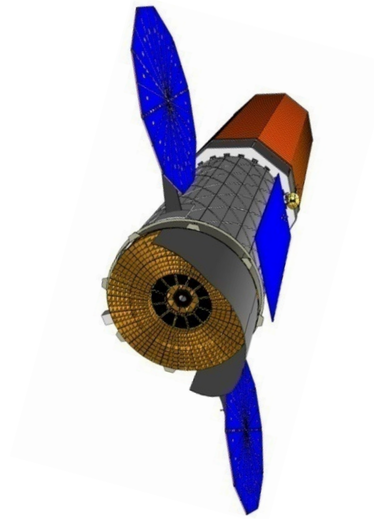
FMA Requirement Summary		
Requirement	**Value**	**Prediction**
Effective Area	3.0 m^2 @ 1.25 keV 0.6 m^2 @ 6.0 keV	3.2 m^2 @ 1.25 keV 0.8 m^2 @ 6.0 keV
Angular Resolution	4.1 arc-sec	TBD
Mass	1750 kg	1731 kg
First Axial Mode	35 Hz	60 Hz
First Torsional Mode	15 Hz	17 Hz
Quasi-static design loads	7.5 g lateral 10.5 g axial	Positive Margins

FMA Summary Mass Information (kg)	
	Current Best Estimate Mass
FMA Total Mass	**1731**
Total SXT Glass Mass	733.2
Total SXT Module Structure Mass	482.1
Total SXT Thermal Heaters System	119.3
Mass of FMA Structure	339.8
Total HXMM Mass	50.8

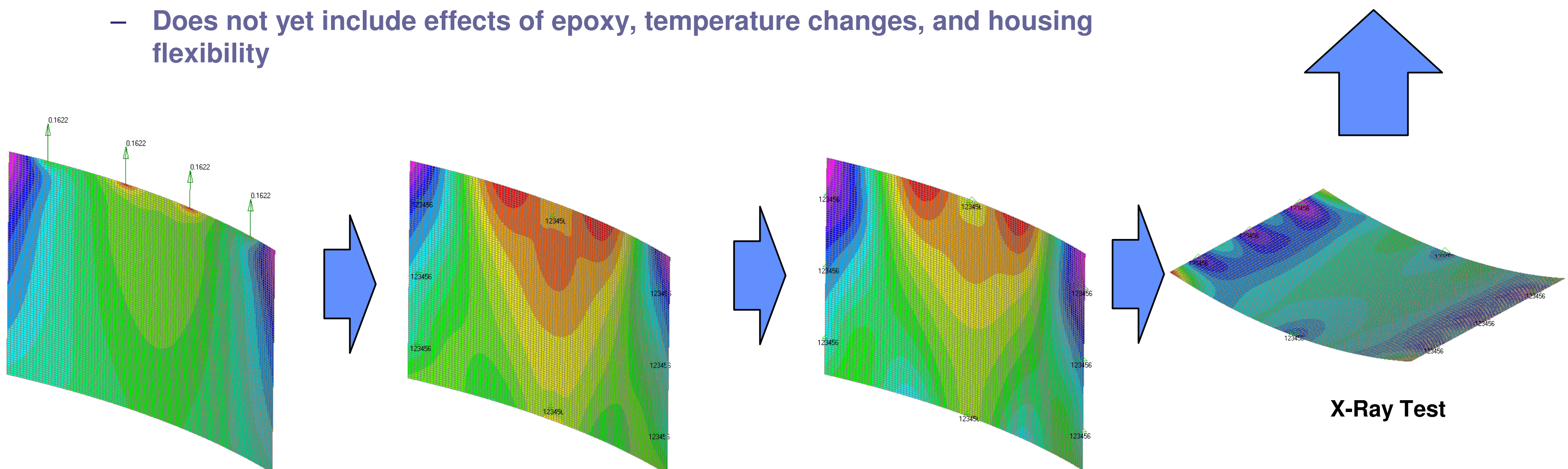


Scaling of Suspension Mount Process

- **Demonstrate suspension mount process is scalable to larger segments while meeting IXO requirements**
  - Largest segments in FMA module design are larger and flatter than segments we can produce with current mandrels
  - 1.2 arc-sec HPD budgeted for alignment and mounting of a mirror pair
- **Optimize suspension mount process**
- **Detailed FEA with distortions carried over from each process to the next**
  - Epoxy bonds represented with 6 dof contraintes
- **Idealized model**
  - Does not yet include effects of epoxy, temperature changes, and housing flexibility



Permanent Bonded 0 g



X-Ray Test

Suspended

Temporarily Bonded

Permanent Bonded

End-to-End Analysis Results – Pair Summary

- **485PS**

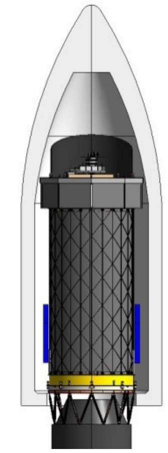
Description	HPD (arc-sec)	RMS (arc-sec)	Radius Var. (RMSum)	Cone Ang Var (RMSarc-sec)	Sag var (RMSum)
Primary hung	0.3	1.4	0.03	0.06	0.02
Primary temp bonded	0.2	0.6	0.11	0.04	0.02
Primary permanent bonded	0.3	0.6	0.03	0.05	0.01
Secondary hung	0.3	1.4	0.02	0.09	0.02
Secondary temp bonded	0.5	0.7	0.02	0.12	0.02
Primary perm w/ Secondary temp	0.6	0.9			
Pair permanent bonded	0.5	0.8			
Pair horizonral X-ray	1.3	9.9			
Pair 0 g on-orbit	0.5	0.7			

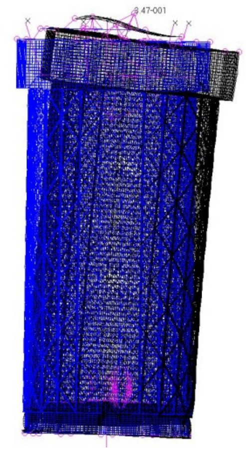
- **1386PS**

Description	HPD (arc-sec)	RMS (arc-sec)	Radius Var. (RMSum)	Cone Ang Var (RMSarc-sec)	Sag var (RMSum)
Primary hung	0.4	2.8	0.12	0.19	0.02
Primary temp bonded	0.9	1.3	0.12	0.27	0.03
Primary permanent bonded	1.0	1.4	0.12	0.31	0.02
Secondary hung	0.3	2.7	0.13	0.11	0.02
Secondary temp bonded	0.7	1.1	0.13	0.20	0.03
Primary perm w/ Secondary temp	0.6	0.9			
Pair permanent bonded	0.5	0.8			
Pair horizonral X-ray	1.5	19.1			
Pair 0 g on-orbit	0.5	0.7			

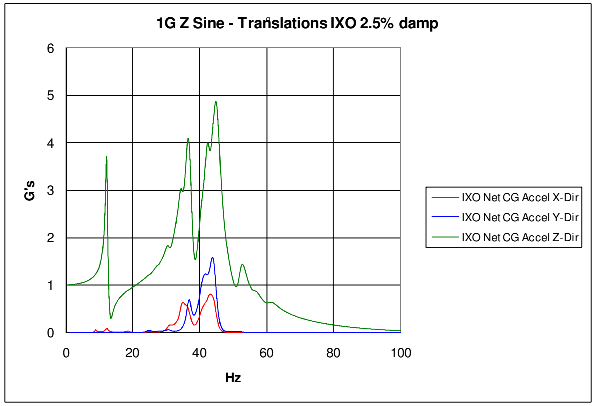
- **Results in-line with error budget per Mirror Technology Development Roadmap**
- **No difference in final on-orbit HPD between 485 and 1386 pairs**

Mirror Structural Analysis

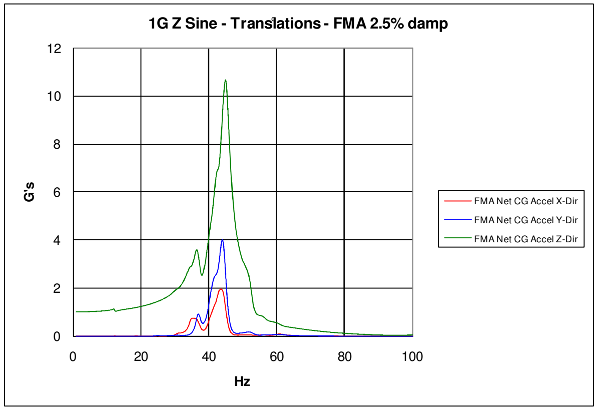




- Developed robust stress margins for mirrors
  - Quasi-static design loads
  - Glass allowable
  - FEA stress prediction
- Verify with testing



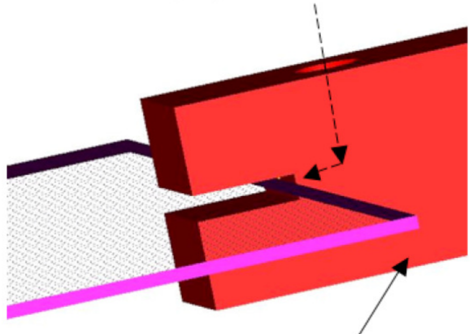
- Quasi-static design loads determined by sine response analysis
  - Apply sine input at launch vehicle interface per Atlas V users guide (sine equivalent dynamics)
  - Improved fidelity vs. generic Mass Acceleration Curve in absence of Coupled Loads Analysis
  - Recover cg accelerations of spacecraft, FMA, and module
  - Inner module accelerations worst case
- Results
  - FMA: 10.5 axial, 7.5 lateral
  - Module: 18.0 axial, 8.5 lateral



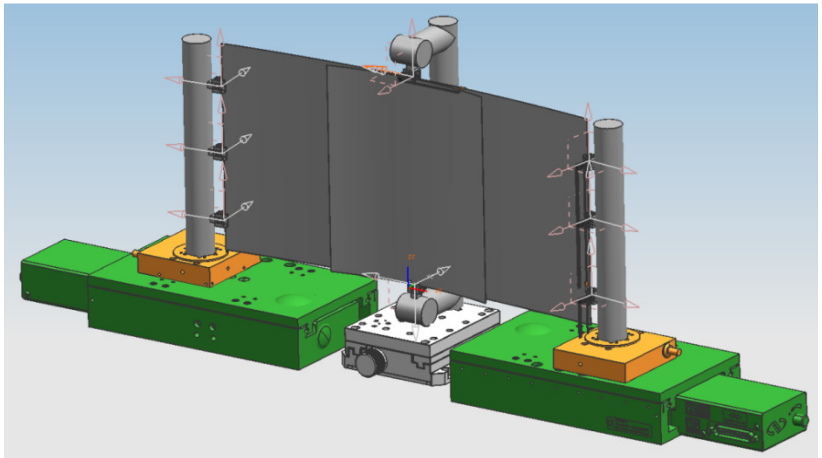
Glass Strength Determination

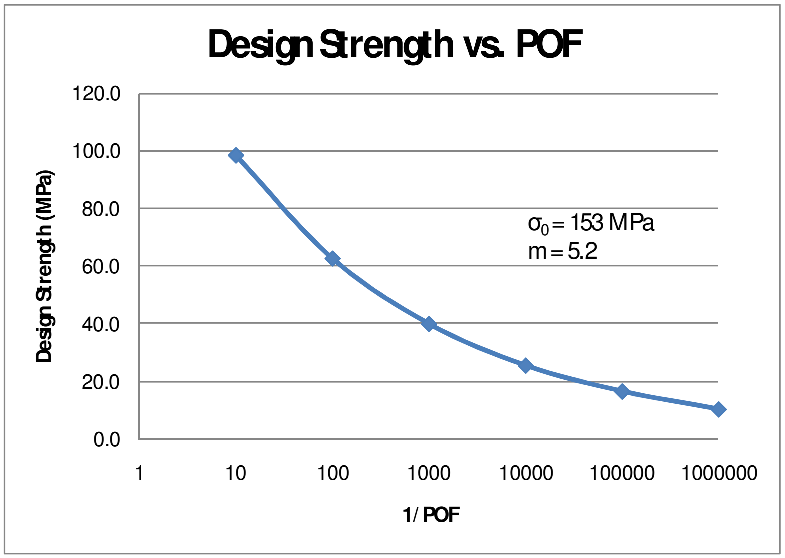
- Strength of glass characterized by testing of a single bonded joint
  - Weibull parameters determined; σ_0 = 216 MPa, m = 5.2
  - Strength scaled by test area vs. application area

$$POF = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^m\right] \qquad \frac{\sigma_1}{\sigma_2} = \left(\frac{A_2}{A_1}\right)^{\frac{1}{m}}$$



- Due to large number of glass segments and desired reliability design strength would be 10MPa using statictical analysis
- Proof test each segment to screen weak segments
  - Apply design stress to glass bond areas
  - Weibull analysis determines scrape rate from testing
- Baseline 40 MPa design strength

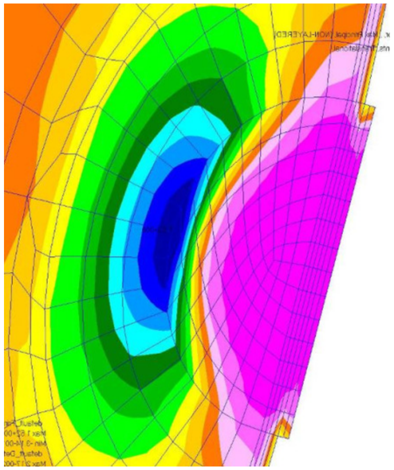




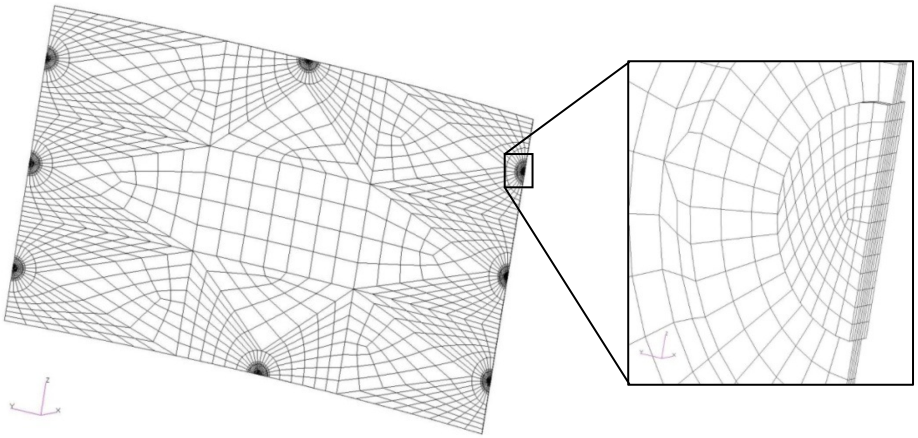
Stresses and Margins

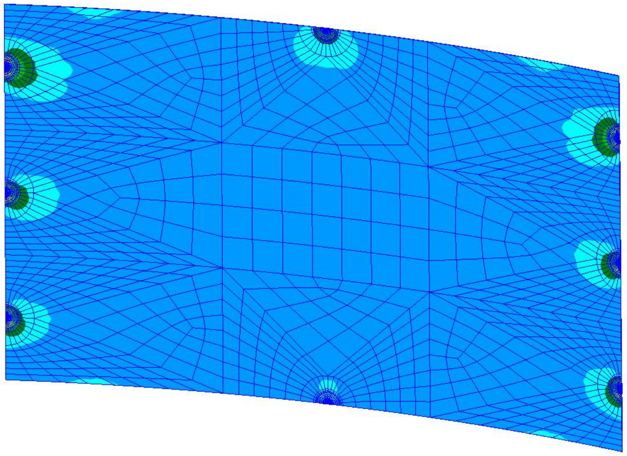
$$MS = \frac{\sigma_{all.tu}}{\sigma_{max.prin} \cdot FS} - 1$$

- Created detailed solid element FEM of worst case segment
  - Used baseline Suspension Mount permanent bonding points
  - Also investigated effect of bond shape and adhesive stiffness
- Quasi-static design loads applied
- Maximum principal stress criteria used
- Factor of Safety 3.0 per NASA-STD-5001



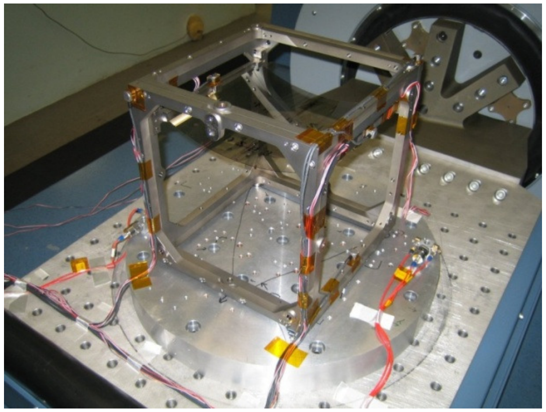
Stress Margin Summary - Solid Model With Epoxy - 2 Sided, Fully Constrained		
Axis	Stress at Predicted QSL	Margin of Safety
Combined X and Z	3.07	3.3
Combined Y and Z	2.86	3.7
Combined 45° and Z	2.39	4.6

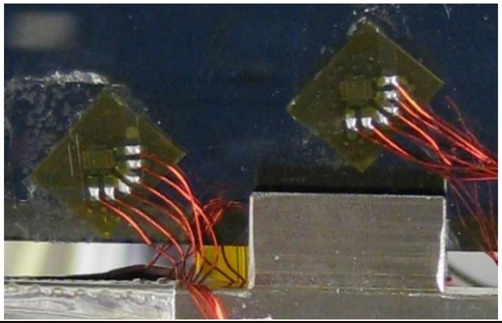




Environmental Testing

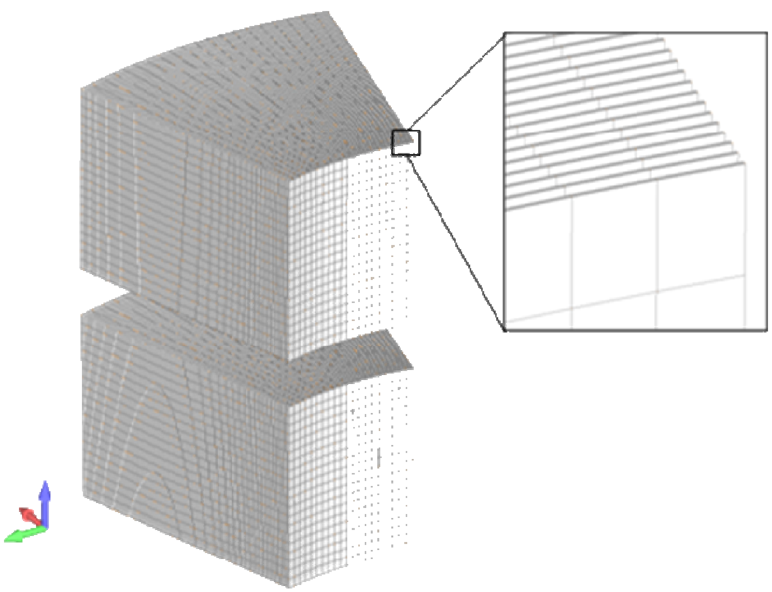
- Performed a series of test on single and multiple mirror mounted in a simulated housing
  - Modal tap test
  - Sine and random vibration test
  - Acoustic tests
    - Single mirror in open structure
    - Three mirrors in closed-out structure
    - Closed out structure exhibited much lower stresses
    - Tested at Atlas 551 qualification levels
- Good acceleration and stress correlation with FEA
- Mirror figures did not change as a result of testing
- Combination of detailed FEA and extensive testing give us high confidence FMA can be successfully launched

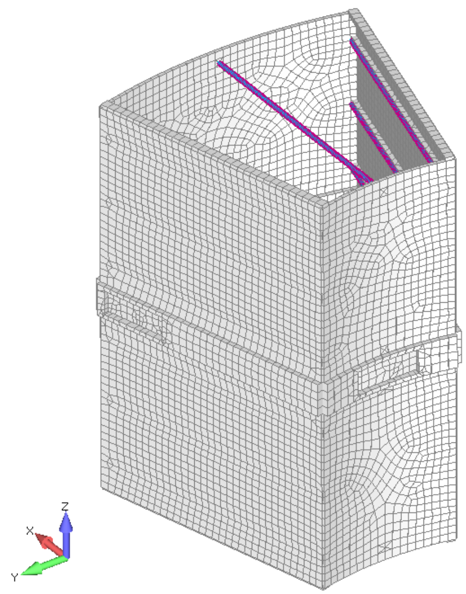




Preliminary STOP Analysis

- **Sensitivity to thermal loads investigated using Structural Thermal Optical Performance (STOP) analysis**
- **Process**
  - **Generate geometrically correct FEM of all segments in module using custom software**
  - **Combine with module structure FEM**
  - **Apply thermal loads**
  - **Recover distortions of mirror surfaces**
  - **Predict module performance with custom ray-tracing software**

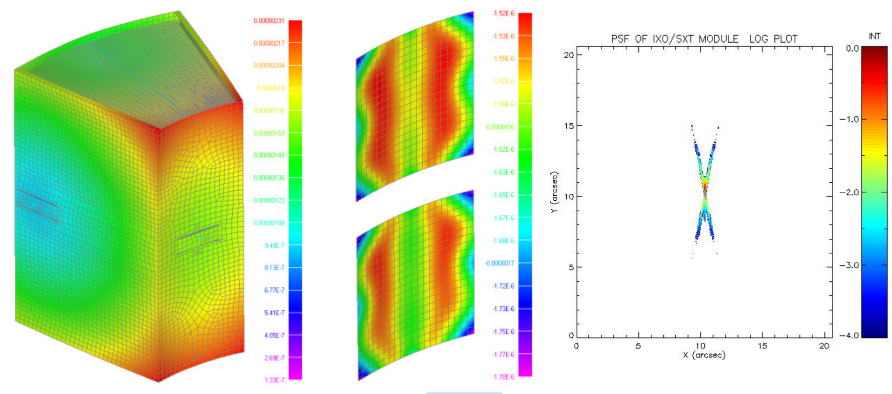


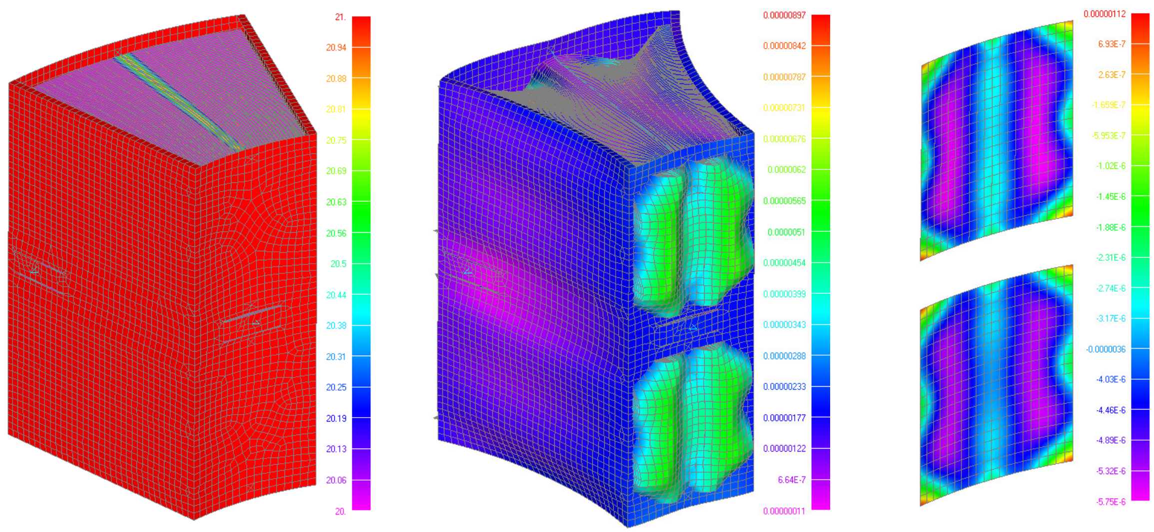


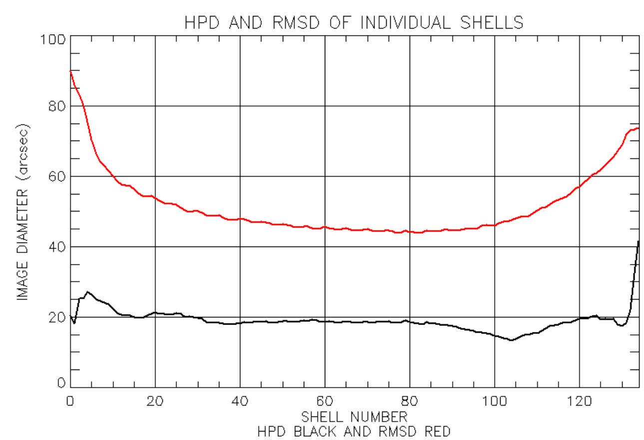
Preliminary STOP Analysis - Results

- Sensitivity to CTE mismatch and thermal gradient between mirrors and module structure

Case	HPD (arc-sec)	RMS Diameter (arc-sec)
1C Bulk Temperature 0.0ppm/C CTE Mismatch	0.0	0.0
1C Bulk Temperature 0.2ppm/C CTE Mismatch	0.6	1.6
1C Bulk Temperature 0.4ppm/C CTE Mismatch	1.2	3.2
1C Bulk T CTE Match with Flexures	2.6	3.7
1C Bulk T CTE Match with Half Thickness Flexures	0.5	0.6
Structure 21C, Segments 20C	19.5	52.9
Structure 21C, Segments 20C CTE Matched	20.0	54.5
Structure 22C, Segments 20C ideal CTE	0.0	0.0





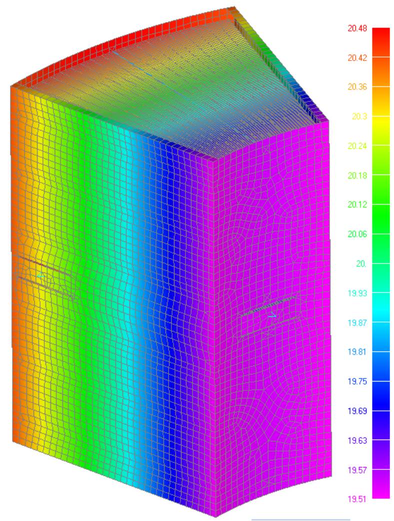


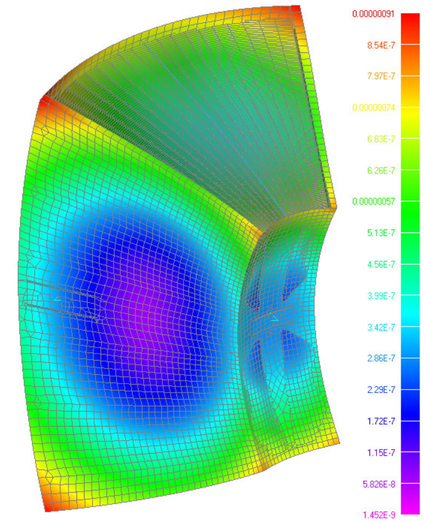
Preliminary STOP Analysis - Results

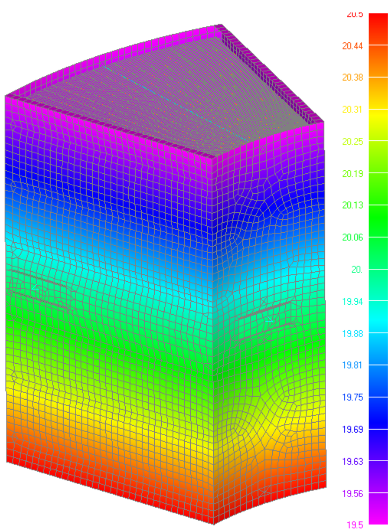
- Sensitivity to thermal gradients

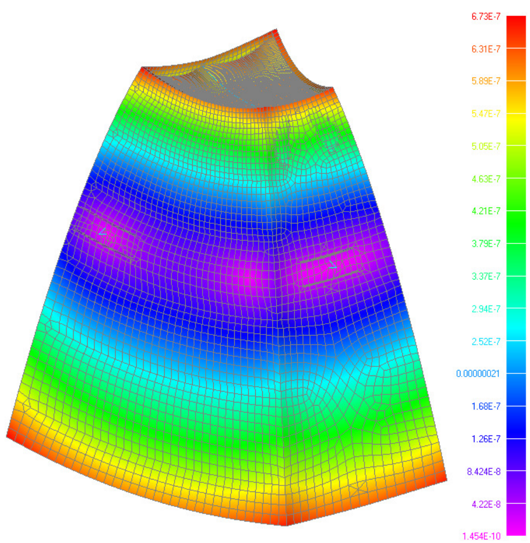
(arc-sec)

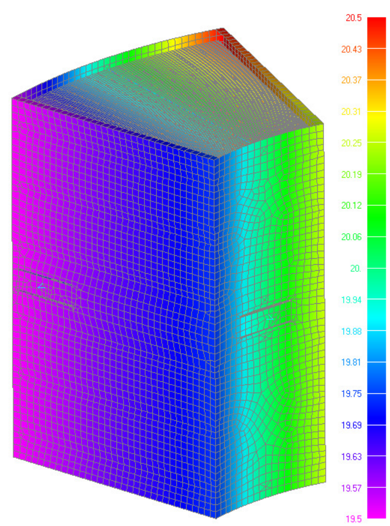
Case	HPD	RMS Diameter
1C radial Gradient	1.6	1.9
1C tang Gradient	0.3	0.6
1C axial Gradient	0.1	0.1

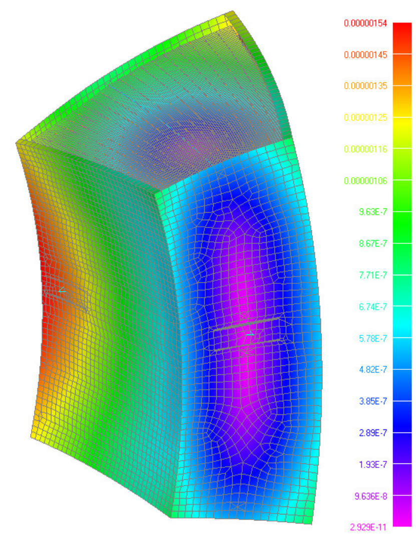








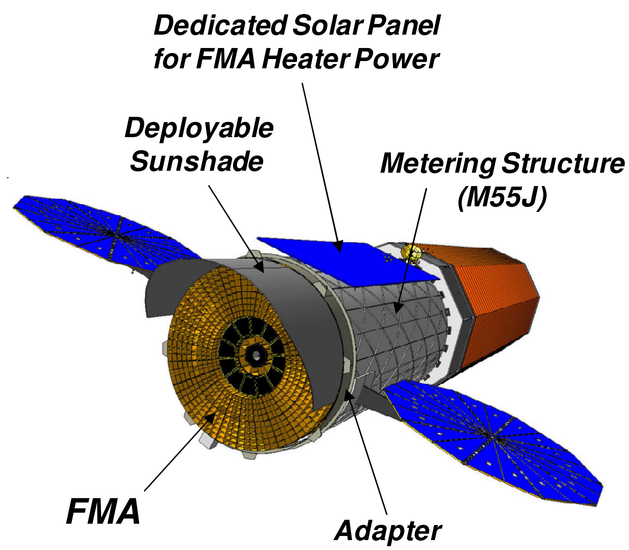


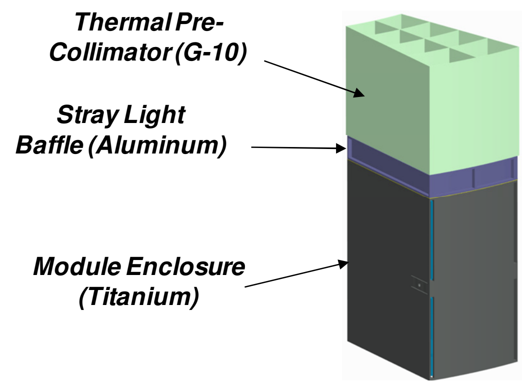


Thermal Design and Analysis

- Thermal design based on keeping modules at room temperature
  - Preliminary STOP analysis guides design
  - 1.0 arc-sec HPD budgeted for thermal effects
- Stable thermal environment
  - L2 orbit
  - Earthshine and moonshine thermally negligible
  - ±20º yaw, ±5º roll limitations
- Thermal control method
  - Cold bias to allow for active heater control
  - MLI on structure exterior
  - Deployable sunshade
  - Heat pipes around spacecraft adapter ring
  - Active heater control on Stray Light Baffle and forward section of Metering Structure
  - Limit heat loss from mirrors with Thermal Pre-Collimators

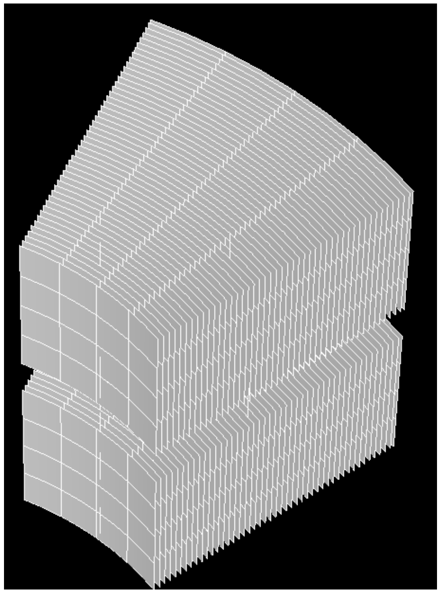
FMA Thermal Requirements	
Operating Temperature	20C±1C
Module Gradient	<1C
Survival Temperature	10C-30C
Maximum Heater Power	1540 W

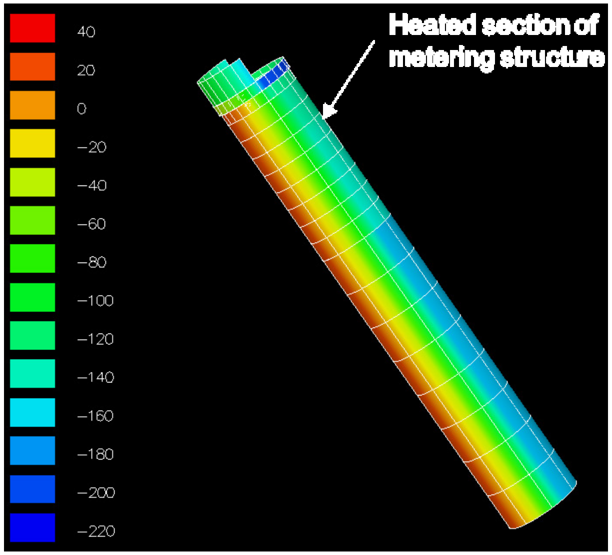


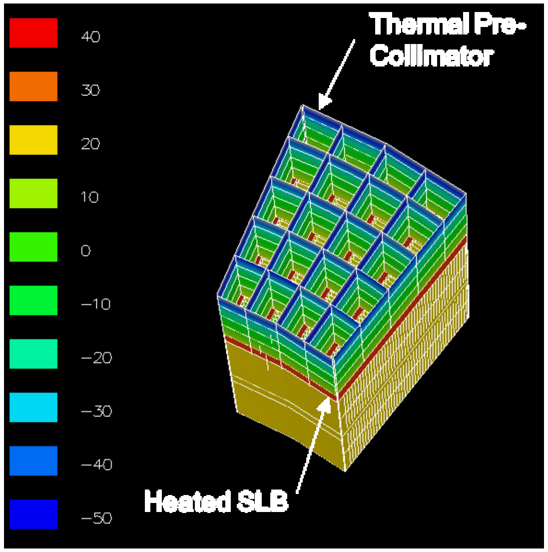


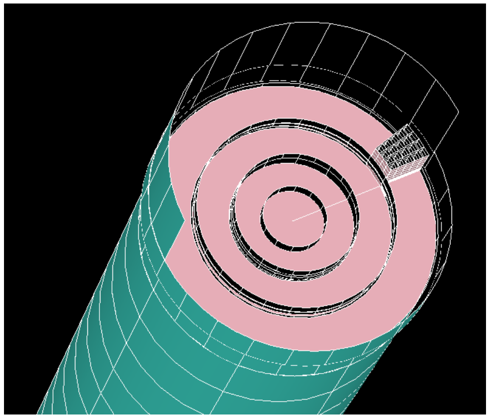
Thermal Analysis

- Thermal Model
  - All segments modeled
  - Each module controlled independently
  - 5 million+ radiation couplings
  - Separate model for inner, middle, outer
    - Outer is worst case
  - Poor conductive coupling between mirrors and structure
  - 1540 Watts needed









Conclusions and Future Work

- Baseline design and analysis of the FMA complete with level of detail commensurate with Pre-Phase A
- Design meets requirements using standard engineering materials and practices
- Additional detailed analysis performed to mitigate specific risks
  - Scaling of Suspension Mount process
  - Glass launch stresses
  - Thermal distortion of modules
- Future work
  - Include epoxy, thermal, and housing stiffness effects in end-to-end analysis
  - Shock test of three mirror test article
  - Mature thermal design and analysis to verify performance