Development of a direct fabrication technique for full-shell x-ray optics

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X-ray Optics after Chandra

The challenge is to develop optical fabrication technology capable of producing x-ray optics with high angular resolution but with an order of magnitude lighter mirrors and at an affordable price.

The challenge can be approached from different directions:

- Very thin mirrors (0.2-0.4 mm):
    - Replicated optics
    - Pore Optics
    - Figure Correction

- Intermediate thickness mirror (0.5-2.0 mm):
    - Direct fabrication, Chandra-like
        - Figure corrections can be applied too

Direct Fabrication

Material	Density (g/cm^3)	CTE (10^{-6} / K^{-1})	Elastic Modulus GPa	Yield Strength MPa
Fused Silica	2.2	0.5	72	48*
Beryllium	1.8	12	318	240
BeAL-162MET	2.1	24	69	276
AlSi	2.8	13.9	193	314
Duralcan F3S.30S AlSi+SiC(30% by vol)	2.8	14.6	120	210

Mechanical Properties of Potential Mirror Substrate Materials
*Maximal achievable value. The ‘working’ value is typically much less and depends on the surface/subsurface condition.

Companies are confident they can deliver the Be, BeAl and AlSi substrates fabricated with necessary tolerances for fine-figuring and polishing

Additional Benefits of metal substrate:

- Fewer joints – smaller epoxy-induced errors
- Thermal design could be simplified with the support structure fabricated from the same material

Ideally, the mirror shell has low density, low coefficient of expansion (CTE), high modulus of elasticity and high yield strength. It should also be a material that is not too difficult to figure and polish.

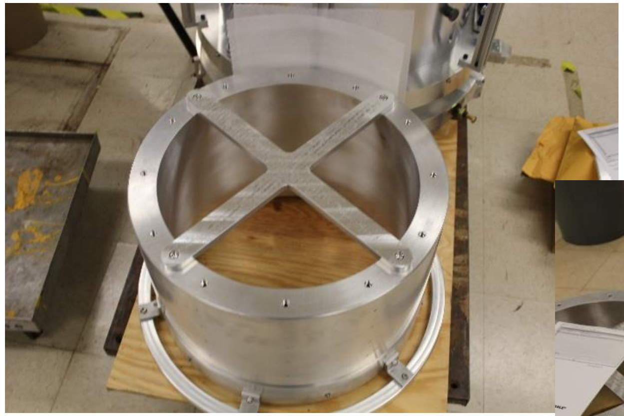
Substrates can be plated with the nickel phosphorous alloy:

- Be + NiP (CATS-ISS telescope)
- BeAl +NiP
- AlSi + NiP

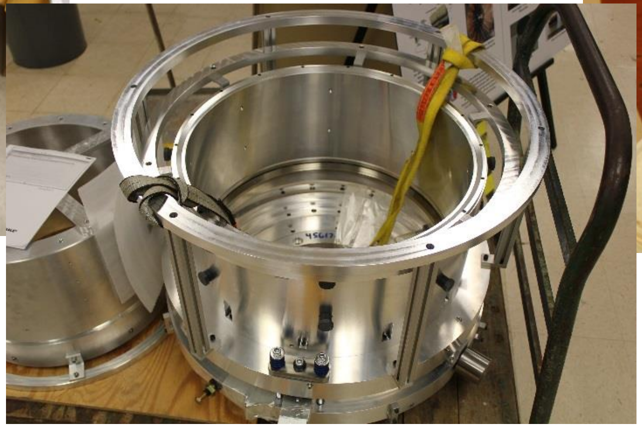
Direct Fabrication - Metal

Diamond turning → Figuring → Super-polishing → Differential Deposition

Challenge of shell thickness - fixtures



OD DT fixture



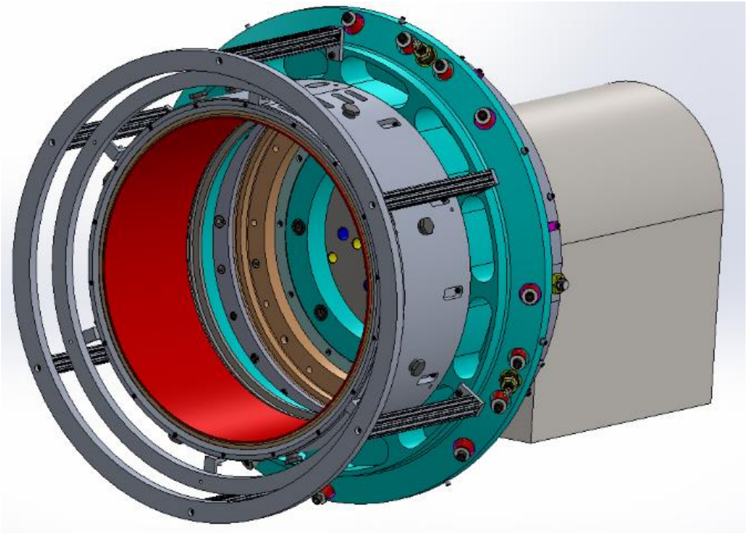
ID DT fixture

Polishing fixture

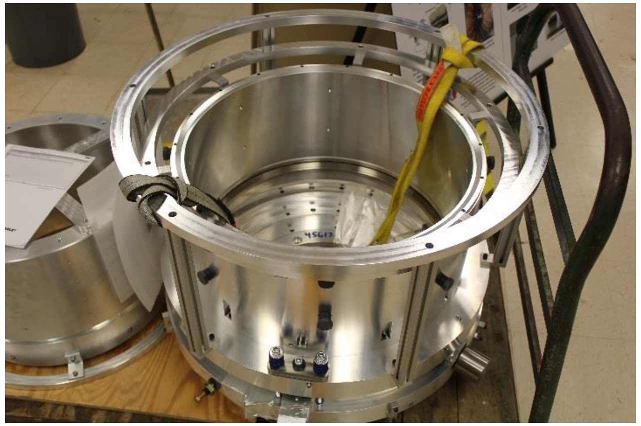
Whiffle tree station with an aluminum shell supported at 12 points.

A metrology fixture to support the mirror shell during the skip test.

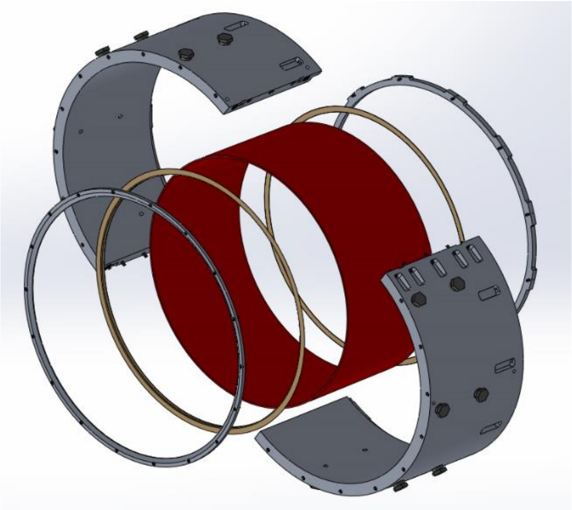
Direct Fabrication

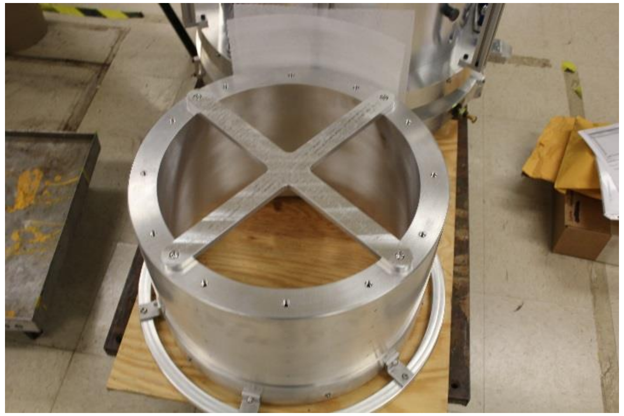


Backing support system installed on the precision lathe for diamond turning. The precision stage (blue) permit alignment of the mirror shell (red) with the lathe.



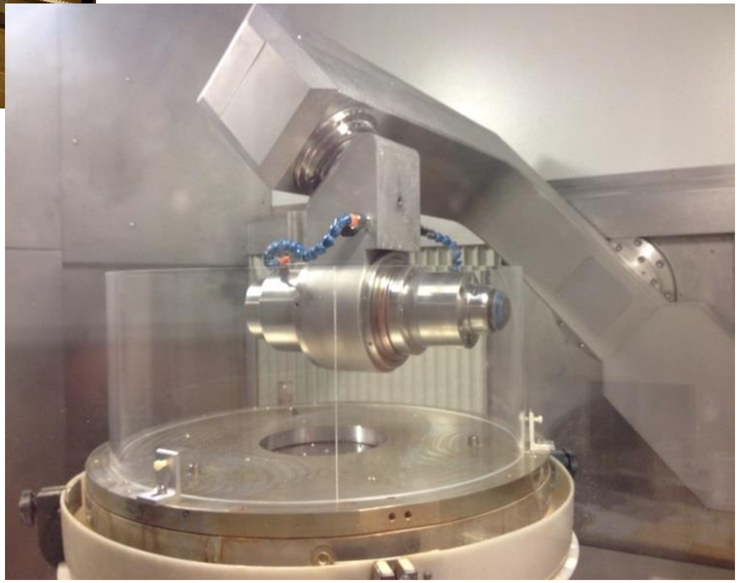
Thin-shell backing support system. A thin layer of backing material (not shown) acts as interface between the mirror shell (red) and the stiff outer support clam-shell (gray). The support rings and the gaskets shown contain the backing material.





Zeeko machine

- The machine utilizes a “bonnet” technique in which an inflated rubber hemispherical diaphragm supports the polishing medium.
- there are different “bonnet” sizes (20 mm, 40 mm and 80 mm radii of curvature)
- This computer-controlled deterministic polishing processes leads to a high convergence rate.



Wear function characterization

Parametric wear pattern simulation enables a more efficient method of exploring the polishing parameter space.

Based on Preston's law:

Wear rate is proportional to

- Bonnet pressure distribution
- Velocity of bonnet surface

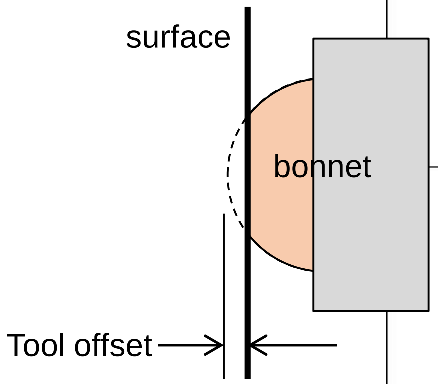
Velocity depends on

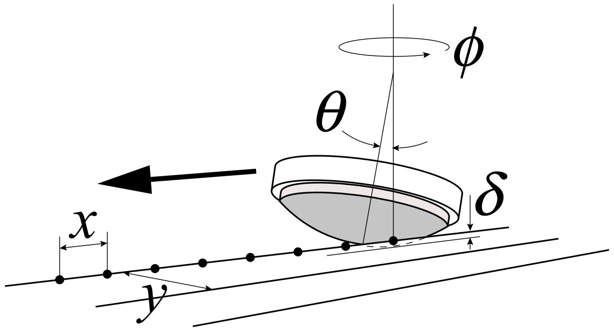
- Spindle rotation
- Head attack angles

Pressure depends on

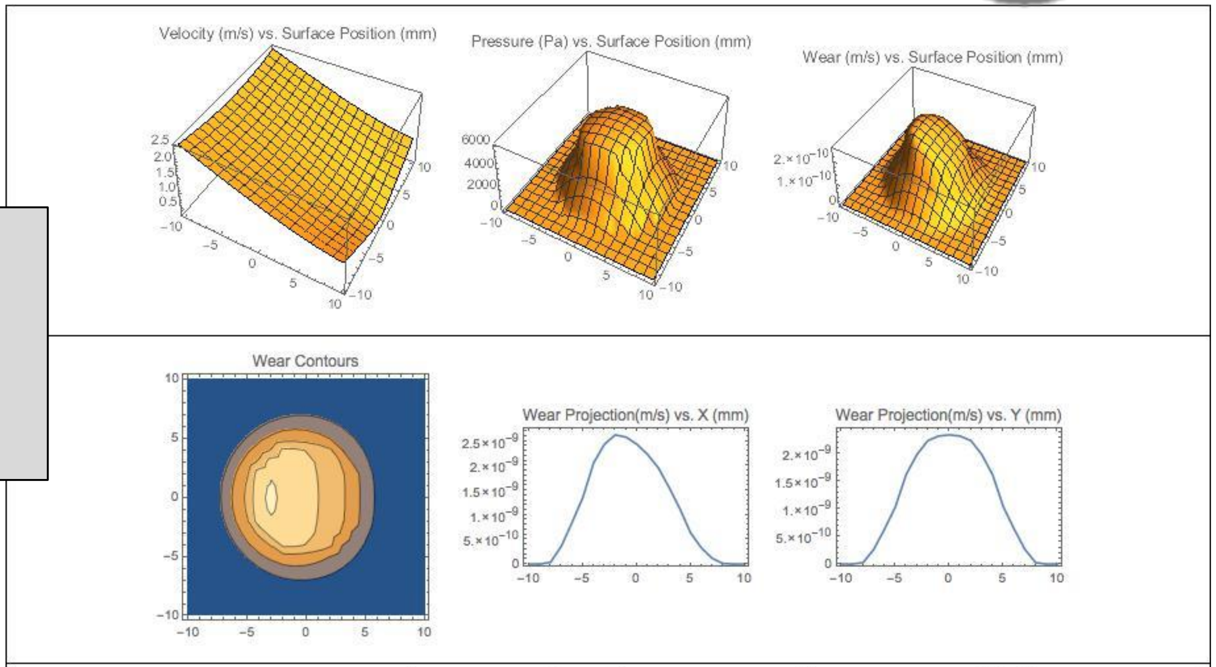
- Internal pressure of bonnet
- Bonnet structural and mechanical properties
  - Static (current)
  - Dynamic (future)

Model is validated using measured data.





Example of Output from **Model** Run



bonnet

	value	unit
pressure	0.05	bar
thickness	0.5	mm
radius	41.	mm
density	1.3	g/cm^3
elasticModulus	20.	MPa
eModChangewFreq	0.01	MPa/Hz
poissonRatio	0.45	
damping	0.05	
dampChangewFreq	0.01	1/Hz
maxDamping	0.35	

2 levels | 10 rows

bonnetCover

	value	unit
thickness	0.5	mm
friction	0.04	
fracContact	0.5	

2 levels | 3 rows

slurry

	value	unit
viscosity	0.05	Pa s
fracSolids	0.1	
gritSize	0.03	micron
prestonCoef	2.9	10^{-14}/Pa
smoothScale	1.	mm

2 levels | 5 rows

machineAxes

	value	unit
springK	100000.	N/m
rotationRateSpindle	1000.	RPM
toolOffset	0.3	mm
precessAngle	17.	deg
phiAngle	0.	deg

2 levels | 5 rows

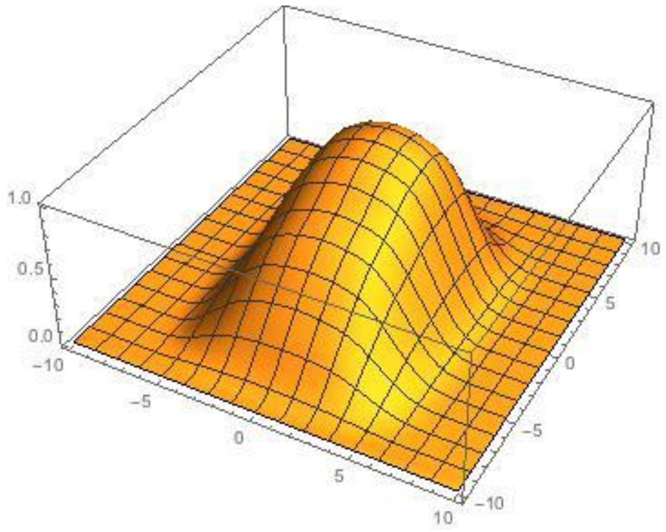
surface

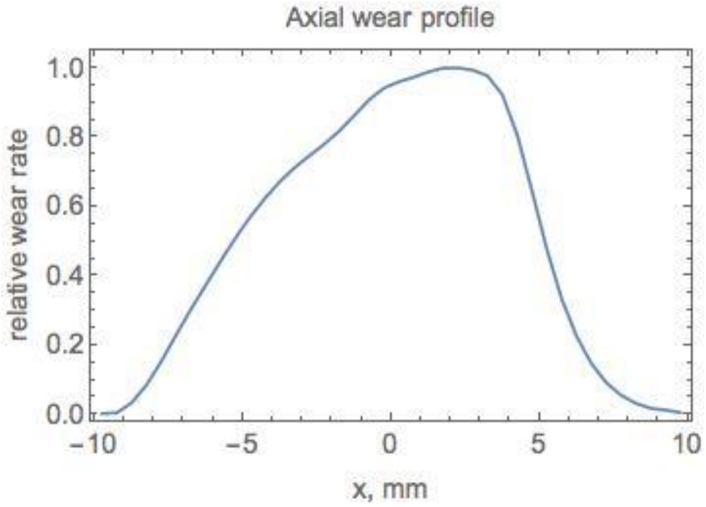
	value	unit
radiusofCurvature	20.	cm
wearGridHalfWidth	10.	mm
wearGridStep	1.	mm

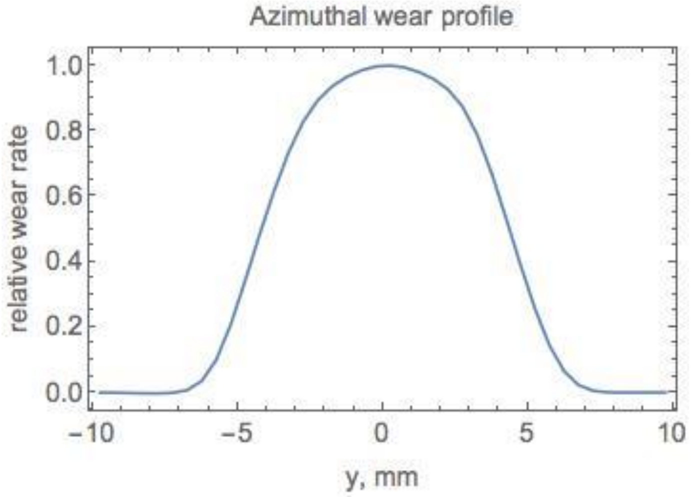
2 levels | 3 rows

Wear function characterization

- Measured wear function



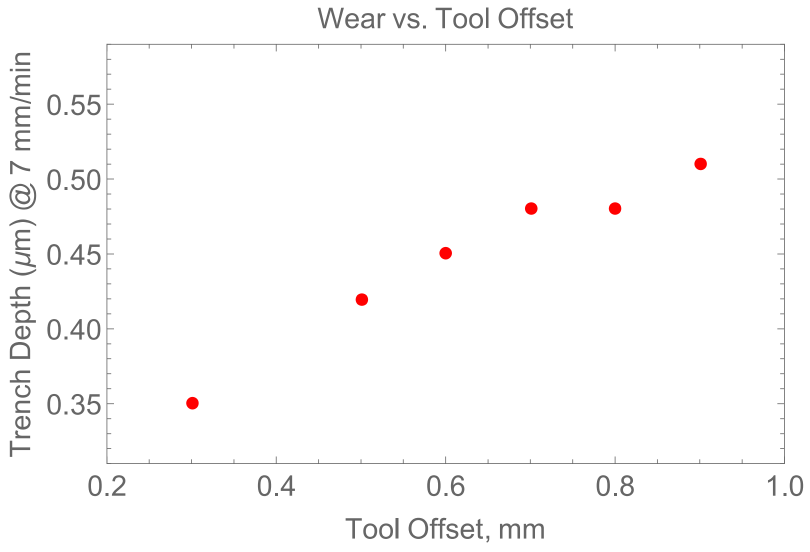




- Axial profile is asymmetric
  - Due to radial dependence of bonnet velocity relative to surface
  - Operate at 15° "precess" angle
- Axial and azimuthal directions are selected based on clearance considerations for shell polishing

Wear function characterization

- Explored polishing parameter space to balance:
  - Wear rate
  - Accuracy
- Parameter optimization
  - Bonnet pressure
  - Spindle speed
  - Tool Offset



•Example: Tool Offset

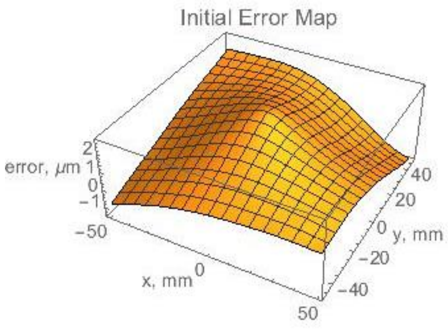
Trench depth vs. tool offset flattens in 0.7-0.8 mm range

Results in minimal sensitivity to alignment in a ±50 μm range around 0.75 mm

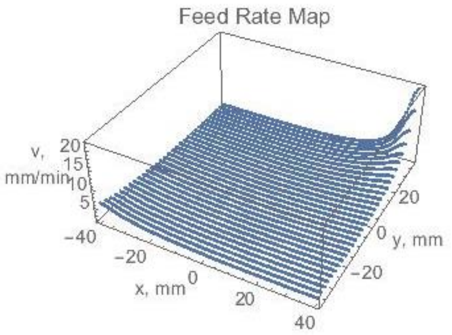
Selected 0.75 mm as operational tool offset

Wear function characterization

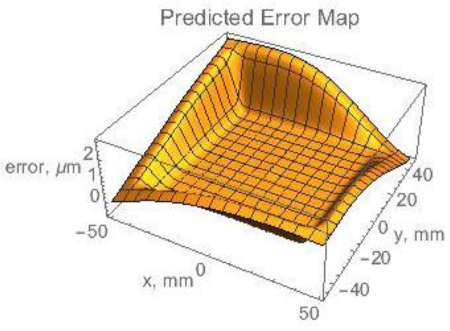
- Several options for determining the feed rate map from error map have been explored
    - Initially using a Richardson-Lucy deconvolution algorithm + small nonlinear correction
        - Tends to generate smoother edge transitions



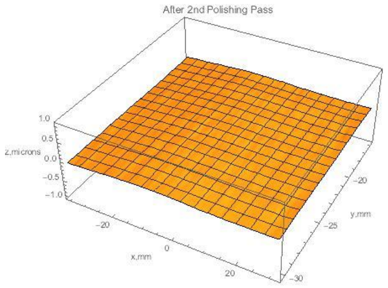
- Initial error map derived from metrology data.
- RMS slope errors along x-axis are **8 arcsec.**



- Derived feed rate map.
- Feed rates range from 1.35-20 mm/min.



- Predicted result of polishing iteration.
- Predicted RMS slope errors are **0.6 arcsec**

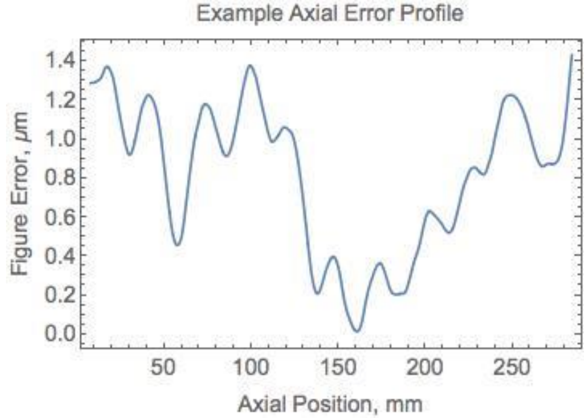


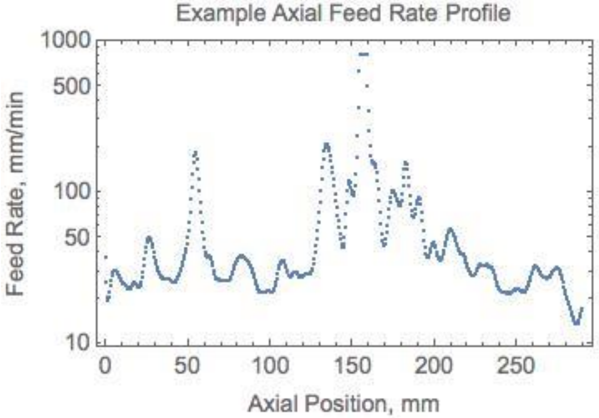
- Error map derived from metrology data.
- RMS slope errors were reduced to **0.5 arcsec**

The polishing routine software developed is validated and permit the fabrication of high resolution x-ray optics!!

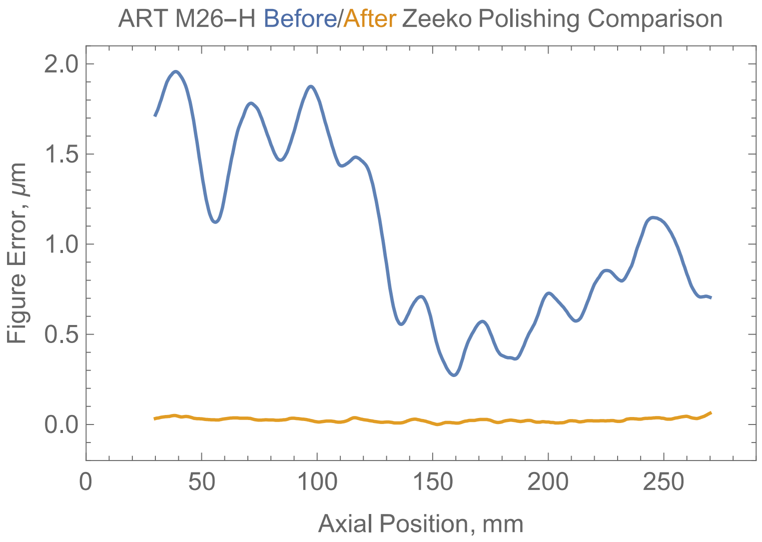
Mandrel Demonstration

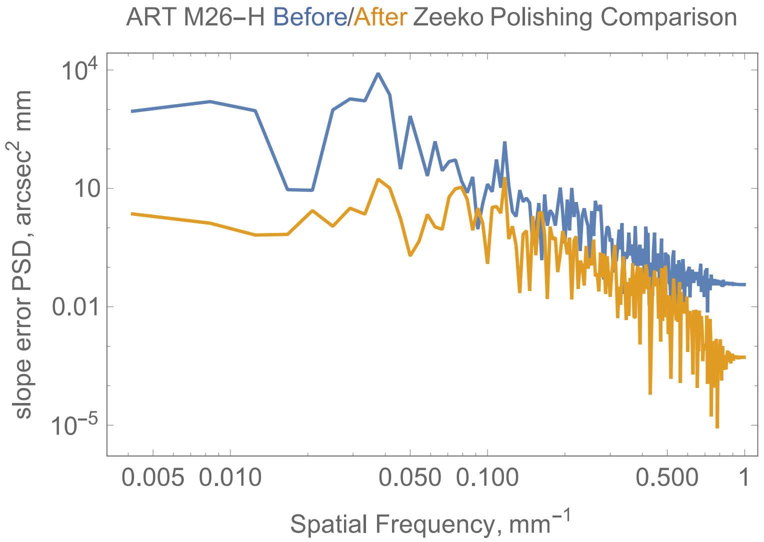
- Figure error correction process:
  - Initial Radii vs. axial position measured with CMM
  - Axial error map generated from Zygo data (36 meridians measured).
  - Feed rates determined from error map
    - Use axial wear function as deconvolution kernel
    - Use iterative Richardson-Lucy deconvolution algorithm
    - Select iteration that produces the smallest residual RMS slope errors
- Overall strategy
  - Initial mandrel errors >99.5% cylindrical so derive a feed rate map from 1D deconvolution of axial error map and apply to all meridians scaled for small azimuthal variations.
  - Scale the feed rates so run time fits in a work day
  - Perform a series of runs over required number of days alternating CW-CCW on alternate days to minimize daily wear rate drift
  - Iteratively measure(Zygo) and generate new feed rate map as required
  - Continue until cylindrical errors are comparable to azimuthally incoherent errors
  - Derive a feed rate map from 2D deconvolution of 2D error map
  - Perform a final series of polishing runs, possibly alternating with lap polishing to reduce out-of-band errors.





- Cylindrical Correction Complete, Polishing time: 71.5 hours

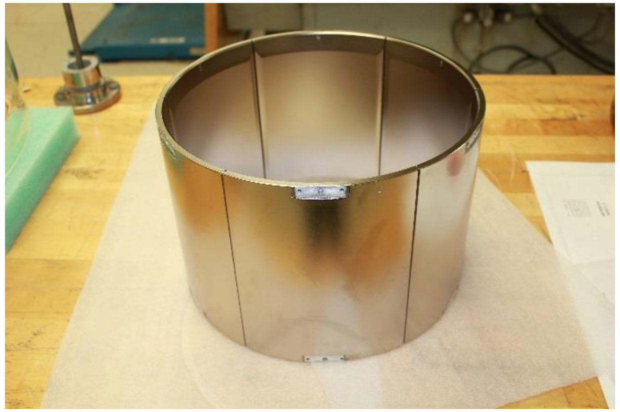




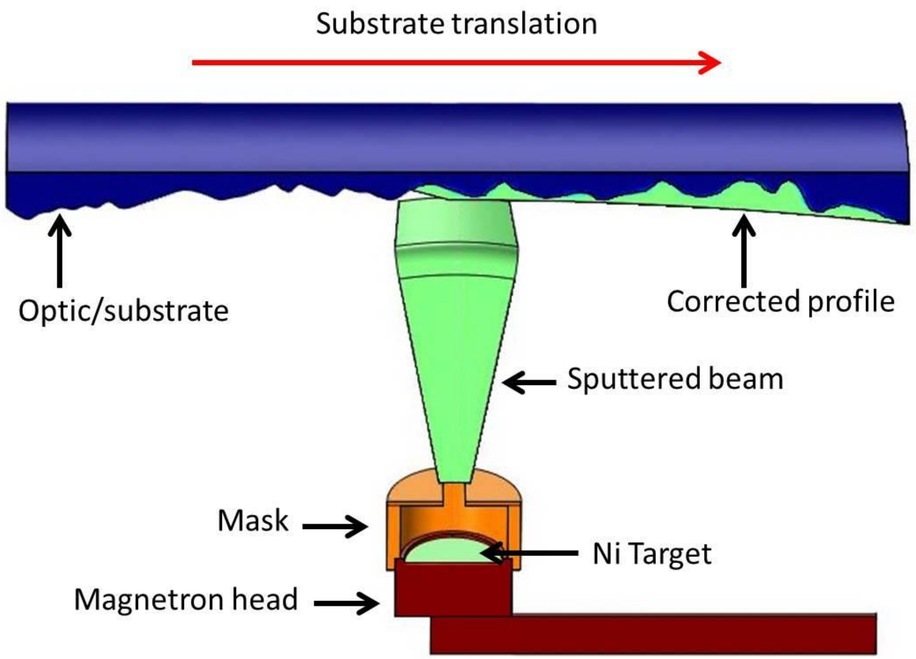
	before	after
Figure error (St. Dev.)	500 nm	10.7 nm
Slope error (> 2 cm) (RMS)	6.32 arcsec	0.30 arcsec
Low frequency (> 7 cm) slope error (RMS)	2.66 arcsec	0.09 arcsec
Mid frequency (2-7 cm) slope error (RMS)	5.73 arcsec	0.29 arcsec

Future Work

- Demonstrate the technology on a mandrel from scratch.
- Transfer the technology to NiP plated shells and segments.
- Use the differential deposition technique for further improvement of the angular resolution (to remove features with spatial extend below 7 cm)



- A NiP plated, segmented aluminum pipe with a conical inner figure fabricated for metrology, figuring and superpolishing experiments



Conclusions

- MSFC is developing direct fabrication technology for full-shell x-ray optics made from metal substrates;
- Support fixtures for diamond-turning, polishing and metrology have been developed;
- Wear functions were determined using NiP plated flat samples;
- Tool path generation software has been developed;
- Slope error level is consistent with 1-2 arcsec optics
- The technique can be married with the Differential Deposition for further improvements