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Analysis of active figure control effects on mounting strategy for x-ray optics

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SPIE: Adaptive X-Ray Optics III

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Outline

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- Key Questions
- Approach
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- Model Validation
- One-D illustration.
- 2-D Flat illustration.
- 2-D shell segment.
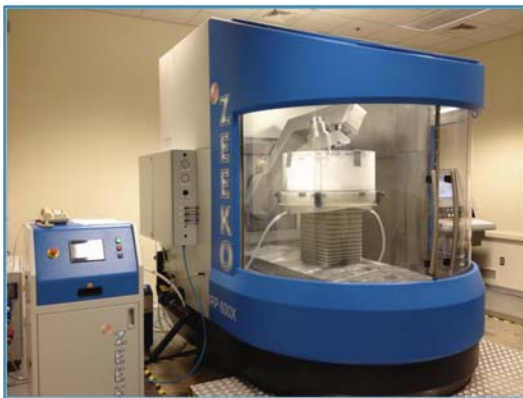- Shell Optical Performance vs. Mounting parameters
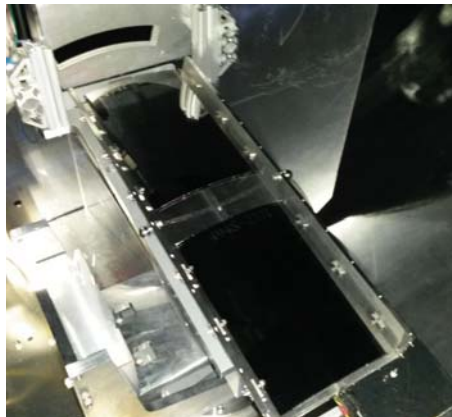- Conclusions

Overview and Motivation

- Manufacturing process development and product design with the goal of performance optimization within specified constraints can often involve a very large trade space.

- Not only the selection of technological methods and design parameters, but the sequence of process steps can significantly influence the resulting performance.

- Such efforts benefit from the early development of high-fidelity simulations, which can illuminate the tall poles and guide the choices toward performance optimization.

- Ideally these simulations would provide an integrated end-to-end picture of the entire process so that one option can be weighed against another, i.e. to investigate strategic alternatives.

- We anticipate that the manufacturing process required for the production of large-area actively-controlled x-ray optics modules falls into this category.
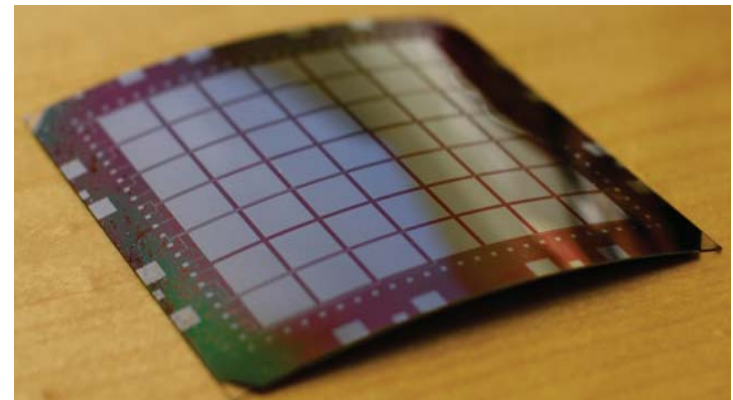
Overview and Motivation

- At MSFC, we are involved in several technology development efforts for higher resolution / larger area / lighter weight x-ray optics.

- All of these technologies share the need to be mounted/assembled/aligned into modular units for testing or for flight.

- We have identified a requirement to develop the capability to assess the impact of mounting options on performance.

- The goal is to develop an optimal mounting strategy or a small set of testable strategic options for any specified x-ray optics technology, which would be applicable to the fully-developed manufacturing process.

- We are in the very early stages of developing this capability for active optics, so results, so far, are relatively simplistic and naive.

- Nevertheless, we feel that including active optics mounting strategies in our repertoire will help to drive our understanding of technical challenges and capabilities to overcome them to a higher level in the future.
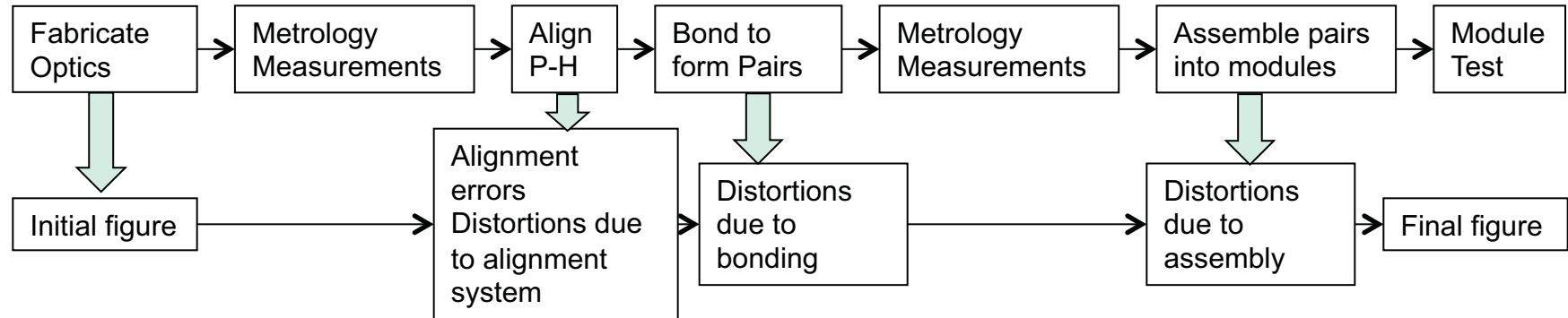
Posing Key Questions

- The process involved may be very complex

| Fabricate Optics | → | Metrology Measurements | → | Align P-H | → | Bond to form Pairs | → | Metrology Measurements | → | Assemble pairs into modules | → | Module Test |

| Initial figure | → | Alignment errors Distortions due to alignment system | → | Distortions due to bonding | → | Distortions due to assembly | → | Final figure |

- Key questions for mounting strategy
  - What kind of distortions are uncorrectable by bimorphs?
  - How are uncorrectable distortions minimized?
    - Which design parameters?
    - Which process techniques?
    - In what sequence are processes performed?

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Approach

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- Since this is virtual development, we use simulations to begin to answer key questions

- Steps:

  – generate large samples of initial figure error maps

  – develop deflection models based on plate/shallow shell theory and validate against FEM

    • Develop and apply boundary conditions as appropriate to address the question in terms of figure distortions

  – compute influence function basis for response to piezo actuation "voltage"

  – fit basis to initial figure + distortions to determine final figure which minimizes RMS axial slope errors or RMS 2-reflection ray divergence

  – Compare results from configuration alternatives

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Modeling Methods

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- Monte carlo technique to generate figure error maps
  - Probably should just operate on Fourier components instead.
- Finite difference deflection model based on Kirchhoff's plate bending theory (1850), and Donnell–Mushtari–Vlasov shallow shell theory.(Ventsel & Krauthammer, 2001)
  - Numerically solve "biharmonic" equation with boundary conditions
    - approximate piezo with a force distribution
  - For curved plates plan to solve a pair of 4th order equations with boundary conditions (not yet implemented)
    - For now using influence functions from FEM (Carolyn Atkins) for curved plates
- Rationale
  - Quicker to run, implemented in Mathematica®
  - No additional expense and training
  - No need to take time from trained FEM experts

Kirchhoff:

$$\nabla^4 \eta(x,y) = p(x,y)/D,$$
$\eta(x,y) = \text{deflection in plate coordinates},$
$p(x,y) = \text{pressure distribution orthogonal to the plate, and}$
$D = \text{flexural rigidity} = \frac{Eh^3}{12(1-\nu^2)},$
where $E = $ is Elastic Modulus,
$h = \text{thickness, and}$
$\nu = \text{Poisson's Ratio}.$

DMV:

$$\nabla^4 \eta(x,y) = (p(x,y) + \frac{1}{R\cos^2 \frac{\Theta}{4}} \frac{\partial^2 \Phi(x,y)}{\partial y^2})/D,$$

$$\nabla^4 \Phi(x,y) = -Eh \frac{1}{R\cos^2 \frac{\Theta}{4}} \frac{\partial^2 \eta(x,y)}{\partial y^2},$$
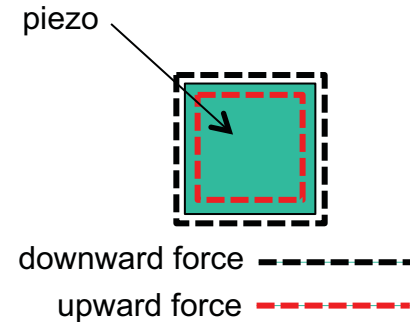
$\Phi(x,y) = \text{Airy stress function},$
$\Theta = \text{shell azimuthal extent, and}$
$R = \text{shell radius}.$

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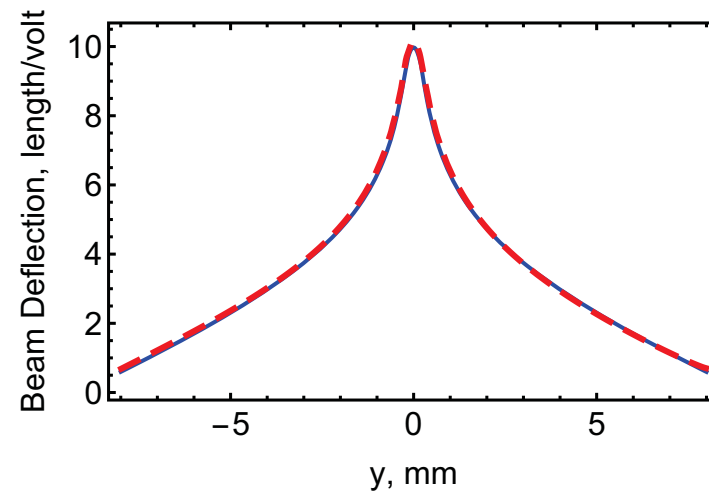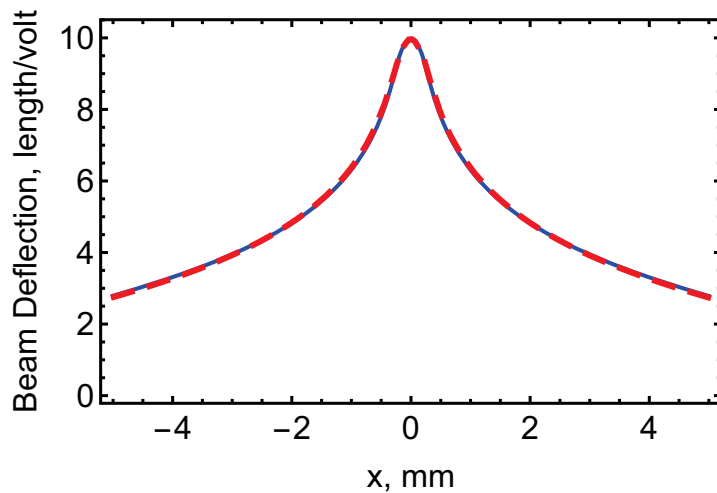Administration

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Model Validation

- Compared finite difference(FD) solutions to FEM solutions with modeled piezos
    - 16 cm x 10 cm simply constrained flat
    - 5 mm x 5 mm piezo with 0.5 mm separation
    - 0.4 mm thick glass
    - 0.2 mm thick piezo
- FEM mesh is automatically generated (Comsol®)
- FD is on 0.25 mm grid (x elements)
- FD approximates piezos with a distribution of localized forces
- Agreement is very good.

piezo

downward force ▬ ▬ ▬
upward force ▬ ▬ ▬

2-D influence functions for FD (solid blue) and FEM (dashed red)

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One-D illustration

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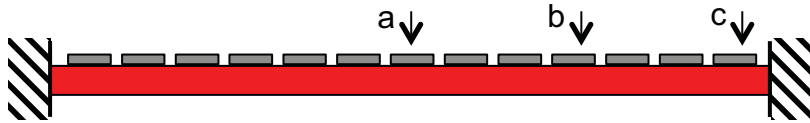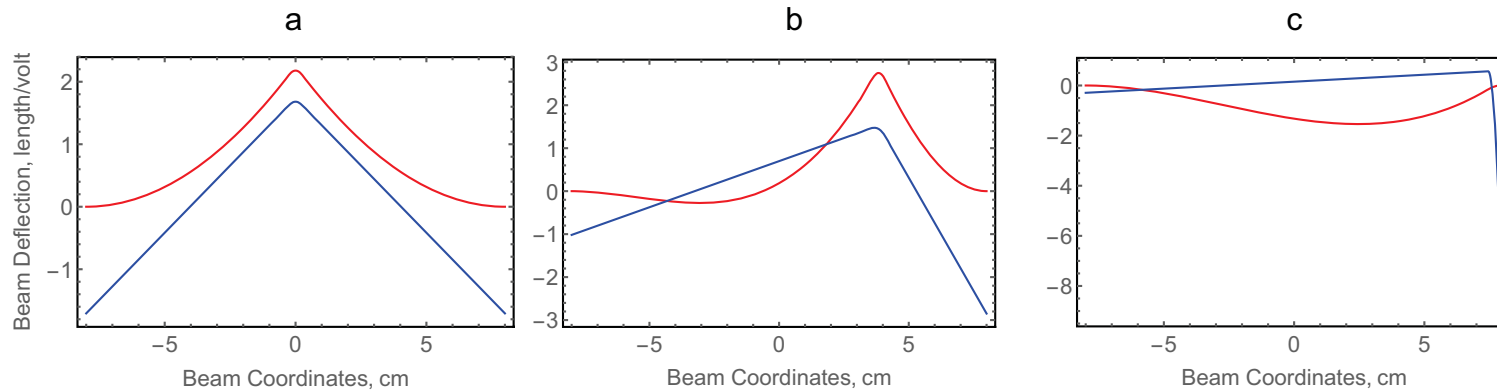CENTER

- Use simple beam theory to illuminate questions in 1 dimension

a↓   b↓   c↓

- Fixed mount vs. simply supported
  – Influence functions are obviously different for a beam with fixed ends, vs. an unconstrained beam

a   b   c

Beam Deflection, length/volt

Beam Coordinates, cm

- Actuator effectiveness depends on position
- Actuators are relatively ineffective near mounting points
- Completeness of resulting basis composed of the full set of influence functions is affected by mounting ⟹ Performance improvement is affected

One-D illustration II

- Begin to quantify effects using simulated error maps
- Assume a surface error spectrum

$$f(\sigma_s, \omega) = \sigma_s \sqrt{\frac{\sin\frac{3\pi}{k}}{\pi(k-3)\lambda} \frac{k\lambda^{k-1}}{\lambda^k + \omega^k}},$$
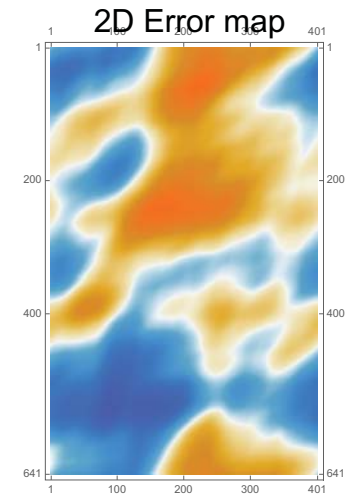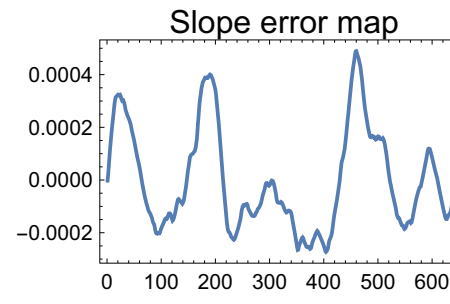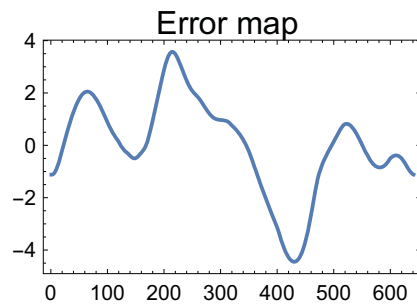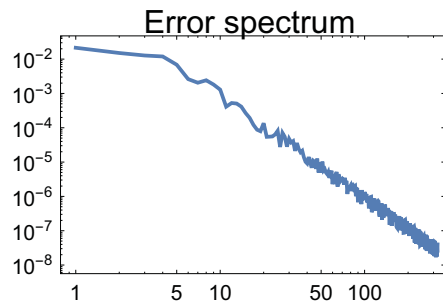
  where σ_s is the RMS slope error,
  ω is the spatial frequency,
  k is the assymptotic power law index and,
  λ is a cutoff parameter to tune the low frequencies.

- Surface map is the discrete inverse Fourier transform of the above spectrum

- Monte Carlo phases $\pm\pi$ and 0.5–2x amplitudes to generate a series of similar surface maps

- Adjust λ to match adjustability response which cuts off at Nyquist of piezo frequency.

- Adjust k to control high frequency content, performance floor

- For 2D let: $\omega^2 \rightarrow \omega_{ax}^2 + \omega_{az}^2$ for axial and azimuth frequencies

2D Error map

Error spectrum

Error map

Slope error map

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One-D illustration III

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- ## Unconstrained (upper) vs. fixed (lower)
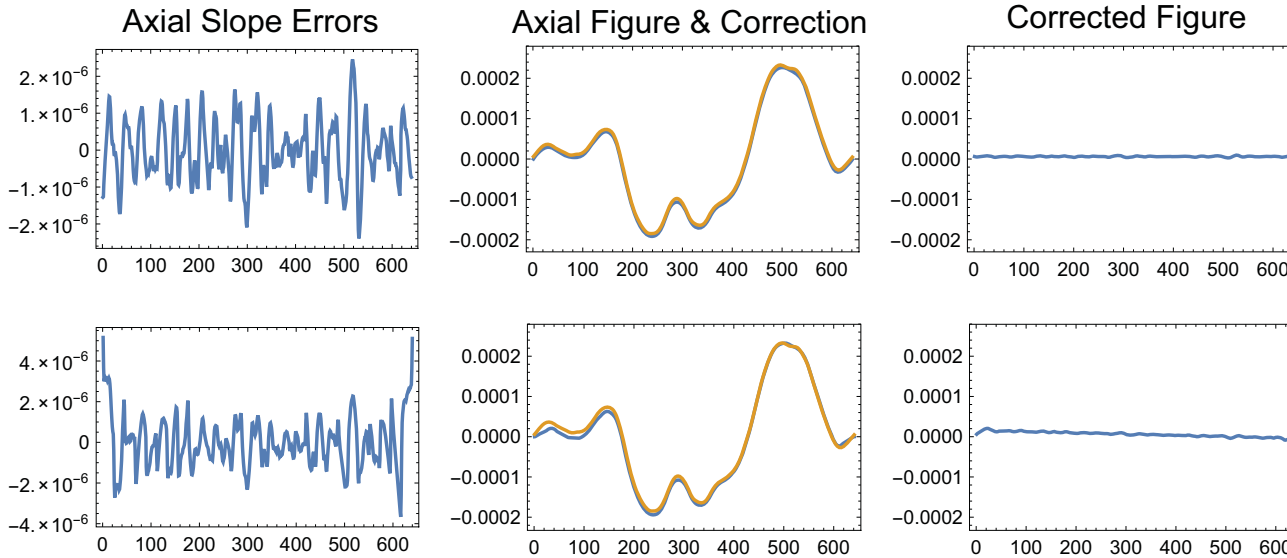
Initial RMS slope errors:
4.4 arcsec

Axial Slope Errors

Axial Figure & Correction

Corrected Figure

After unconstrained
adjustment:
0.48 arcsec

After adjustment in fixed
configuration:
0.71 arcsec

1000 simulated cases

ratio fixed-to-
unconstrained
RMS slope errors
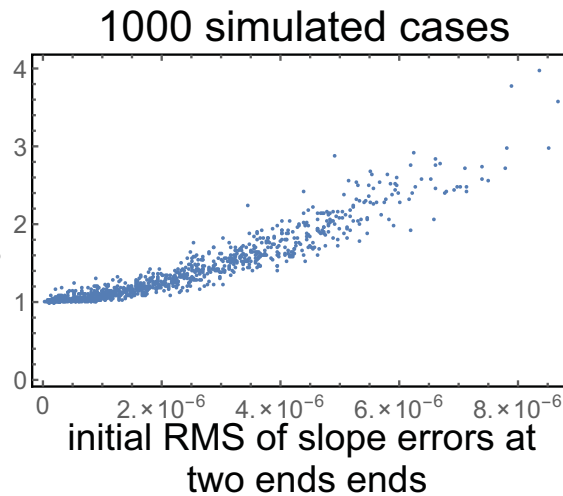
**Mounting with adjusters
activated would
generally yield improved
performance**

initial RMS of slope errors at
two ends ends

2-D Flat illustration

- Similar analysis for a 2–D flat plate

Optimize for
RMS axial slope
error

RMS axial slope
errors:
3.0 arcsec

Initial RMS
axial slope
errors:
10.6 arcsec

Optimize for
RMS deviation
from prescription

RMS axial slope
errors:
3.5 arcsec
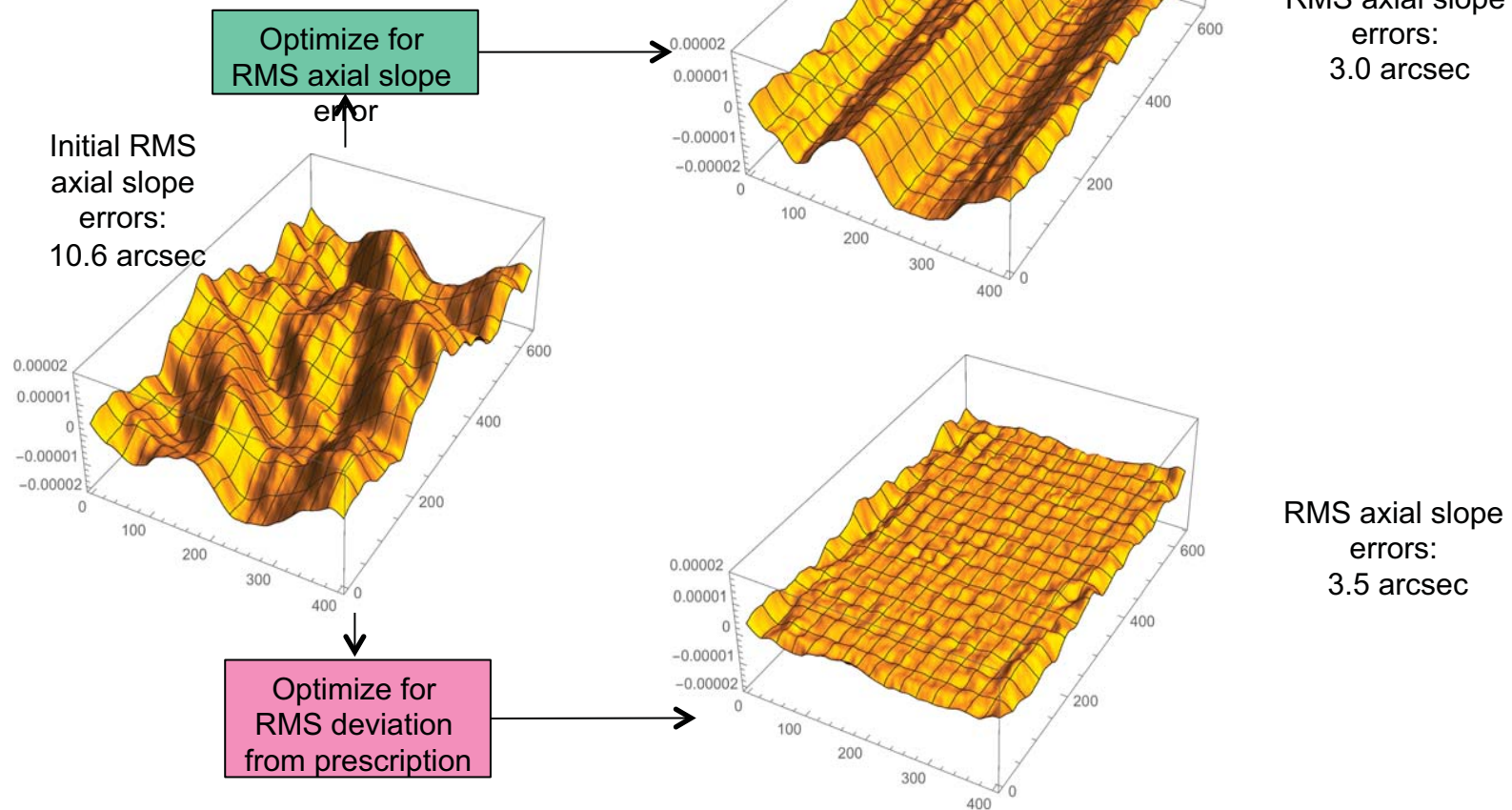
- Which results in better performance after mounting?

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2-D shell segment

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- Differences in influence functions
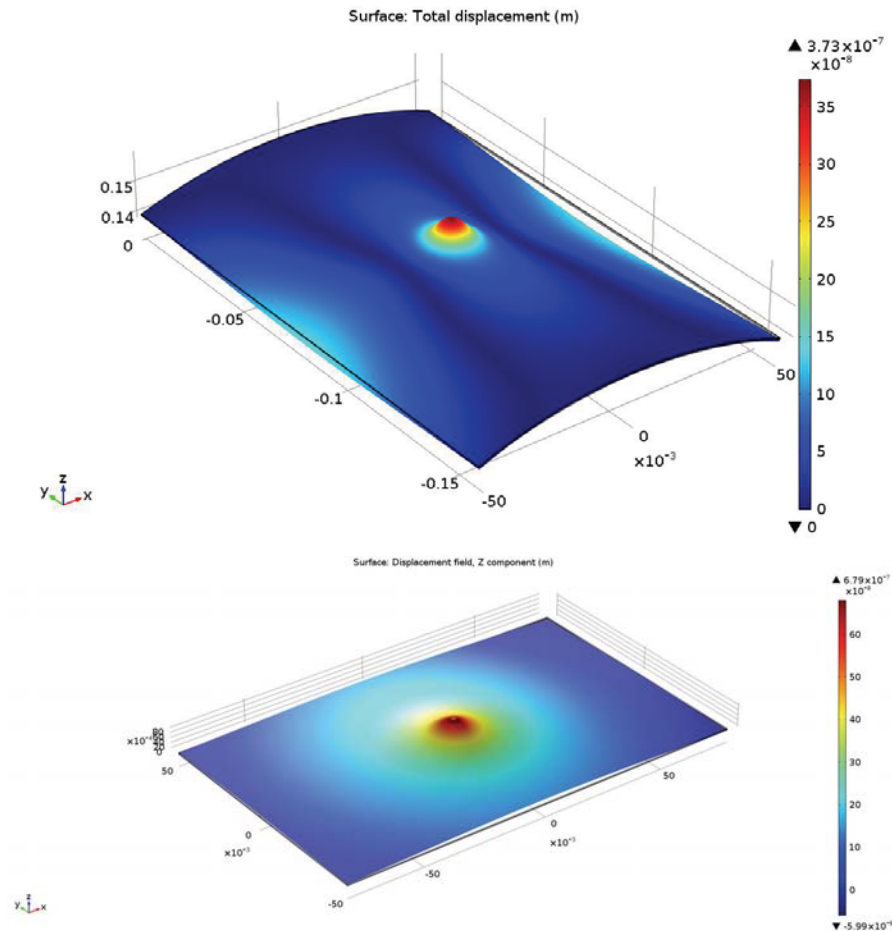
- Influence functions on curved optics can differ significantly from flat.
  - due to the effective rigidity caused by the curvature
  - The central displacement/ volt is smaller.
  - The edge displacement/ volt is about the same.
  - The surface deforms more along the azimuthal direction than the axial direction
- So edge displacement for a given central displacement is larger.
  - This must be included in the analysis of mounting distortions

Shell Optical Performance vs. Mounting parameters II

- Some sample end–to–end trade spaces

Adjusted performance of initially 10 arcsec optics (arcsec)

Dimensions	Case	k: asymptotic power law index: 3	3.5	4
1	unconstrained beam	0.9	0.7	0.4
1	fixed ends beam	1.4	1.1	0.9
2	unconstrained mirror surface	0.9	0.7	0.4
2	3 fixed points mirror surface	1.2	0.9	0.7
2	4 fixed points mirror surface	1.4	1.1	0.9
2	6 fixed points mirror surface	1.8	1.3	1
2	aligned unmatched pairs	1.3	1.0	0.6
2	aligned adjust 1 mirror only	1.4	1.0	0.6
2	aligned matched pairs	1.2	0.9	0.5
2(R = 15 cm)	unconstrained mirror surface	0.9	0.7	0.4
2(R = 15 cm)	3 fixed points mirror surface	1.2	0.9	0.7
2(R = 15 cm)	4 fixed points mirror surface	1.4	1.1	0.9
2(R = 15 cm)	6 fixed points mirror surface	1.8	1.3	1

Conclusions

- Expect that considering mounting strategy early, and allowing some flexibility in options could lead to better overall result
    - NOT: given mounting, what's the best optical configuration
    - NOT: given optics, what's the best mounting
    - INSTEAD: given nothing, what's the best combination of design parameters, technologies and processing sequence.
- Considering adjustable x-ray optics in a non-specific context, while something of an exercise, helps us to quickly come in-tune with significant mounting issues, in addition to producing some interesting strategic principles.
- We plan to:
    - Expand the finite difference approach to curved segments (shallow shells) and full shells
    - Develop an interface to efficiently investigate larger parameter spaces
    - Develop and test prototypes of promising concepts
- Attention to mounting details will obviously not improve optical system performance by orders magnitude but may lead to factors in the 1.4-2 range.