Current Status of Replicated Optics at MSFC

B. Ramsey[1], C. Speegle[3], D. Engelhaupt[4], M. Gubarev[5], G. Thornton[2], Ryan Upton[6]

1 MSFC/NASA, VP62, Huntsville, AL 35812
2 MSFC/NASA, VP63, Huntsville, Al 35812
3 Raytheon IS, NSSTC 320 Sparkman Drive, Huntsville, AL 35805
4 Center for Applied Optics, University of Alabama in Huntsville, AL 35899
5 Universities Space Research Association, VP62, Huntsville, AL 35812
6 ERC, Inc., VP63, Huntsville, AL 35816

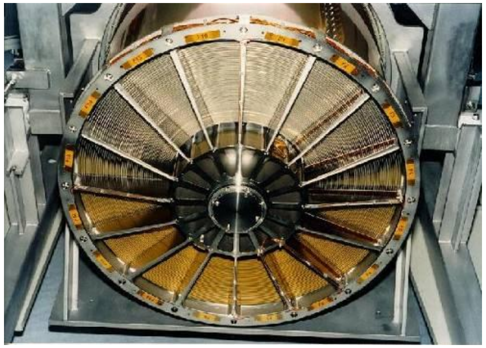
Grazing-Incidence X-Ray Optics Fabrication Techniques (For X-ray Astronomy)

•***Classical Optical grinding and polishing***

Missions: Chandra, Rosat, Einstein

Advantage: Superb angular resolution

Disadvantage: High cost, large mass, difficult to nest

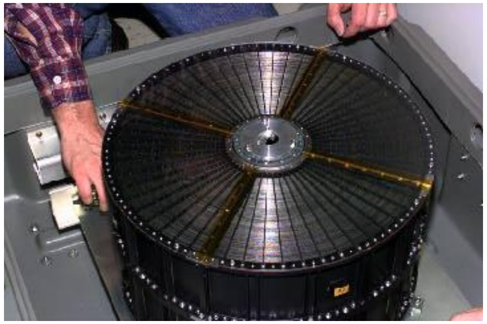


•***Electroformed Nickel Replication*** √

Missions: XMM, JETX/Swift, SAX

Advantage: High nesting factor, good resolution

Disadvantage: Significant mass (high density of nickel)



•***Segmented foil***

Missions: ASTRO-E, ASCA, BBXRT, HEFT, ConX (Development)

Advantage: Very high nesting factor, light weight

Disadvantage: Serious challenge to get good angular resolution

Approach adopted at MSFC

Electroform Nickel Replication (ENR)

Pioneered in Brera Observatory Italy for x-ray optics (Oberto Citterio)

~ 1992 - Work starts at MSFC

Electroformed Nickel Replication Process

Mandrel Preparation

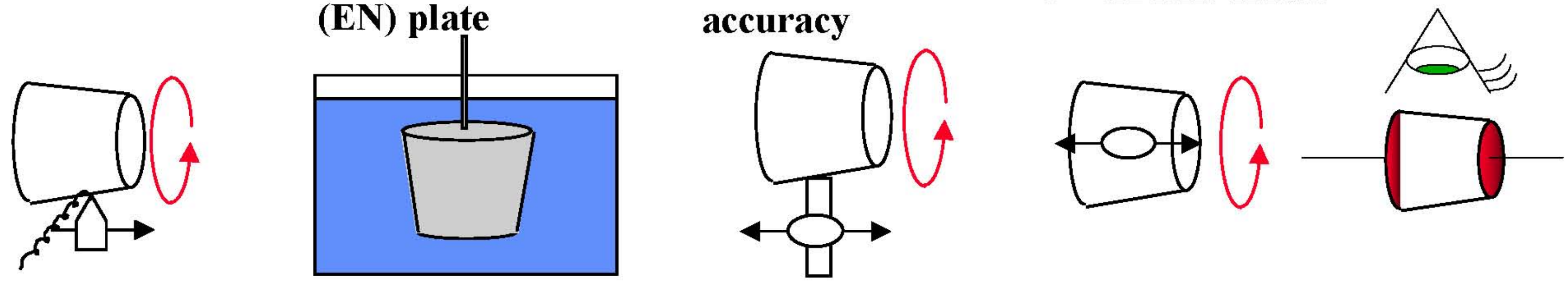
1. CNC Machine, Mandrel Formation From Al Bar

2. Chemical clean and activation & Electroless Nickel (EN) plate

3. Precision Grind to 600Å, sub-micron figure accuracy

4. Polish and Superpolish to 3 - 4Å rms finish

5. Metrology On Mandrel



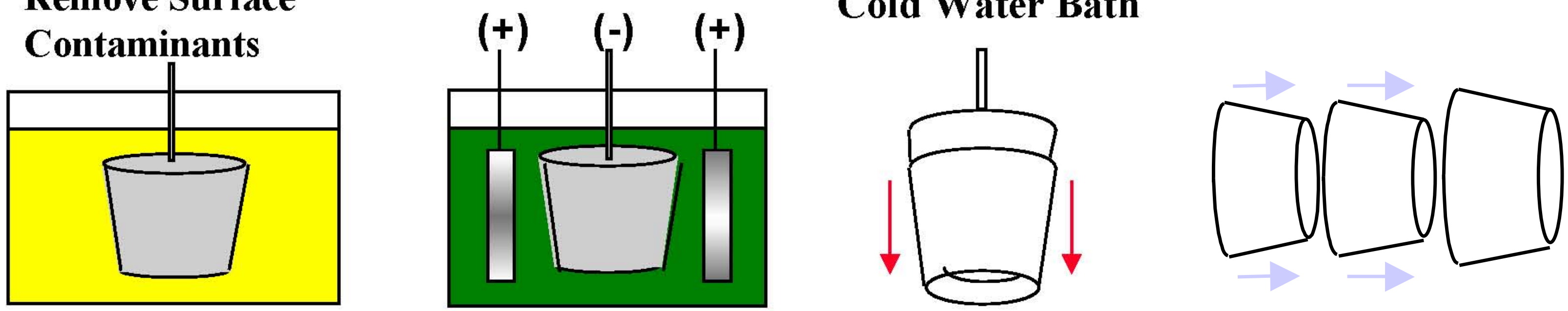
Shell Fabrication

6. Ultrasonic clean and Passivation to Remove Surface Contaminants

7. Electroform Ni Shell onto Mandrel

8. Separate Optic From Mandrel in Cold Water Bath

9. Nesting of Mirror Shells



Material Properties for Mirrors & Mandrels

Material	*Modulus* E_M (Pa)	*Density* ρ (kg/m³)	*Specific Stiffness* E/ρ (MPa m³/kg)	*Expansion Coefficient* CTE (ppm/F)	*CTE comparison to EN* No units
Nickel-Cobalt (mirror shells)	1.86E+11	8900	20.9	7.2	1
Copper (OFHC)	1.17E+11	8940	13.1	9.4	1.3
Ni-11%P (EN)	6.20E+10	7750	8.0	7.2	1
Al-6061-T6 (mandrels)	7.10E+10	2710	26.2	13.1	1.82
Be (S-65H HIP)	3.03E+11	1840	164.7	6.4	0.88
304 SS	1.93E+11	8000	24.1	9.5	1.32
316 SS	1.93E+11	8000	24.1	8.9	1.23
416 SS	2.15E+11	7800	27.6	5.5	0.76
17-4PH SS	1.96E+11	7800	25.1	6.0	0.83
K-500 Monel (annealed)	1.80E+11	8440	21.3	7.6	1.05
Titanium: 6Al4V	1.14E+11	4430	25.7	4.9	0.68

Thermal Separation of Shells

	CTE (Ni-Co)	***7.20E-06***	***/F***	***CTE (304 SS)***	***9.50E-06***	***/F***	
			Ni-Co	**304 SS**	**Ni-Co**	**304 SS**	
Room temp (°F)	Separation Temp (°F)	ΔT (F°)	Initial shell dia. (in)	Initial mandrel dia. (in)	Final shell dia. (in)	Final mandrel dia. (in)	Delta layers (in)
70	32	-38	2.59842	2.59842	2.59771	2.59748	0.00023
70	-109	-179	2.59842	2.59842	2.59507	2.59400	0.00107
70	-330	-400	2.59842	2.59842	2.59094	2.58855	0.00239

Diamond Turning Capabilities

Moore M-40

- 40-inches of travel in X-Axis
- 30-inches of travel in Z-Axis
- Maximum swing up to 100-inches
- 4000-lbs rated Hydrostatic Spindle
- Laser feedback for positioning
- 6-Decimal Positional Accuracy

Precitech Optimum 4200

- 9.5 inches of travel in X-Axis
- 9.5 inches of travel in Z-Axis
- Maximum swing up to 12-inches
- Air bearing spindle w/ hydrostatic slides
- Positional slide feedback resolution (2.5 nm)
- 6-Decimal Positional Accuracy

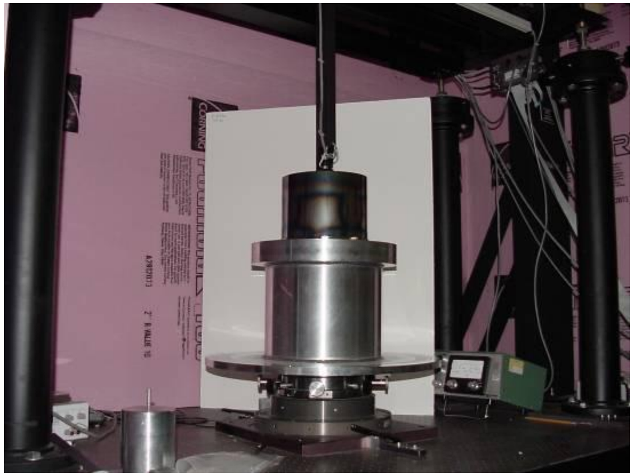
Electroforming & RF Sputtering Capabilities

Plating Baths

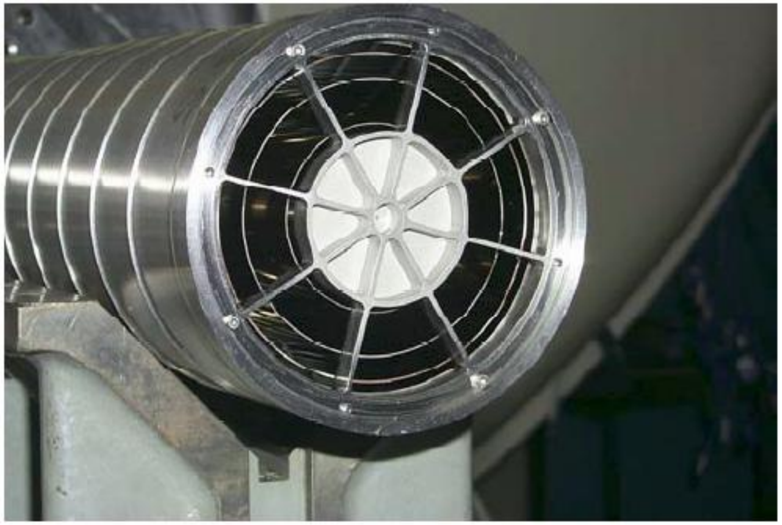
- Electrolytic Ni-Co sulfamate
- Electrolytic Nickel sulfamate
- Electrolytic Nickel phosphorus

Iridium coating chamber

Optical Testing Facilities



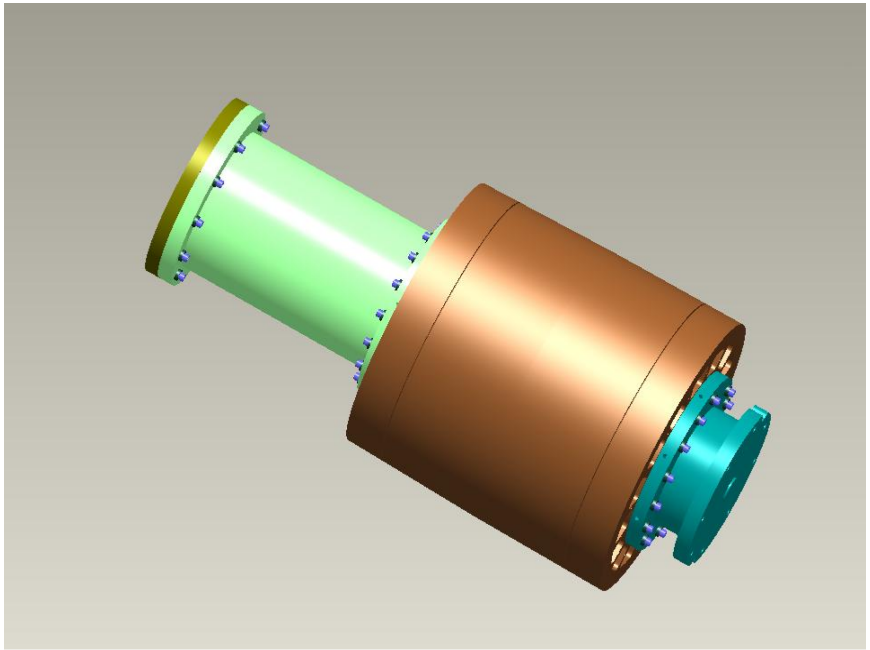
Vertical long-trace profilometer

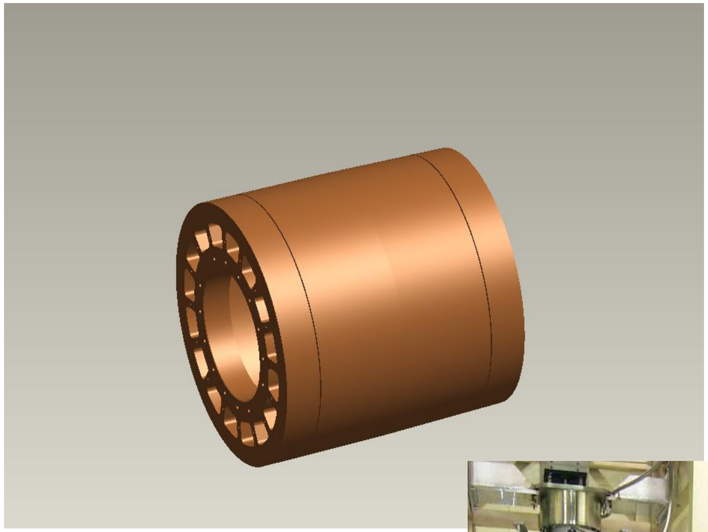


Optical Test Configuration

Stray light Facility

0.7 meter Mandrel Fabrication

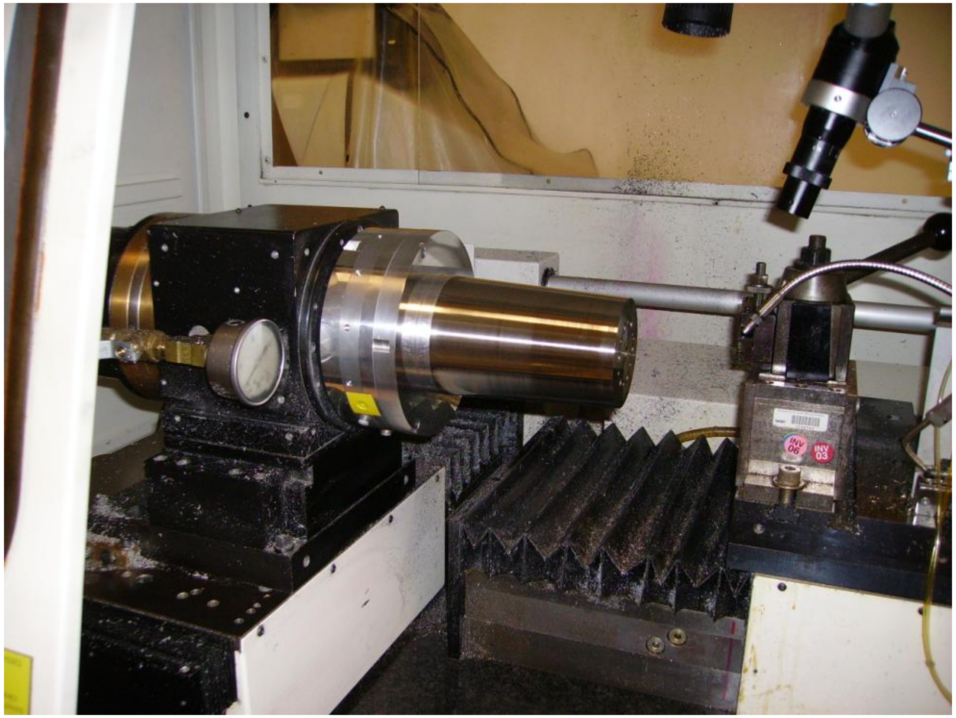




- Al 6061-T6 centrifugally cast alloy
- 0.7 meter intersection diameter
- 0.711 meters long
- 10 meter focal length
- Two castings completed

0.5 meter dia. shell ➔

XNAV Prototype Mandrel



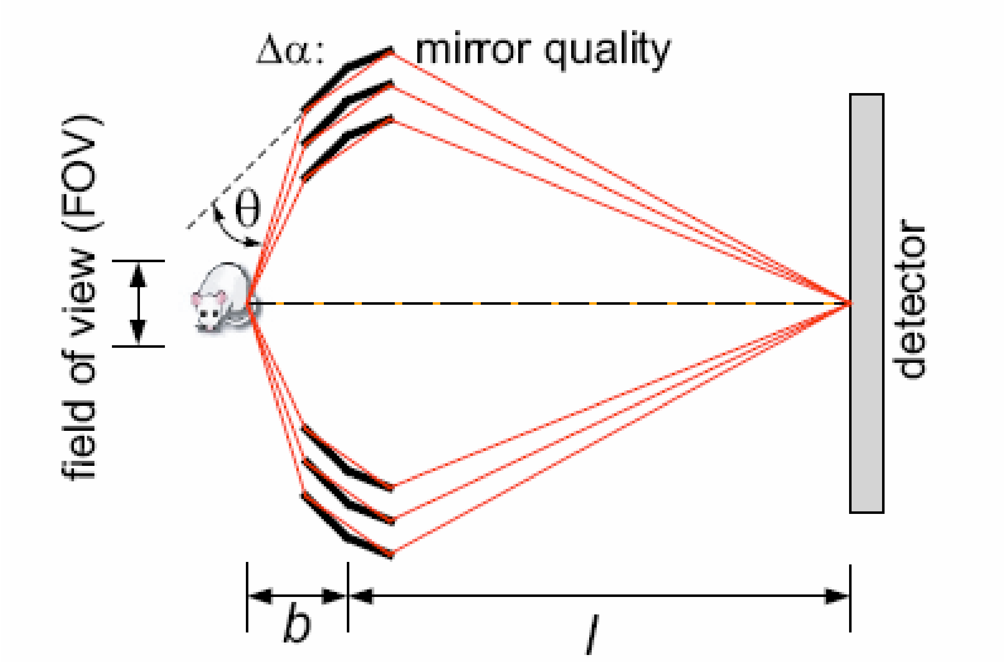
304-L SS mandrel being precision turned on the Precitech 4200

304-L SS mandrel awaiting CMM measurement

National Institutes of Health (NIH) Mandrels

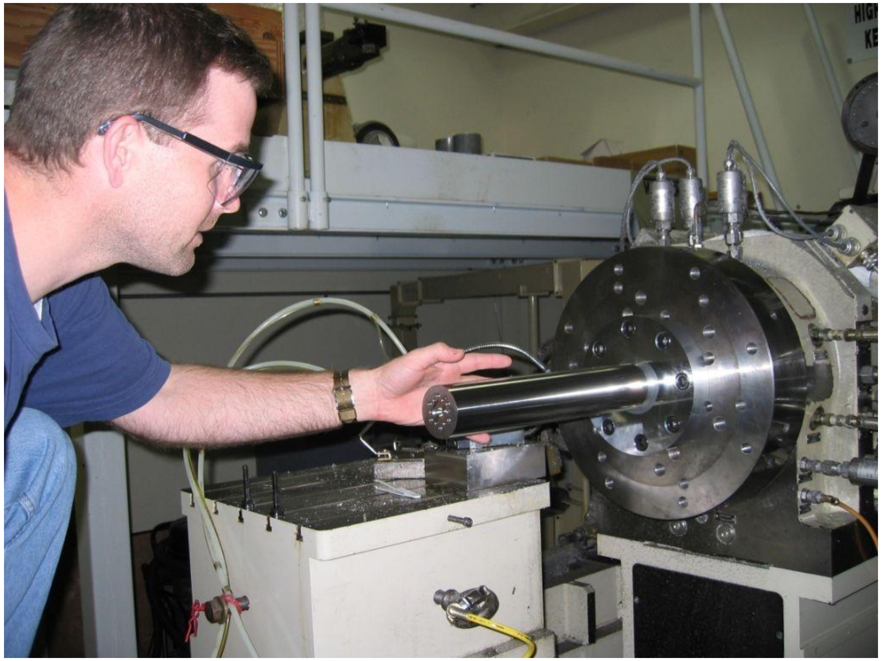
- *8 mandrels are currently in production*

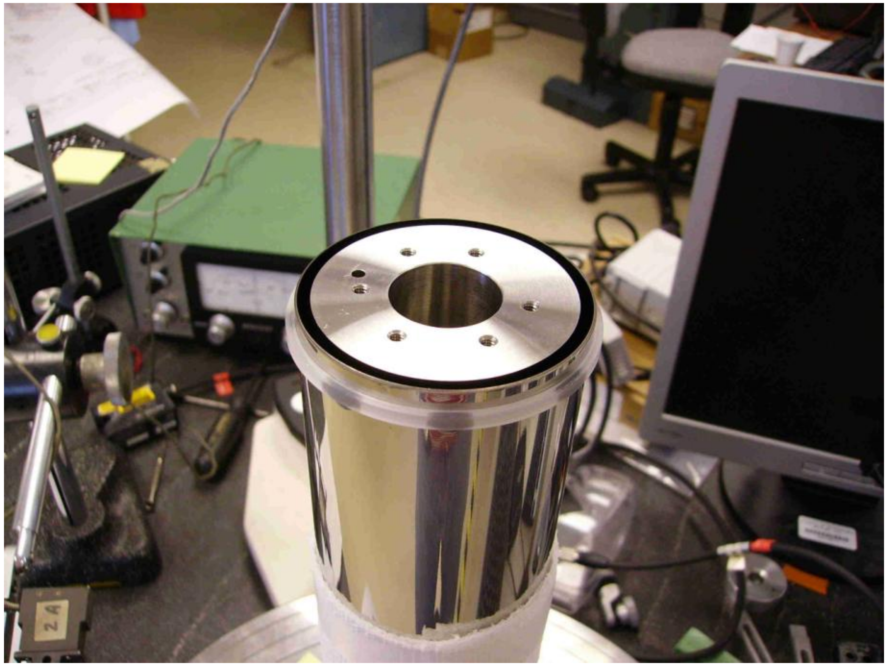
- *2.5 cm diameter shell for animal imaging*



- Ellipsoid-Hyperboloid segments
- $1/f = 1/b + 1/l$
- Magnification = 4.0
- Object to image = 3.2 m

Helix Mandrels & Shell





- Part of a high resolution charged particle time-of-flight (TOF) mass spectrometer.
- Helical path taken by the particles traveling between the tapered parabolic surfaces of the TOF section.
- Replicated optics allow very accurately shaped cylinders and smooth surfaces with the potential for low cylinder mass.

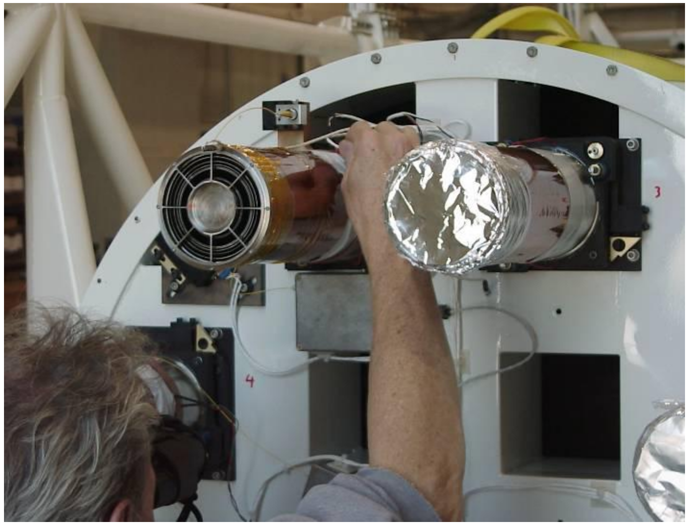
HERO Program

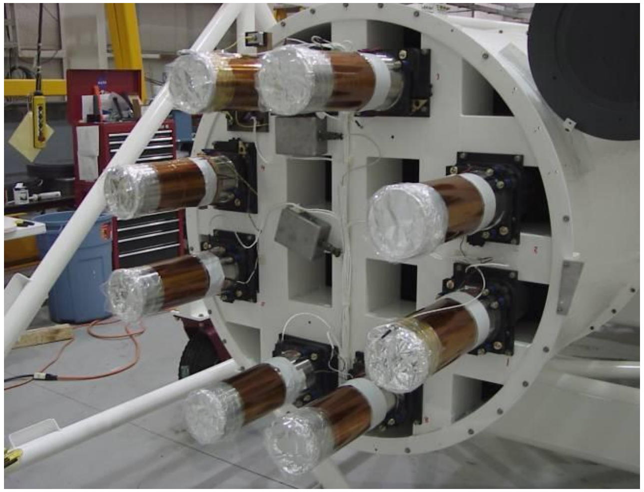
- ***HERO, for High Energy Replicated Optics, is a balloon program designed to demonstrate MSFC optics and perform science.***

- ***Utilizes in-house-fabricated hard-x-ray mirrors plus supporting x-ray detectors, gondola and pointing system.***

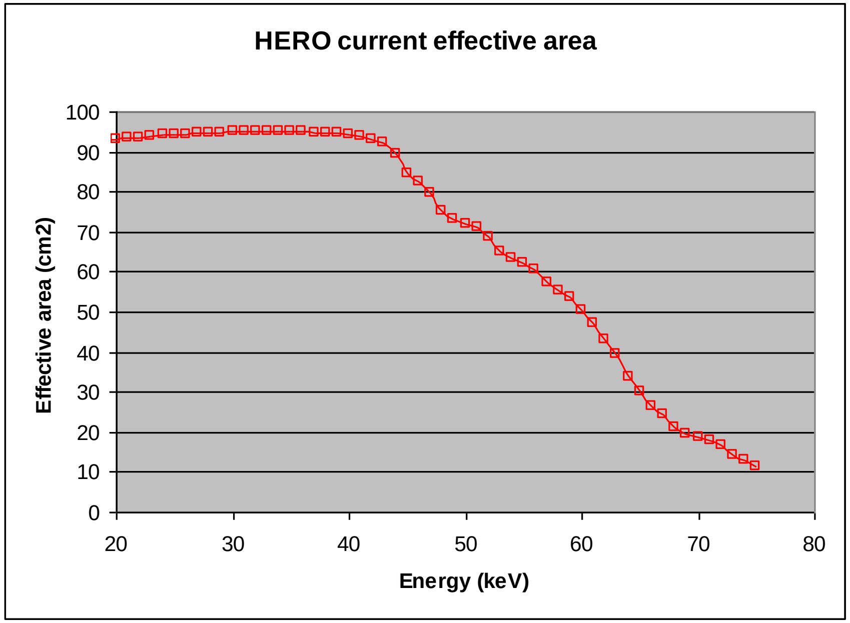
- ***Payload features a tubular 6-m-long optical bench housing ~ 100 MSFC-fabricated mirror shells***

HERO Current Status

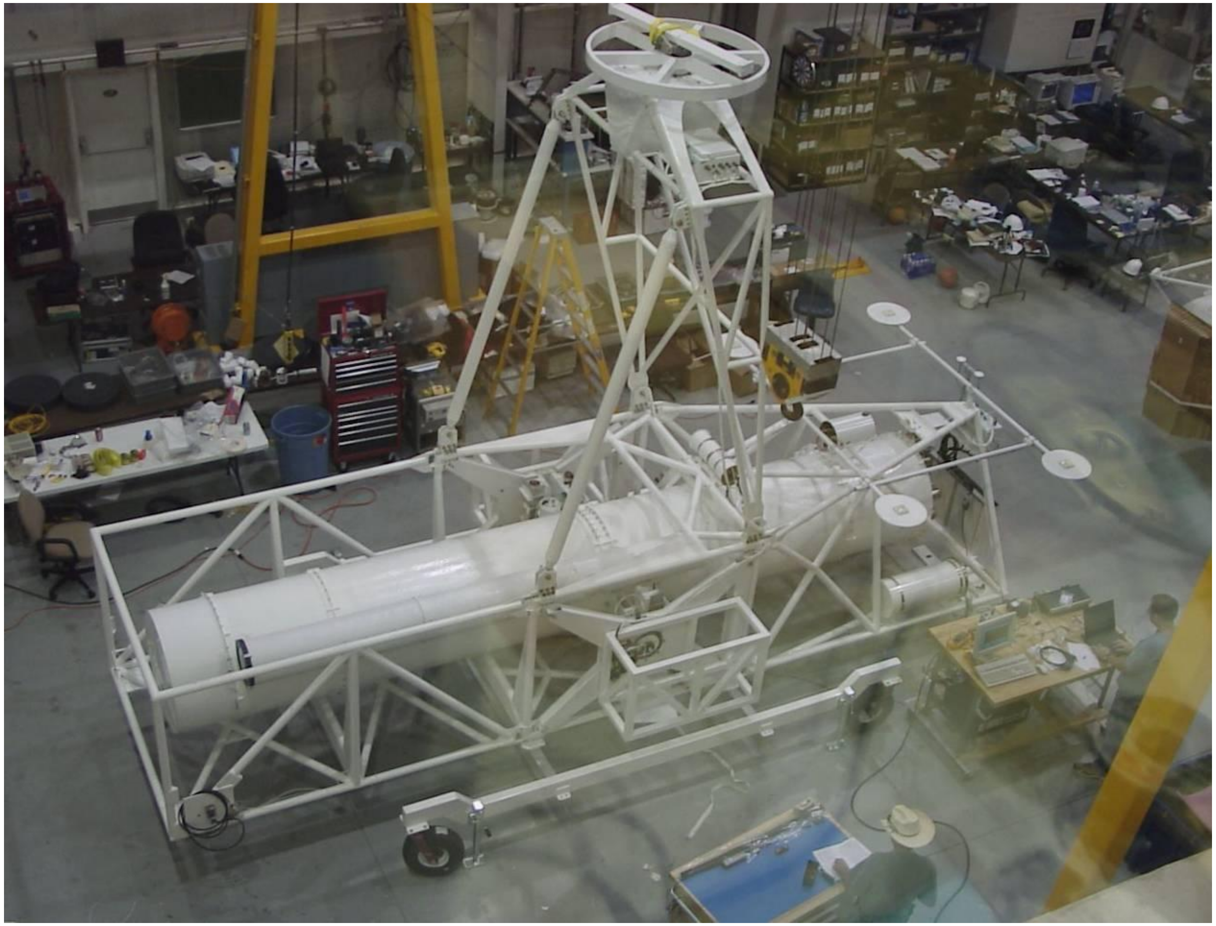




Number of modules	8
Number of shells	14
Inner, outer diameters	50, 94 mm
Shell thickness	0.25 mm (~0.010 inch)
Focal length	6 m
Angular resolution	~ 13-15 arcsec HPD shells 20 arcsec modules
Field of view	9 arcmin at 40 kev



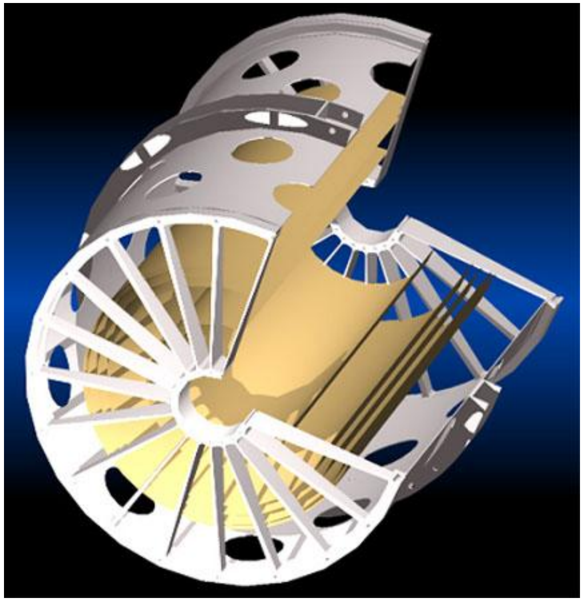
HERO Current Status



HERO payload awaiting launch in New Mexico (Spring 07)

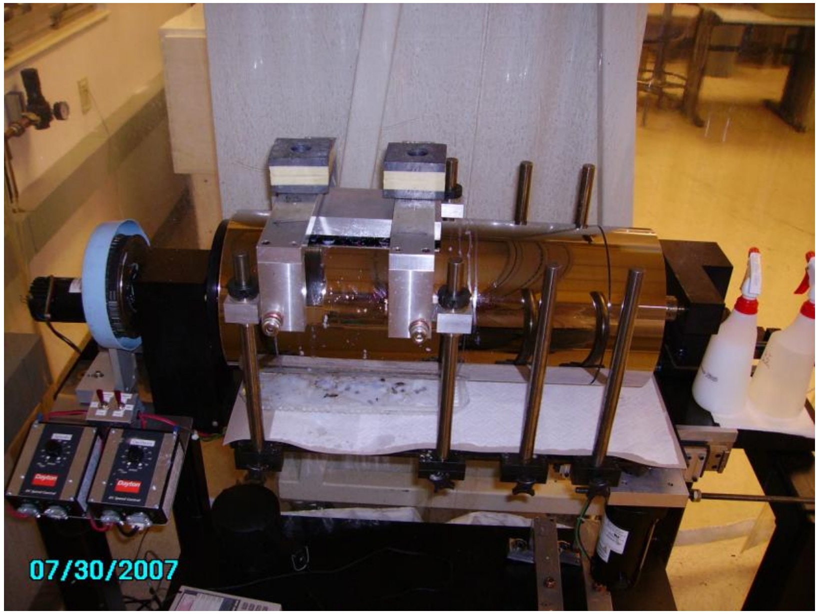
Application: Constellation-X

- **MSFC is collaborating (with Brera Observatory, Italy and SAO) on a hard-x-ray telescope prototype flight unit for the Constellation-X program, NASA's planned successor to Chandra**
  - ***MSFC has produced two prototype mandrels & shells***
    - ***426-mm-long, 230-mm diameter shell to be coated with multilayers (SAO)***
    - ***426-mm-long, 150-mm diameter shell to be coated with Iridium***
  - ***100 micrometer shell thickness requirement to meet HXT weight budget***
  - ***Larger shell must have very good surface finish for multilayer coatings (< 5Å RMS)***



75 micrometer thick shell ➔

1015X and 1023X Shell Production and Data



Conclusions

- **MSFC has an ongoing development program in electroformed-nickel-replicated x-ray optics.**
- **A wide range of infrastructure supports the replicated optics program.**
- **When selecting mandrel & mirror materials, the thermal expansion coefficient property is crucial for separating the mirror shell from the mandrel.**
- **Over 150 shells total have been fabricated for the HERO balloon program and Constellation-X. Shells from 2.5 cm to 0.5 m diameter have been tested.**
- **While ‘routine’ shells have 13-15 arcsec HPD, optics at the ~ 11 arcsec have been demonstrated and 8-9 arcsec should be possible with good stress control and stable high-quality mandrels.**
- **Replicated optic applications have broadened over the past year at MSFC. For example, radionuclide imaging in small animals, mass spectroscopy, and imaging x-rays from celestial sources.**