Opto-Mechanical Analyses for Performance Optimization of Lightweight Grazing-Incidence Mirrors

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Motivation

- New technology in grazing-incidence mirror fabrication and assembly is necessary to achieve sub-arcsecond optics for large-area x-ray telescopes.
- In order to define specifications, an understanding of performance sensitivity to design parameters is crucial.
- Because the lightweight mirrors are typically flimsy, they are susceptible to significant distortion due to mounting and gravitational forces.
- Material properties of the mirror substrate along with its thickness and dimensions significantly affect the distortions caused by mounting and gravity.
- A parametric study of these properties and their relationship to mounting and testing schemes will indicate specifications for the design of the next generation of lightweight grazing-incidence mirrors.

Guiding Principles and Assumptions

1. Do not design the mirror assembly to address thermal and vibration considerations. At least initially, assume that external hardware will provide adequate thermal stability and vibration isolation.
2. Do not design the mirror assembly for 1-g operations in a horizontal orientation. Assume that the mirror assembly will be vertical during alignment, assembly, metrology, and x-ray testing.
3. Do not design the mirror assembly to satisfy an arbitrary mass limit. To the extent possible, scientific performance should take precedence over initial programmatic constraints on mass.
4. Our goal is sub-arcsecond imaging. Achieving 5" would indicate progress, but it's not where we need to be.

Typical Hardware Configurations

- Nested full shells
- Segmented configurations
- Thin glass or nickel
- Thicker lightweight materials

Parameters and Requirements

- Requirements
  - Performance:
    - Resolution
    - Field-of-view
    - Effective Area
  - Properties:
    - Mass
    - Focal Length
  - Interfaces:
    - Thermal
    - Mechanical
    - Optical
  - Testing:
    - Ground
    - Off-loading
    - Verify-by-analysis
    - Horizontal or Vertical
    - In-Flight

- Relevant Design Parameters
  - Material Properties:
    - Modulus of Elasticity,
    - Poisson's Ratio,
    - Density,
    - Tensile/Shear Strength
  - Shell Dimensions:
    - Radius,
    - Length,
    - Thickness,
    - Prescription
  - Mounting Locations:
    - Quantity,
    - Azimuthal Distribution,
    - Axial Distribution
  - Mount characteristics:
    - Translational Constraints and Stiffness,
    - Rotational Constraints and Stiffness

Plan for FEA Approach

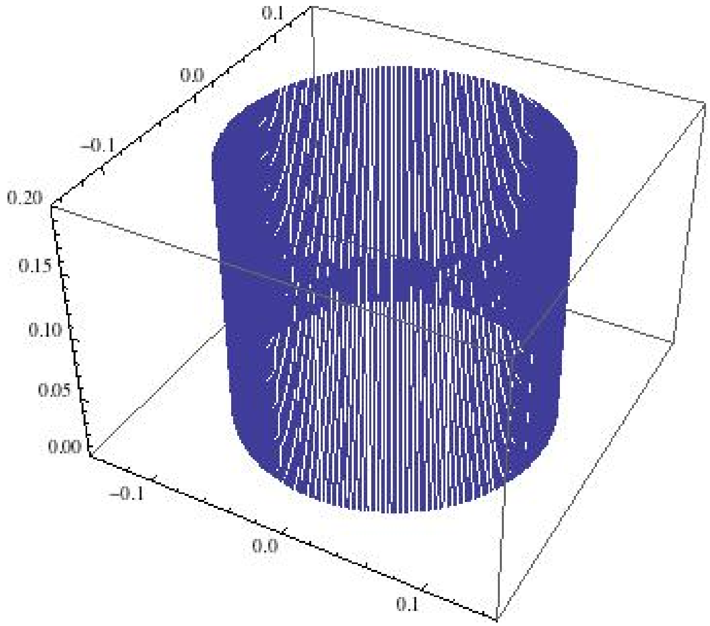
- **Start with simple configurations**
  - cylindrical shell
  - small number of mounting points, e.g. 3
- **Validate**
  - Compare with analytical models
  - Compare with direct metrology
- **Explore parameter space with analytical models**
  - We are using Mathematica code to produce low-order expansions of solutions
  - Can quickly explore a large volume of parameter space
- **Verify conclusions with FEA**
  - Home in on optimal configurations
- **Add required complexity to FE Models, gauging contributions to performance of each**
  - prescription
  - P-H interface
  - segmented configurations
  - gravity corrections
  - active adaptive components
  - mounting details
  - prototype design
- **Build and Test Prototypes**

Special Considerations

- **Accuracy required for optical performance determination is generally higher than that needed for determining stress margins**
  - slope errors are determined by short range differencing
  - The scale depends on the distance between nodes
- **Removal of digital artifacts by filtering is undesirable**
  - conclusions may depend on the filtering method
- **X-ray optics provide some unique challenges**
  - Much larger surface areas
  - limited space and access for mounting hardware

Sample Model

- FEA Code: ANSYS
- Simple cylindrical shell
  - Parameters
    - length = .198 m
    - radius = .113 m
    - thickness = .00008 m
    - Poisson's Ratio = 0.3
    - Young's Modulus = 130 GPa
    - k = 16 mN/mm so apply a force to produce about 10 microns is 0.16 mN.
- FEA Parameters
  - Number of axial nodes: 201
  - Number of azimuthal nodes: 360



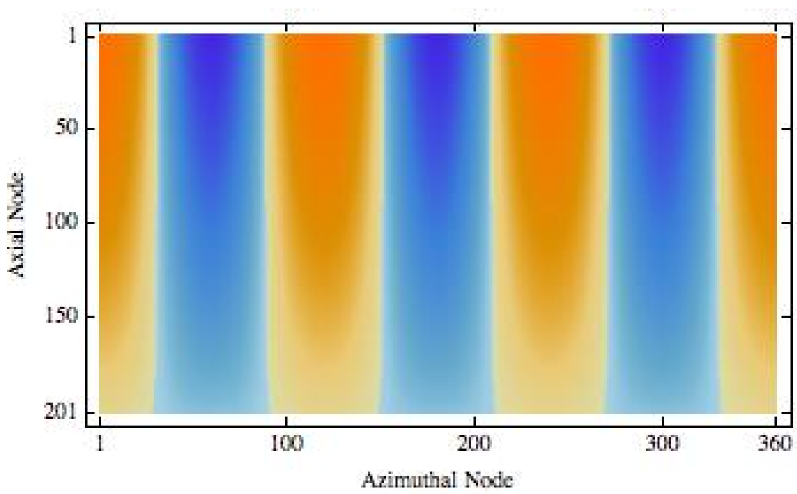
Sample FEA Results

- Application of 0.160 mN force at 3 points at axial station z=0 results in the deflection pattern shown below, max. deflection=10 microns.
- Performance, σ, is 5 arcsec RMS, estimated based on induced axial slope errors as follows:

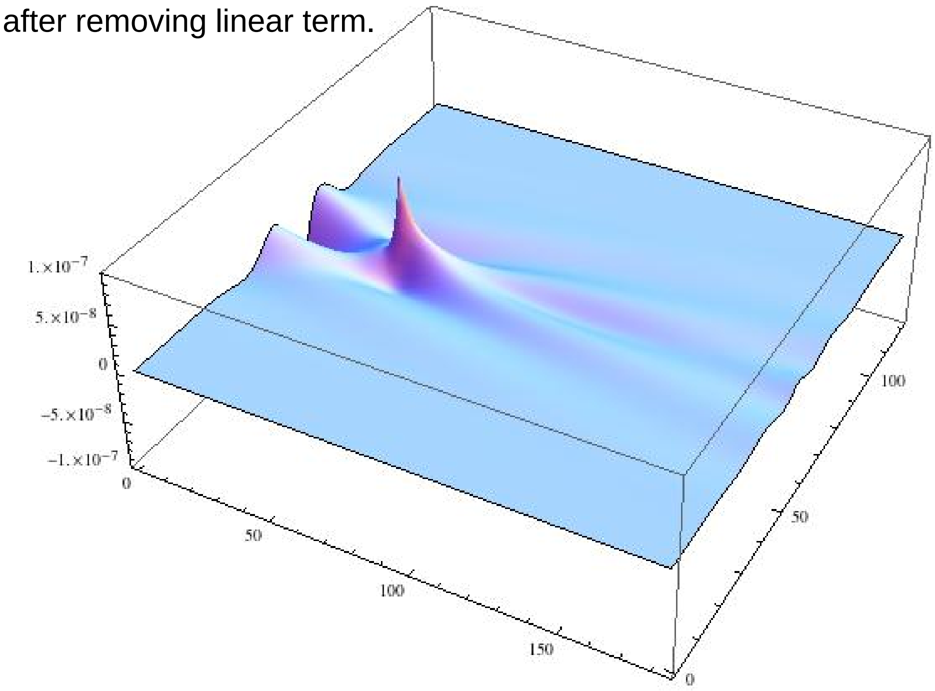
$$\sigma = \sqrt{\int_0^{2\pi} \int_0^{L/2} 2(\Delta\theta(z) - \Delta\theta(L-z))^2 d\phi dz / \pi L},$$

where $\Delta\theta(z)$ is the deflection-induced axial slope error

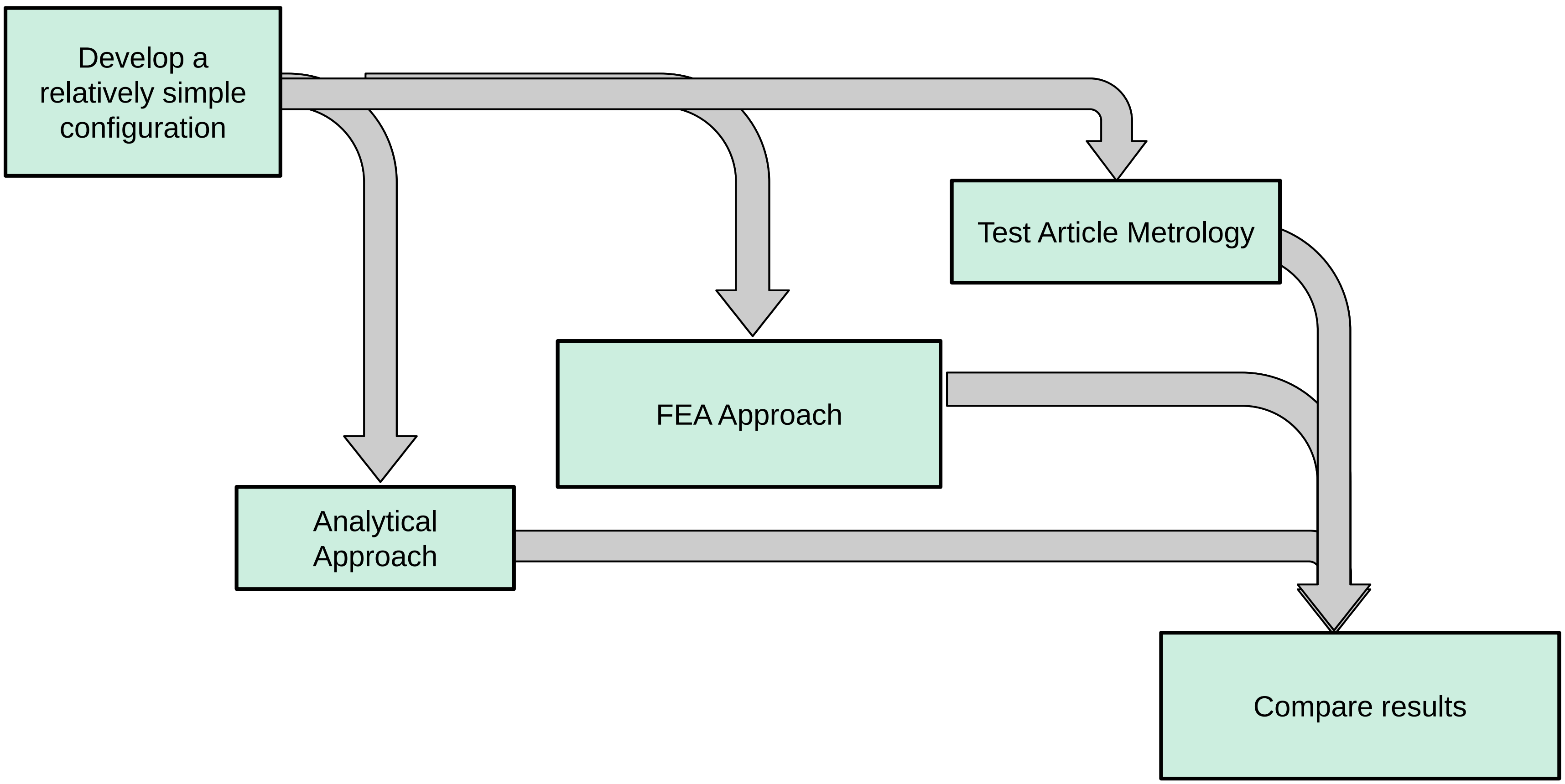
Shell Deflection Pattern



Deflection Pattern over 120° of azimuth after removing linear term.



Validation


Develop a relatively simple configuration
Test Article Metrology
FEA Approach
Analytical Approach
Compare results

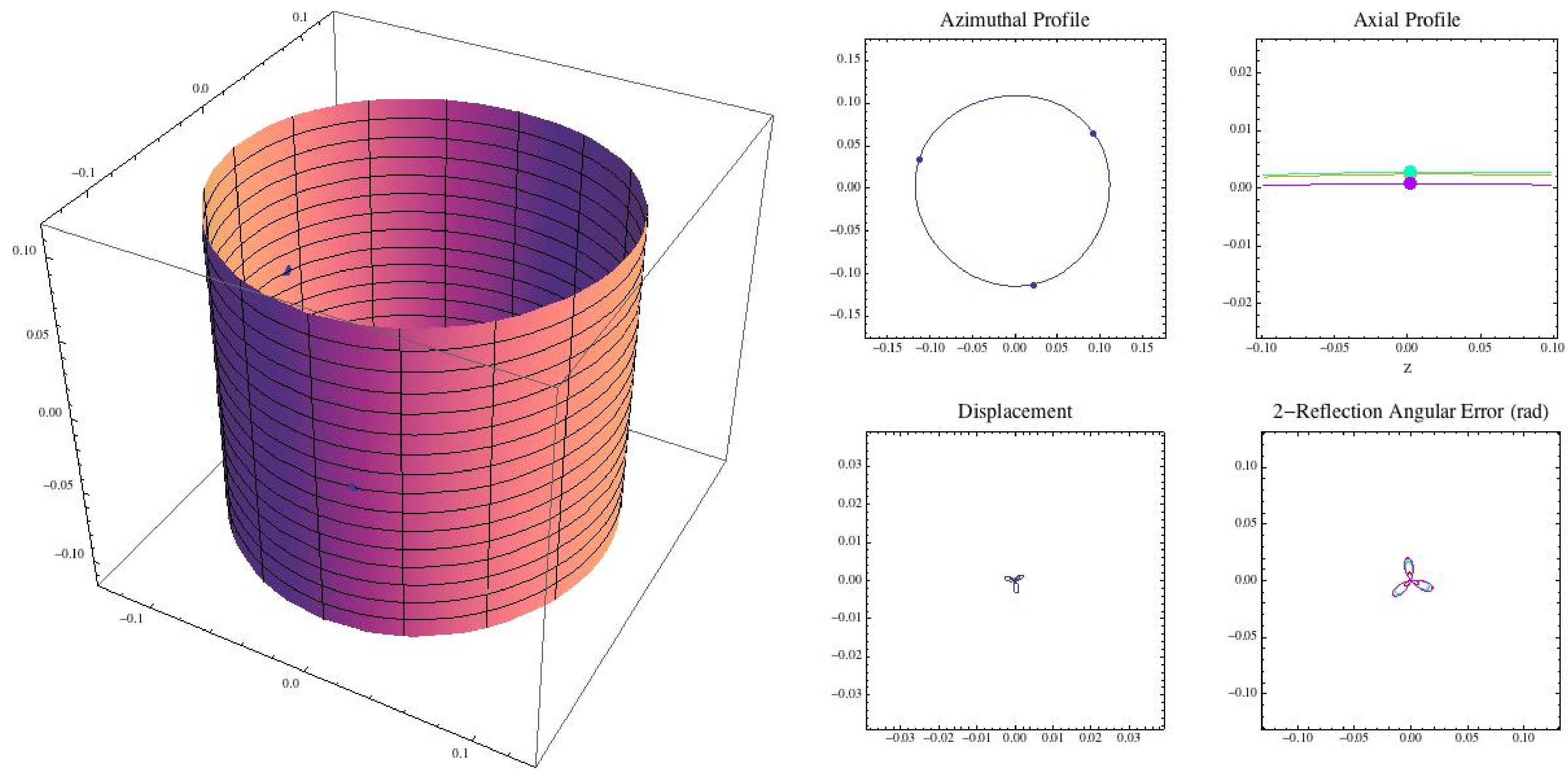
Analytical Model

- Kirchhoff-Love Theory: Linear theory of thin elastic shells
- Assumptions
  - Kirchhoff-Love Assumptions: neglect strains normal to middle surface; displacement<<shell thickness
  - Coplanar mounting points orthogonal to optical axis
  - Plate-like deflection with periodic boundary conditions
  - Neglect cone angles
- Steps
  - Select mounting locations and characteristics
  - Determine boundary conditions
  - Solve for deflections using variational principles for the stationary point of the static total Lagrangian
- General Solution for cylindrical shell
  - Solve for deflection, $\eta(\theta, z)$: $$\nabla^2\nabla^2\eta(\theta, z) = C\,\delta(z - z1)\sum_{n=0}^{\infty} k(n,1)\cos(\theta\, n) + k(n,2)\sin(\theta\, n)$$
  - solution for the n^{th} harmonic of θ, n initially limited to 2&3:

$$
\begin{aligned}
&f(n, \theta, z, R, z1) = \\
&\cos(\theta\, n)\left(\frac{a(n,1,5)}{2\,n^3}\,\theta(z - z1)\left(\frac{n\,(z - z1)}{R}\cosh\left(\frac{n\,(z - z1)}{R}\right) - \sinh\left(\frac{n\,(z - z1)}{R}\right)\right) + a(n,1,3)\sinh\left(\frac{n\,z}{R}\right) + a(n,1,4)\,\frac{n\,z}{R}\sinh\left(\frac{n\,z}{R}\right) + a(n,1,1)\cosh\left(\frac{n\,z}{R}\right) + \right.\\
&\qquad\left. a(n,1,2)\,\frac{n\,z}{R}\cosh\left(\frac{n\,z}{R}\right)\right) + \\
&\sin(\theta\, n)\left(\frac{a(n,2,5)}{2\,n^3}\,\theta(z - z1)\left(\frac{n\,(z - z1)}{R}\cosh\left(\frac{n\,(z - z1)}{R}\right) - \sinh\left(\frac{n\,(z - z1)}{R}\right)\right) + a(n,2,3)\sinh\left(\frac{n\,z}{R}\right) + a(n,2,4)\,\frac{n\,z}{R}\sinh\left(\frac{n\,z}{R}\right) + a(n,2,1)\cosh\left(\frac{n\,z}{R}\right) + \right.\\
&\qquad\left. \frac{n\,z}{R}\,a(n,2,2)\cosh\left(\frac{n\,z}{R}\right)\right)
\end{aligned}
$$

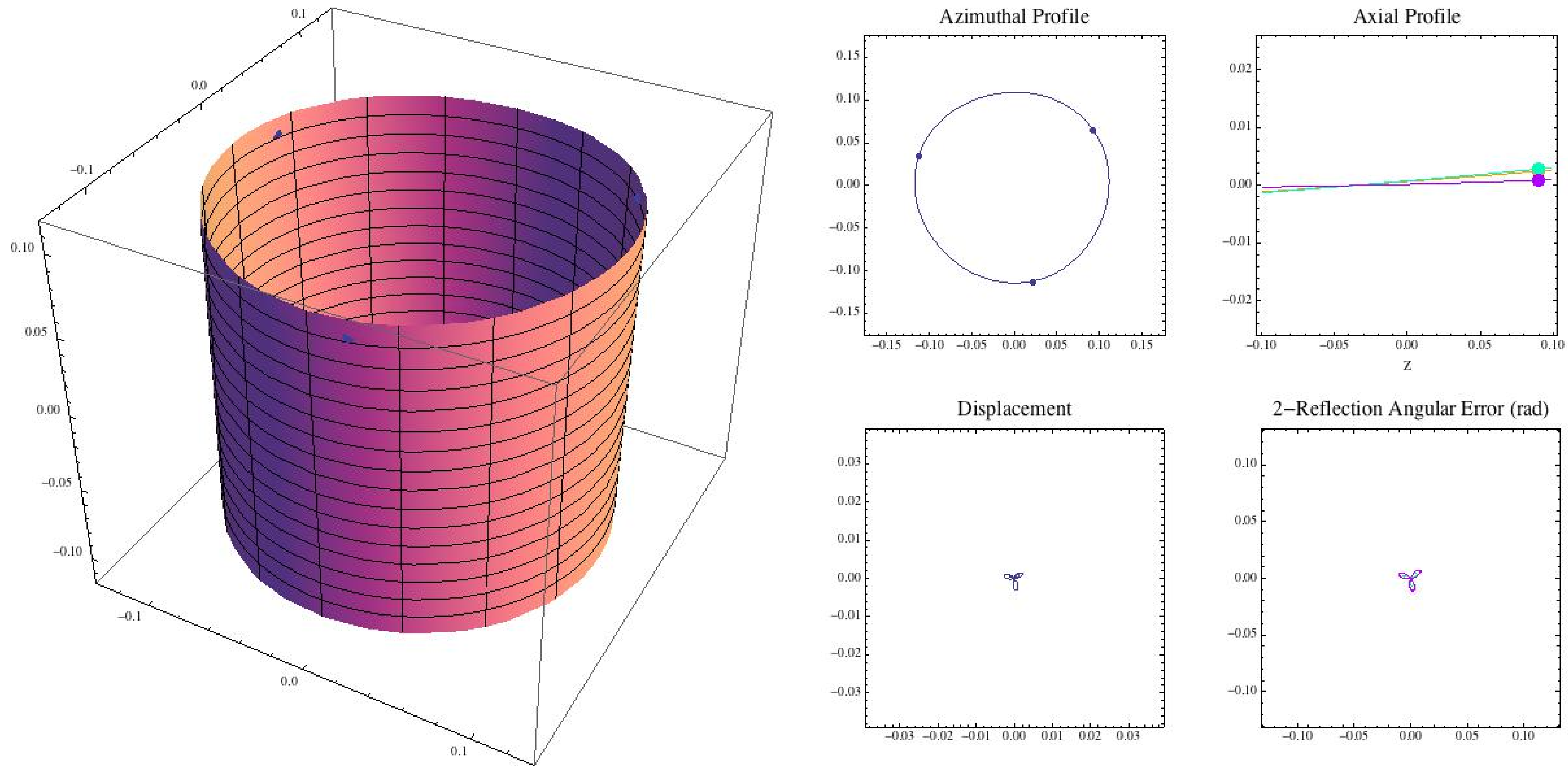
Visualization

- Animation of deflection patterns for applied loads at axial center
  - deflection pattern is exaggerated



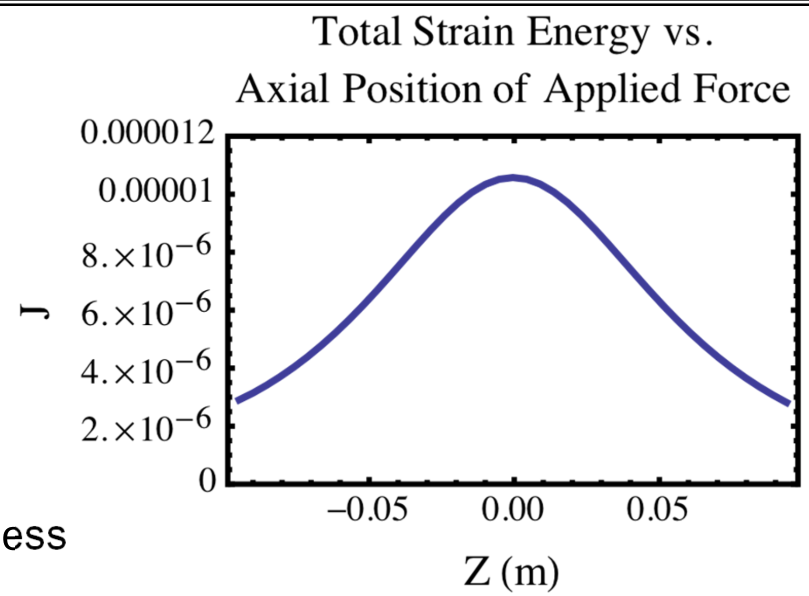
Visualization

- Animation of deflection patterns for applied loads at axial edge

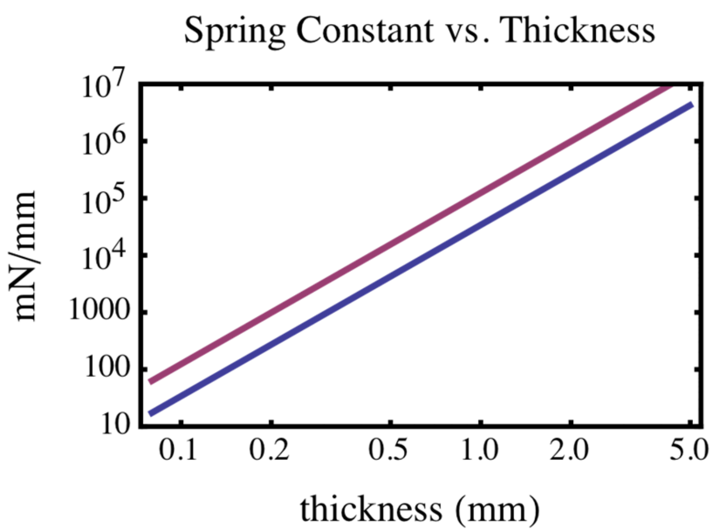


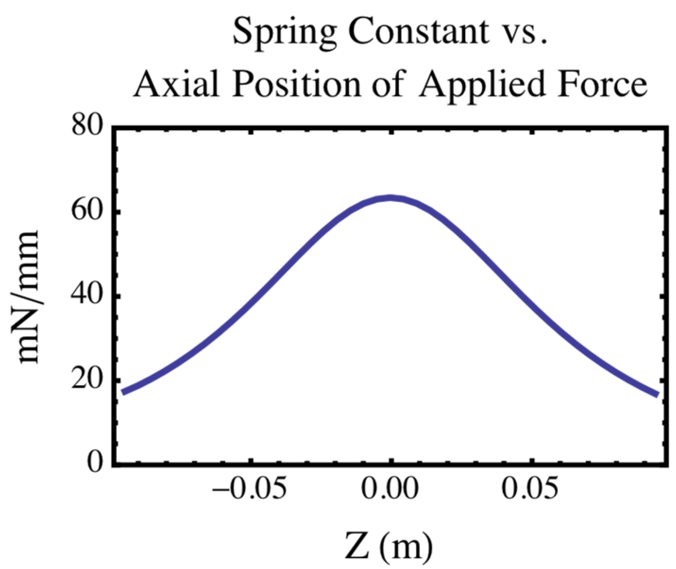
Parametric Studies

- Axial Position dependence of spring constant
  - ~4x higher spring constant at center vs. edge



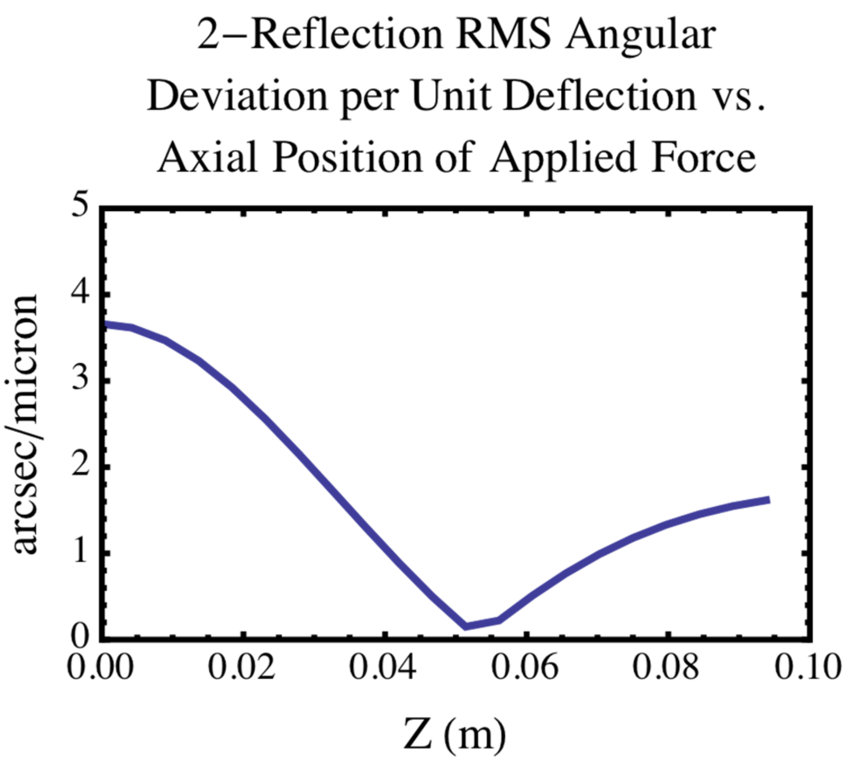
- Center(red) and edge(blue) stiffness vs. thickness

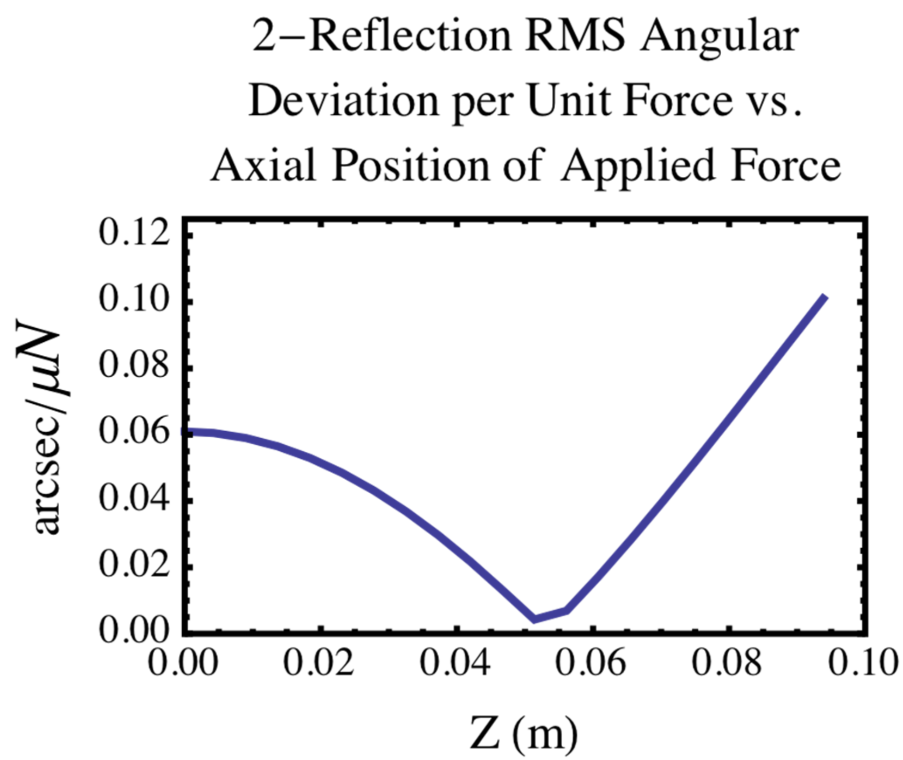




Example: Performance vs. Axial Mounting Location

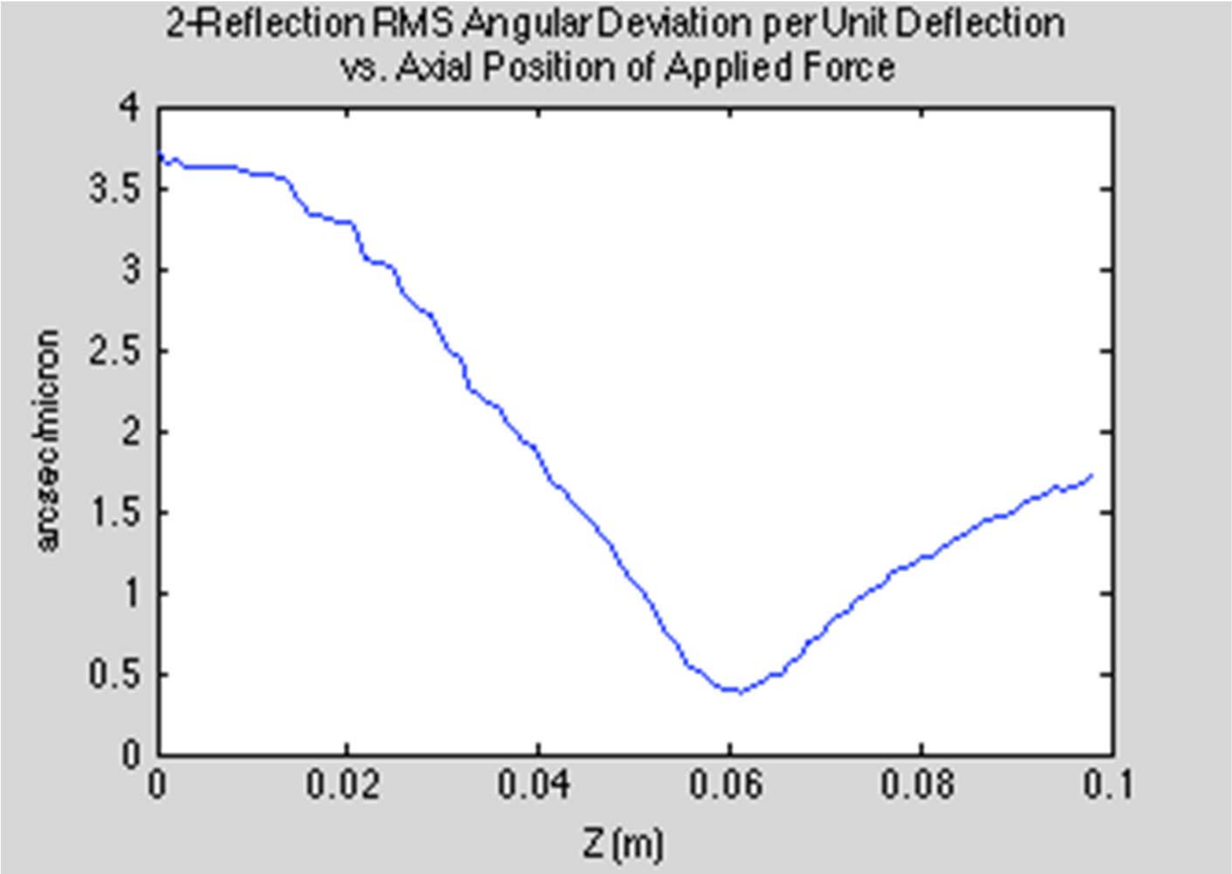
- 2-reflection RMS angular deviation
  - constant deflection
  - constant force





FEA comparison

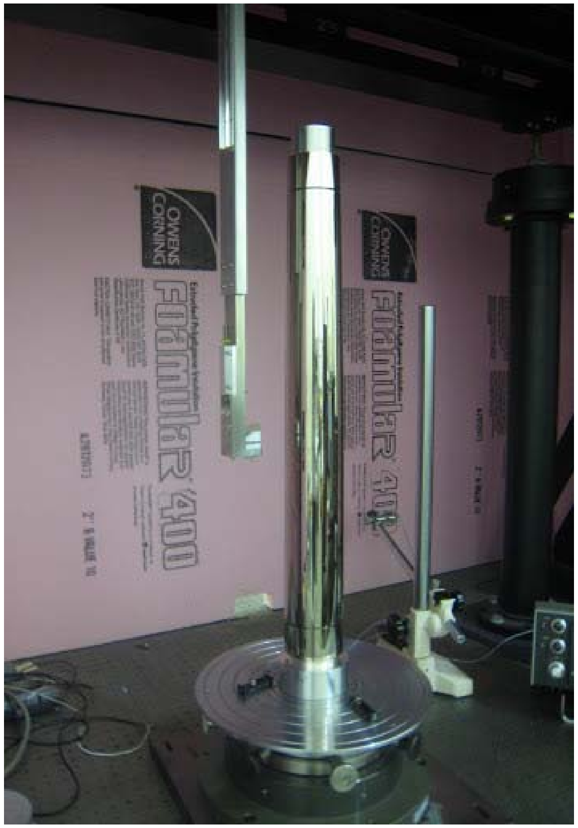
- FEA verifies conclusions of analytic model



Metrology

- MSFC metrology capabilities include
  - Coordinate measuring machine
  - vertical long-trace profilometer(shown)
  - horizontal long-trace profilometer

- We will verify models with metrology on existing test articles and new prototype configurations.
  - apply forces or displacements
  - measure deflections
  - estimate performance parameters



Summary

- MSFC is undertaking a systematic study to specify a mounting approach, mirror substrate, and testing method.
- A combination of FEA, analytical modeling and experimental measurements will be used to produce a verified optimal design
- Preliminary validation tests using analytical models find an optimal axial location for mounting shells near 25% or 75% of shell length
- Preliminary FEA verifies this finding
- Further Work will include:
  - validation by metrology
  - development of flexure designs and assembly techniques for both full-shell and segmented configurations
    - system performance is likely to depend on both
  - assess designs with analysis tools
    - extend analytical approach to higher orders
  - build and test engineering prototypes

MSFC is developing the infrastructure needed for mounting and testing both full shell and segmented optics for the next generation of high resolution x-ray telescopes.