



# MSFC Advanced X-ray Optics Formulation to Flight

## **Presenter**

**Mandrel Fabrication/Polishing**  
**Replication Studies**  
**Mirror Direct Polishing**  
**Mounting and alignment**  
**Post-figure correction**  
**Metrology**  
**Thin-Film Research**

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*Jeff Kolodziejczak*  
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*David Broadway*

# MSFC ADVANCED X-RAY OPTICS

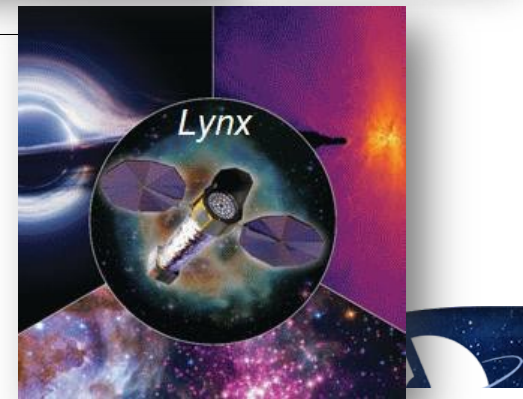
**Description of our program: end-to-end research and implementation designed to achieve light-weight sub-arcsecond full-shell X-ray optics and to enhance the performance of segmented optics for the Astronomy community.**

- MSFC's goal is to develop the next generation of light-weight, high angular-resolution mirrors and assemblies **and** to continue to supply the community with low-cost, moderate-resolution flight mirrors and assemblies.
- Essential and **unique** elements that build on decades of previous investments include:
  - Mirror and module design
  - Mandrel fabrication/polishing
  - Mirror shell replication
  - Mirror direct polishing
  - Mounting and alignment
  - Post figure-correction
  - Metrology
  - Thin-Film Research
  - X-ray test and calibration



## MSFC X-ray optics key capabilities:

- MSFC develops complete mirror assemblies with predictable flight performance for the Astronomy community (we regularly fly full-shell mirror assemblies!), other NASA Science Mission Directorate divisions (Heliophysics) and other government entities (NIF, NIST, etc.)
- Technology developments are relevant to future X-ray missions that use either full-shell or segmented mirrors (e.g. *Lynx*)
- Provides world-class X-ray test and calibration with the MSFC 100-m X-ray Beamline and X-ray & Cryogenic Facility for community testing of technologies and flight hardware

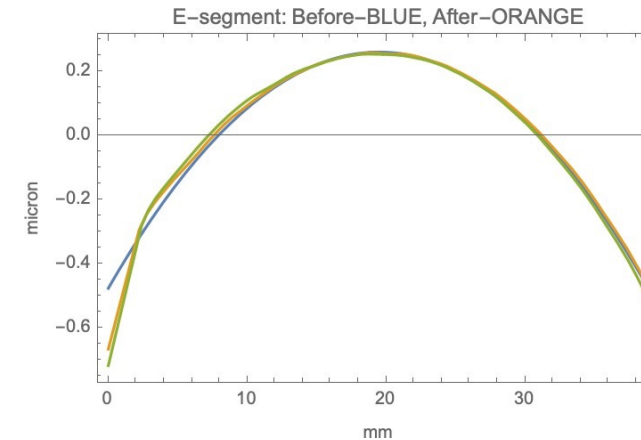
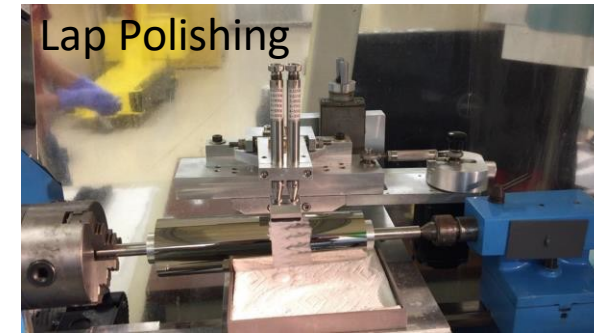
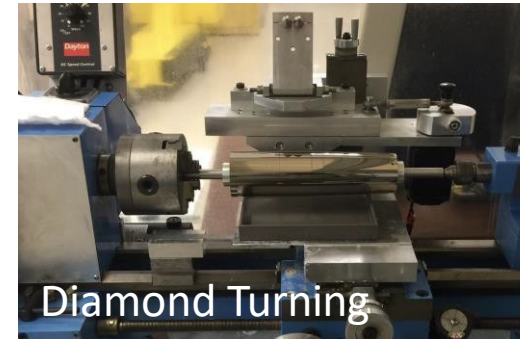


# MANDREL FABRICATION/POLISHING

Jeff Kolodziejczak

**Description:** High-precision mandrels for shell replication will lead to high resolution shells, ready for either installation into modules, full-shell polishing, or application of other shell figure correction techniques.

- MSFC's capabilities in mandrel design and fabrication are well documented. Recent efforts were directed at computer-controlled polishing and achieving arcsecond-level precision in figure and surface quality.
- In the past 3 years we developed a procedure for achieving arcsec-level figure, through work on both large and small mandrels with a Zeeko computer-controlled polisher.
- More recently, we have developed a method to maintain surface roughness below 0.5 nm RMS while maintaining or further improving the final optical figure.
- The procedure has 4 main mandrel polishing steps:
  - Lap polish – optimized lap and stroke for key spatial frequency range
  - Coarse computer-controlled – optimized slurry chemistry, verified alignment and metrology registration relative to machine coordinates
  - Lap super-polish – one step to minimize figure degradation
  - Fine computer-controlled – fine slurry shown to maintain 0.3 nm surface
- Recently we completed a small mandrel composed of ellipsoid + hyperboloid with the following performance parameters based on interferometric metrology.
  - Ellipsoid(E) + Ideal P: 1.0 arcsec (Half Power Diameter)
  - Paraboloid(P) + Ideal E: 1.8 arcsec (HPD)
  - Combined E+H: 2.3 arcsec (HPD)
  - Roughness: 0.5 nm RMS
- In our next opportunity for mandrel polishing our objectives are to improve overall process efficiency, and user friendliness of feed rate generation software application.



## Justification:

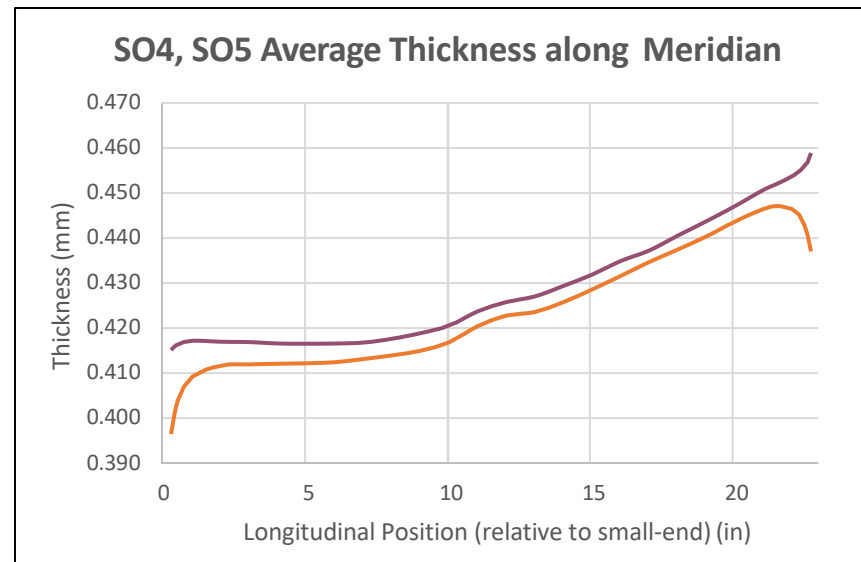
- Mandrel Fabrication capabilities are mature and incrementally improving as opportunities for high resolution work arise.
- **While not yet attained, we have high confidence that 1.5 arcsec HPD performance would be achieved if current processes and procedures were carried through to convergence.**
  - Ongoing metrology work should lead to even better convergence limits.
- This technology combined with replication are ready to create <2 arc-sec shells which could be polished to sub-arcsec with shell polishing currently under development.

# MSFC ELECTROFORMED SHELL REPLICATION WORK

Wayne Baumgartner



- **Focus:** Shells replicated from polished mandrels do not currently have quite the same performance as the mandrel.
- **Hypothesis:** Some process imparts stress on the shell during plating or replication, distorting the figure
- **Plan:** Investigate options to improve the replication process:
  - Optimally shaped end gaskets
  - More uniform electric field
  - More uniform fluid flow
  - Optimized temperature in separation procedure
  - Pulse plating
  - Release layer on mandrel (Au)
  - Different shell alloy (NiCoP v. NiCo)



Measured thickness before (orange) and after (purple) gasket shape optimization to make electric field more uniform: elimination of hooks at end show shell improvement

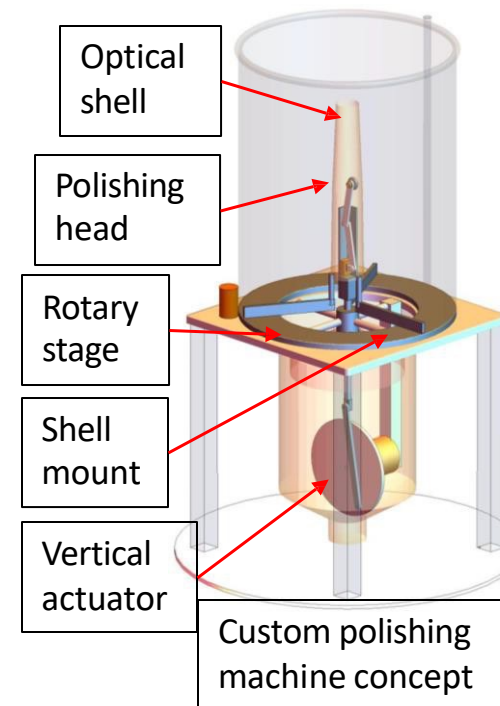
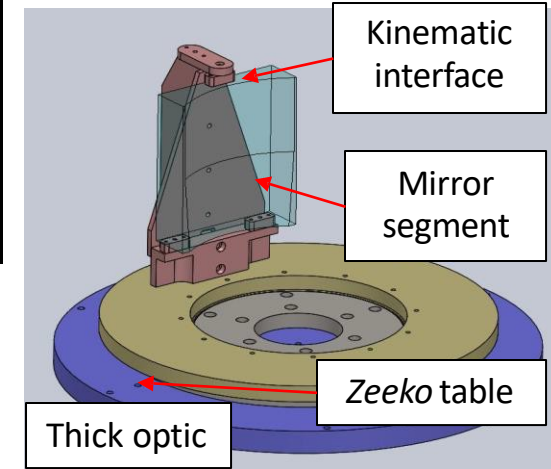
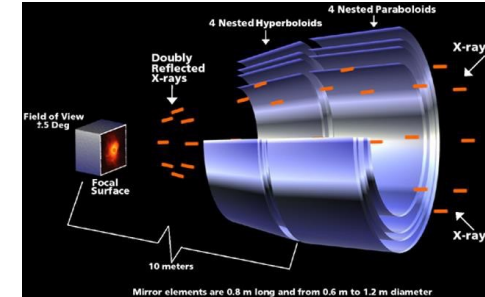
- **Status:** We have -
  - Modeled electric field
  - Optimized end gaskets
  - Checked fluid flow
- **Results:**
  - Shell figure as represented by thickness improved with optimized gasket
  - First change of fluid flow yielded no improvement
- **Next steps:**
  - Check electrode placement
  - Continue with other steps in plan
  - Measure figure on profilometer



# MIRROR DIRECT POLISHING

Stephen Bongiorno

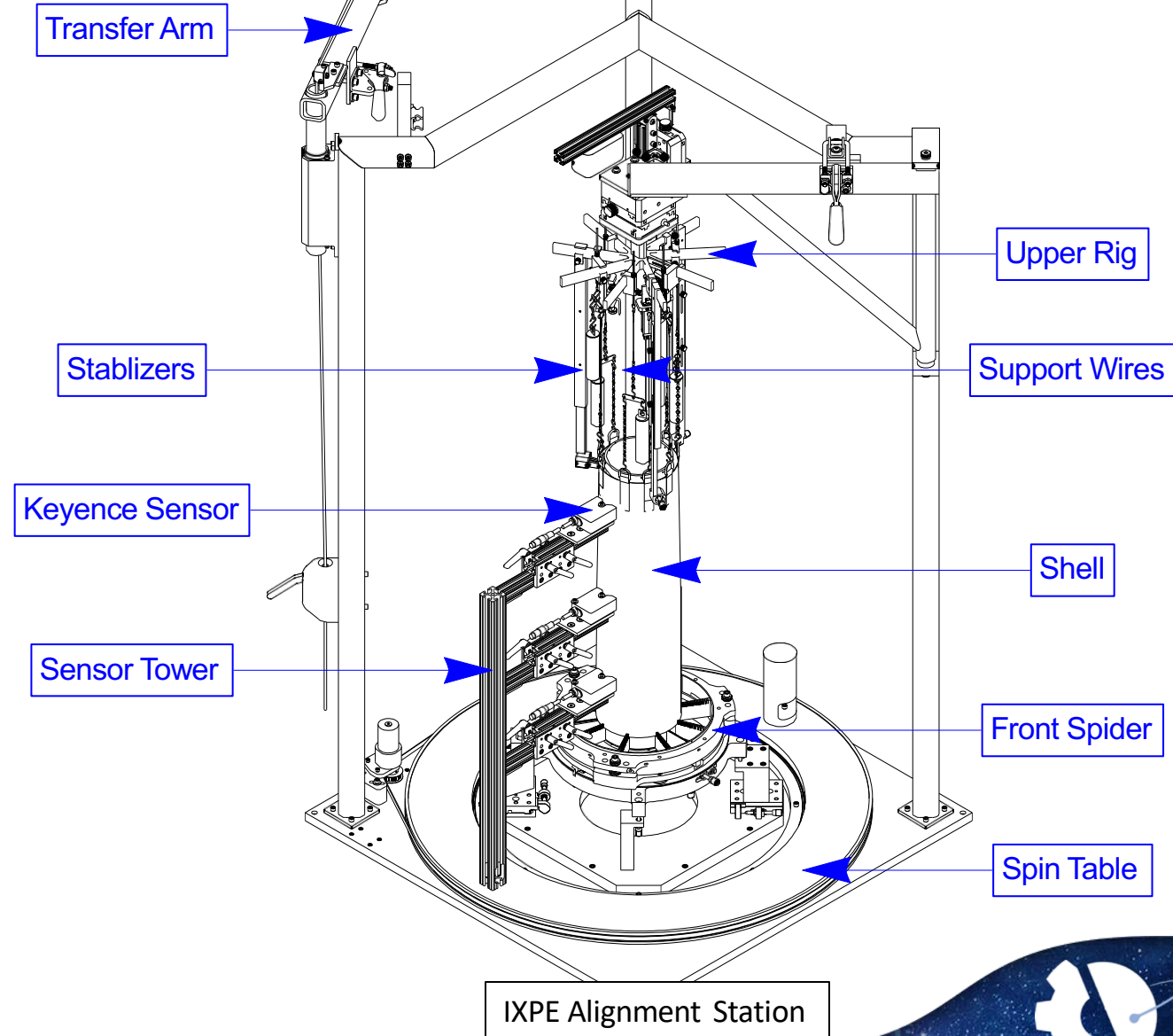
- Goal – Produce lightweight, full-shell x-ray optics with sub-arcsecond half-power diameter angular resolution via direct polishing.
- Background – Planned full-shell fabrication process
  - With existing 0.5 m ConX mandrel, electroform Ni(Co)P shell, direct polish using vertical long trace profilometer metrology for deterministic figure correction, align and mount shell, X-ray test at MSFC 100m beamline.
- Current work
  - **NiP coupon bath** – Build 35L coupon bath to evaluate Ni(Co)P material and inform future full-shell plating plan. Adjust bath chemistry and plating rate/polarity to optimize electroform microyield, yield, hardness, and stress. Status: Bath components procured, assembled, and bath mixed. Awaiting pH balance. Coupon replication and materials testing to follow.
  - **Thick optic** – Before thin-shell polishing work, demonstrate success of deterministic polishing techniques without the added complications of working on a thin substrate. Working temporarily with a segmented optic will reduce fixture and tooling cost and enable polishing on the Zeeko for a faster start. Status: design in progress.
  - **Custom polishing machine** – Develop a simplified (3 vs. 6-axis motion) polishing machine with passive bonnet force control. Leverage CNC and chemical mechanical planarization industry COTS products. Status: slurry pump procured, design in progress.
- Future work
  - Build full-size Ni(Co)P electroforming bath for ConX mandrel
  - Electroform, deterministically polish, and x-ray test full-shell



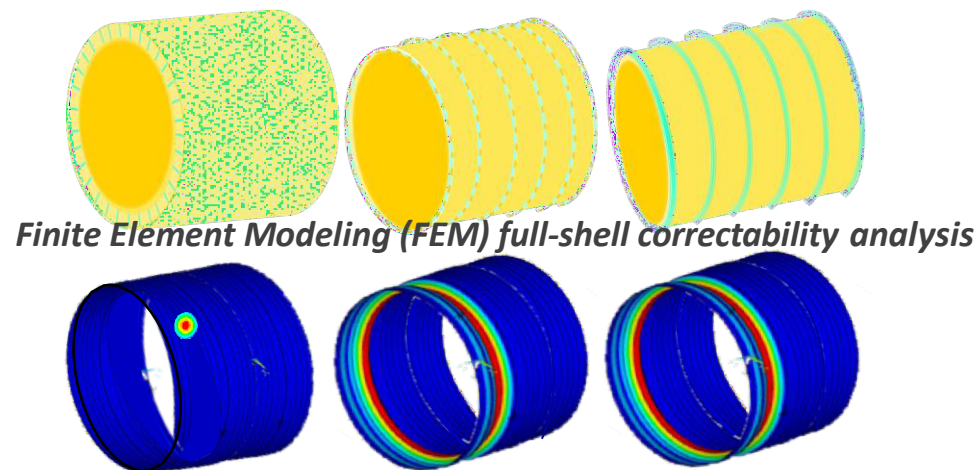
# MIRROR ALIGNMENT

Stephen Bongiorno

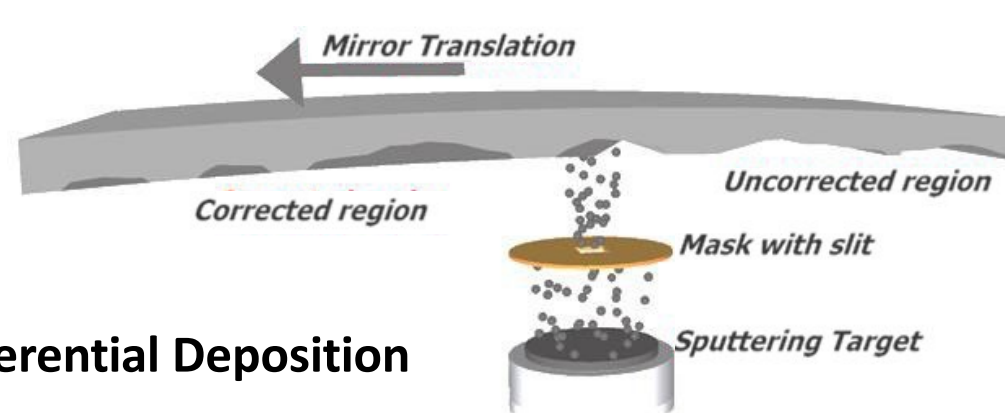
- Goal – Demonstrate capability to align and mount sub-arcsecond full-shell x-ray optics: P-V circularity <10  $\mu\text{m}$ , <5  $\mu\text{m}$  centering, <5 arcsec. tilt.
- Background
  - Thin optics must be aligned and mounted to support structure without imparting significant distortion
  - FOXSI, ART-XC, and IXPE were aligned and assembled at MSFC with Keyence sensor method
  - IXPE successfully implemented gravity offload hanging shell suspension
- Current work
  - **Improved Keyence sensor calibration** – Calibrate sensors on curved surfaces, measure the sensor output sensitivity to misalignment on curved surfaces.
  - **Improve suspension stability** – IXPE assembly noted shell tilt and center drift of approx. 5 arcsec./hr. and 20  $\mu\text{m}$ /hr. Identify and eliminate source(s) of drift.
  - **Improve precision of spin table bearing** – Spin table bearing currently exhibits approx. 30 arcseconds of wobble. High-precision A-68x Physik Instrumente air bearing replacement in procurement will reduce wobble of metrology reference to manufacturer-stated 0.2 arcseconds.
  - **Improved stability** – Granite base will become monolithic platform for bearing, module, and upper rig.
- Future work
  - Piezo actuator adjustment of shell circularity



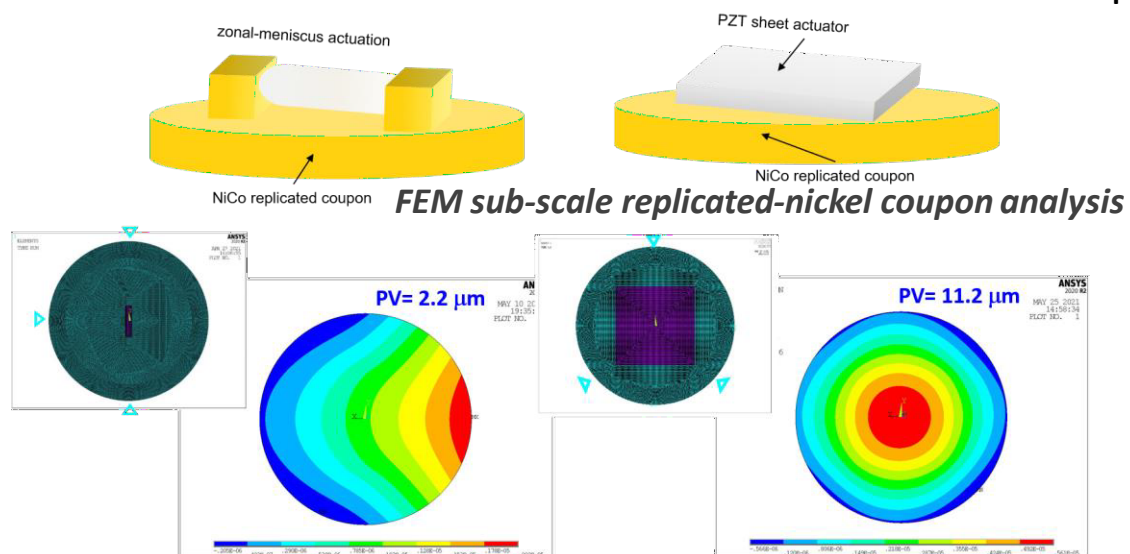
## Active X-ray Optics



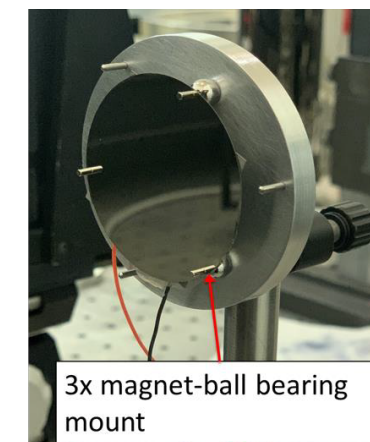
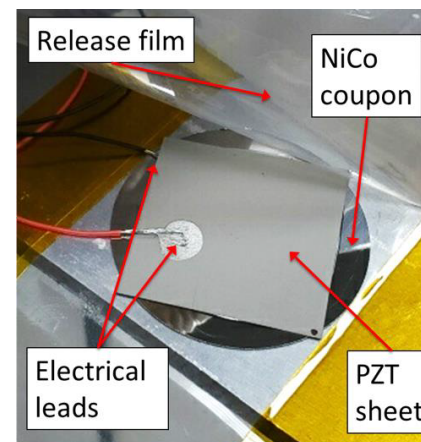
## Differential Deposition



Post-fabrication figure correction is an important step in achieving the final goal of sub-arcsec resolution with full-shell optics. Any figure deviations resulting from the fabrication process will be addressed during this step. This is achieved with **differential deposition** and **active correction**, each targeting a different range of spatial frequencies.



## Hardware development: sub-scale active nickel-replicated coupon



resulting 7.8 mm spatial frequency correction over 48 mm coupon

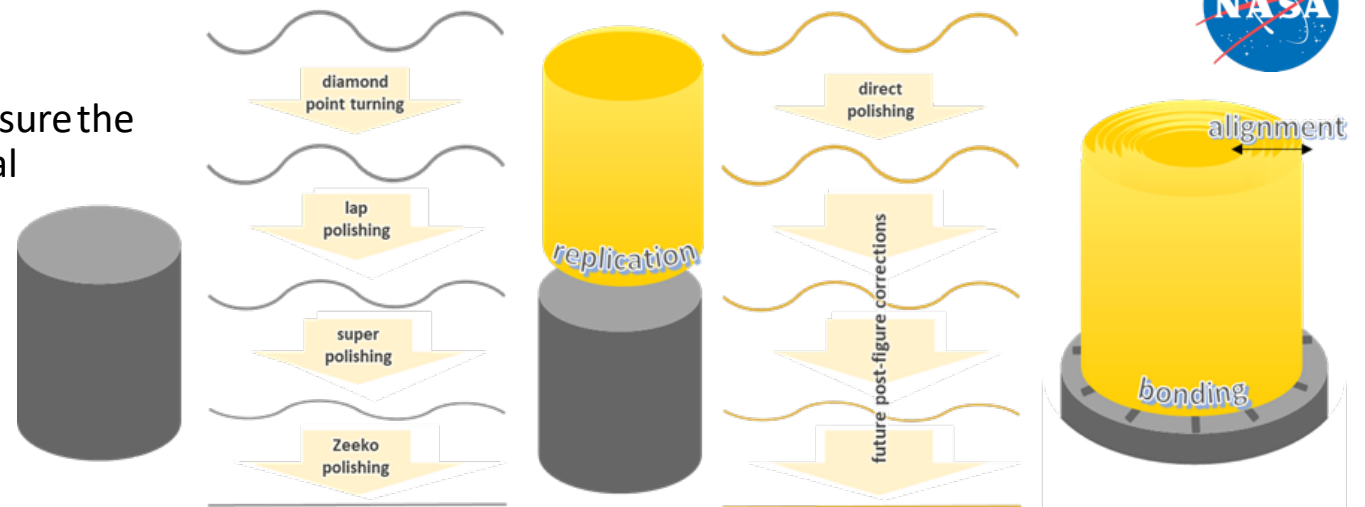
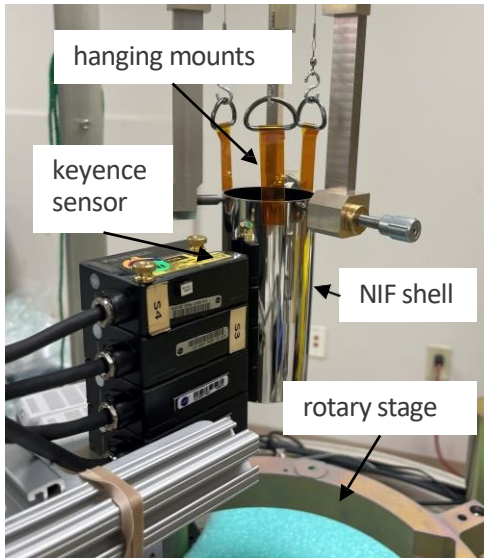


# METROLOGY

Jackie Davis

Set **error budgets** for different metrology instruments to measure the surface characteristics over the entire range of relevant spatial frequencies for each step of manufacturing process.

## replicated shell metrology station



MSFC nickel-replication process & assembly of full-shell, grazing-incidence optics

Develop **high-resolution metrology equipment** to measure the surface characteristics of each step of process, particularly the internal optical surface of the replicated shells.

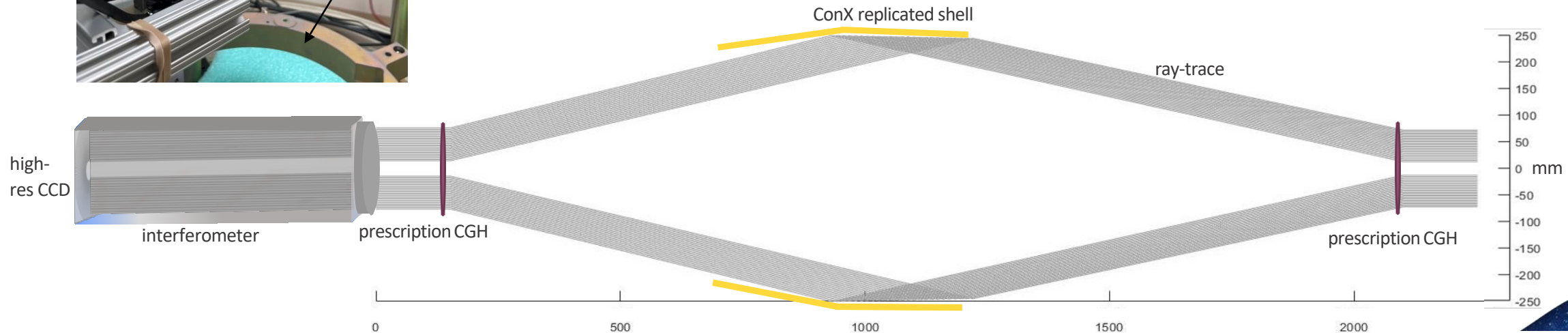


diagram of high-resolution inner shell metrology concept: 2 CGH in line with high-resolution

# THIN FILM RESEARCH

David Broadway



## Low Stress Coatings

The coatings applied to enhance X-ray reflectivity can severely distort the optic's precise figure. The reduction of thin film stress to near zero values is a leading technological challenge toward the goal of sub arcsecond resolution optics.

- Design and fabrication of novel in-situ stress measurement instrument completed.
- Custom, water cooled, fiber optic displacement sensors received from manufacturer
- Instrument is ready for testing upon receipt of cantilever substrates

## Magnetron Sputtering on Full Shells

The restrictions imposed by RF sputtering techniques prevent the use of dielectric overcoats on smaller-diameter full shell electroformed optics, which could otherwise improve their effective area to various degrees depending on the mirror's focal length.

- A new approach using a "segmented" Cylindrical Magnetron sputtering source is being considered.
- The cylindrical target rotates with respect to a fixed magnet offering the capability to sputtering several material from a single sputtering source using segmented target materials.
- Receipt of a specially fabricated boron-carbide planar target has been received for testing. The target can be subsequently hot pressed into a cylindrical segment that can be bonded to a Cmag target assembly.

## Configurable D-shaped Deposition Chamber

A novel deposition chamber has been designed that can be optimally configured to coat a variety optic types including normal incidence, full shell, flat, and segmented substrates. Some of the features include:

- Load lock capability which increases the throughput of the system due to reduce pump down times.
- Cathodes rotate to facilitate in-situ stress measurement for optimization of deposition parameters.
- Includes ion sputtering capability and co-sputtering capability in addition to magnetron sputtering.
- Accommodates planar, circular, and Cmag sputtering sources.

## Adhesion Tester

A custom-built instrument used to quantify the adhesion of the coating to the substrate.

- Instrument has been designed, fabricated, and assembled.
- The integration of electronic components and software development is ongoing.

