Mirror Segment Fabrication and Metrology for the International X-ray Observatory

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Mirror Fabrication Progress and Goals

Date	HPD (two reflections	Comment
December 2008	~16”	Normal incidence metrology, Full illumination X-ray tests; 60-deg segments
August 2009	~12”	Normal incidence metrology; 60-deg segments
October 2009	~10”	Normal incidence metrology; 30-deg segments
December 2009	~8.5”	Normal incidence metrology; 30-deg segments
December 2010	~5”	Using new mandrels which have figure error of 2.5” HPD (two reflections)
December 2011	~3”	Using mandrels meeting IXO requirements; Meeting IXO requirements

Objectives

- Make mirror segments resemble the mandrel as closely as possible
- Use metrology every step of the process
  - to identify, quantify, and isolate every potential source of error
  - to enable the definitive prediction of point spread function for comparison with X-ray tests

IXO Mirror Segments Requirements

- Quantity: 13,896 mirror segments: 6948 parabolic and 6948 hyperbolic
- Quality:
  - Individual mirror segments: 2.2" HPD (one reflection)
  - Pair of mirror segments: 3.1" HPD (two reflections, no alignment error included)
- Mass Areal Density: ~ 1 kg/m^2
- Coating: Iridium or something better

Mirror Fabrication Process

Replicating (or Slumping)

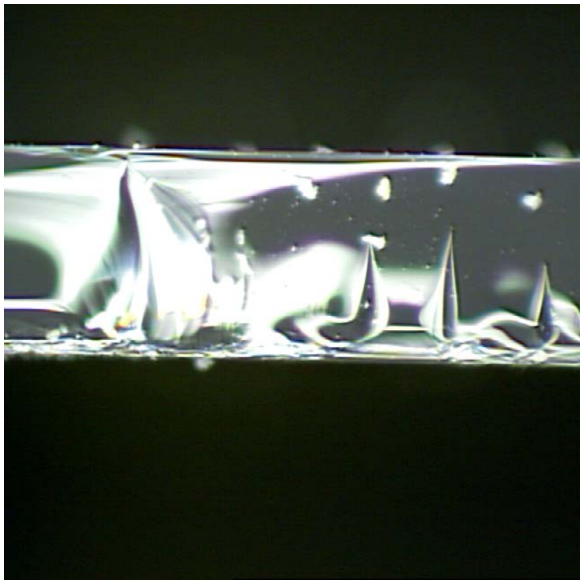
Post-slumping trimming ✔

Ir-coating ✔

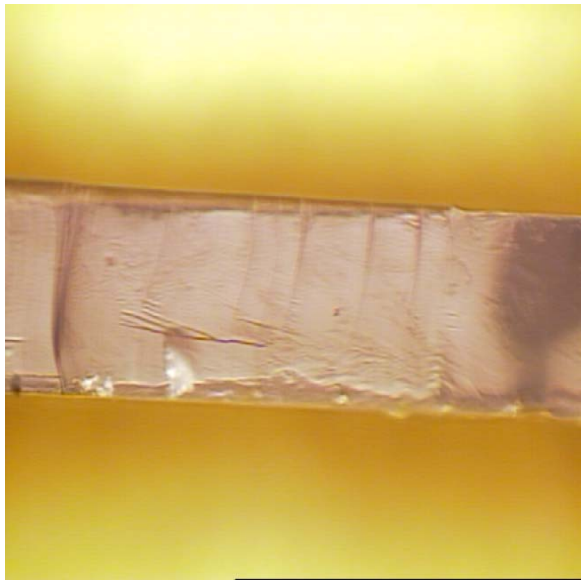
Two Factors Enabling the Making of Good Mirrors

- Mandrel release layer is key to making the best mirror possible
  - Boron nitride
  - Platinum
  - Iridium
  - Titanium nitride, etc.
- Repeatable and definitive measurement is essential in making further progress toward meeting IXO requirements

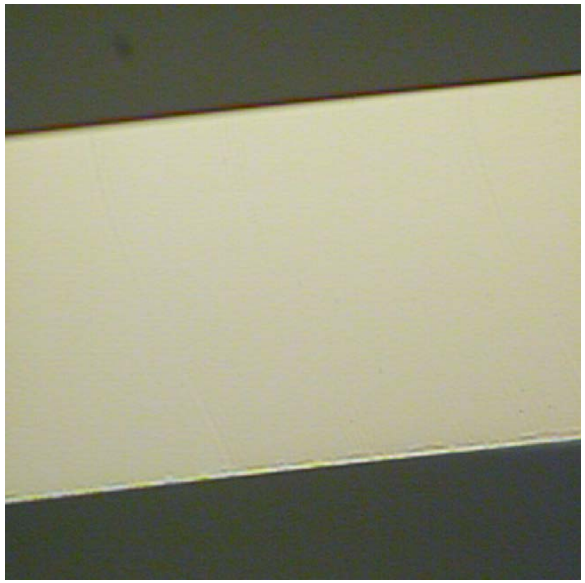
Comparison of three cutting techniques



Diamond Scriber



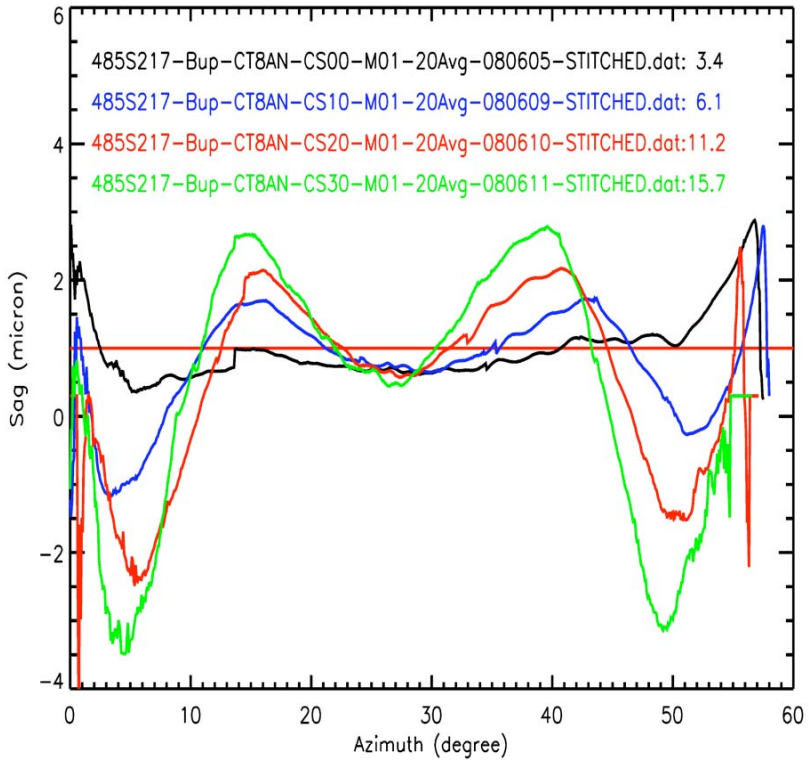
Laser Cutter



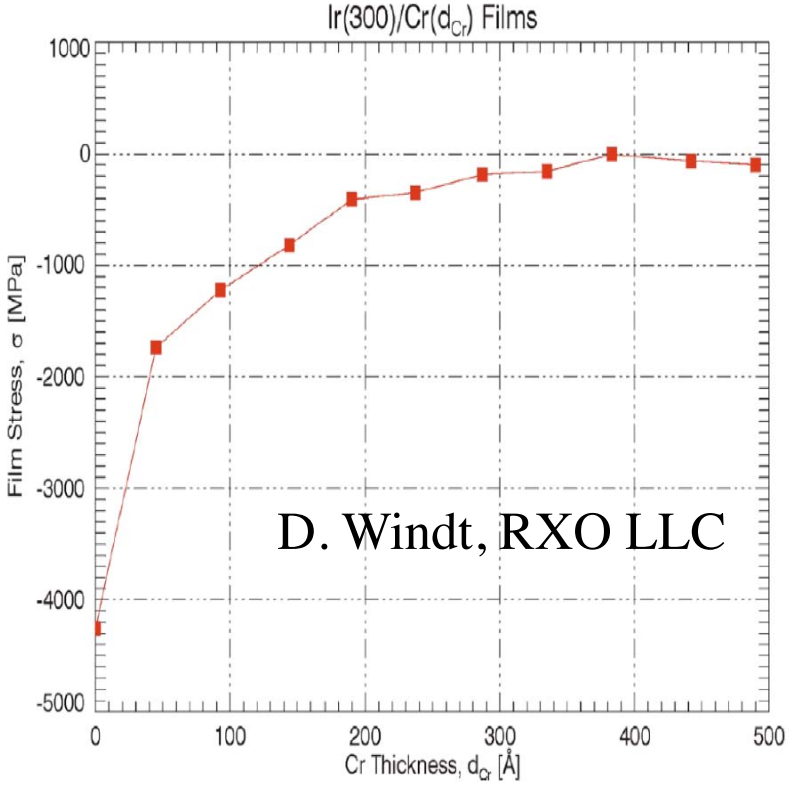
Hot Wire Cutter

Coating Stress: Solution found and being implemented

Problem: Ir coating stress



Solution: Cr+Ir bi-layer coating



Bug to Feature: Stress can be used to improve the mirror figure!

Prescription and Definitions

$$\rho(z,\phi) = \rho_0 + \Delta\rho(\phi) + z \cdot \tan[\theta_0 + \Delta\theta(\phi)] - \left(\frac{2z}{L}\right)^2 \cdot [s_0 + \Delta s(\phi)] + R(z,\phi)$$

$$0 \le \phi \le \phi_{\max}, -\frac{L}{2} \le z \le \frac{L}{2}$$

Average radius: ρ_0

Average sag: s_0

Radius variation: $\Delta\rho(\phi)$

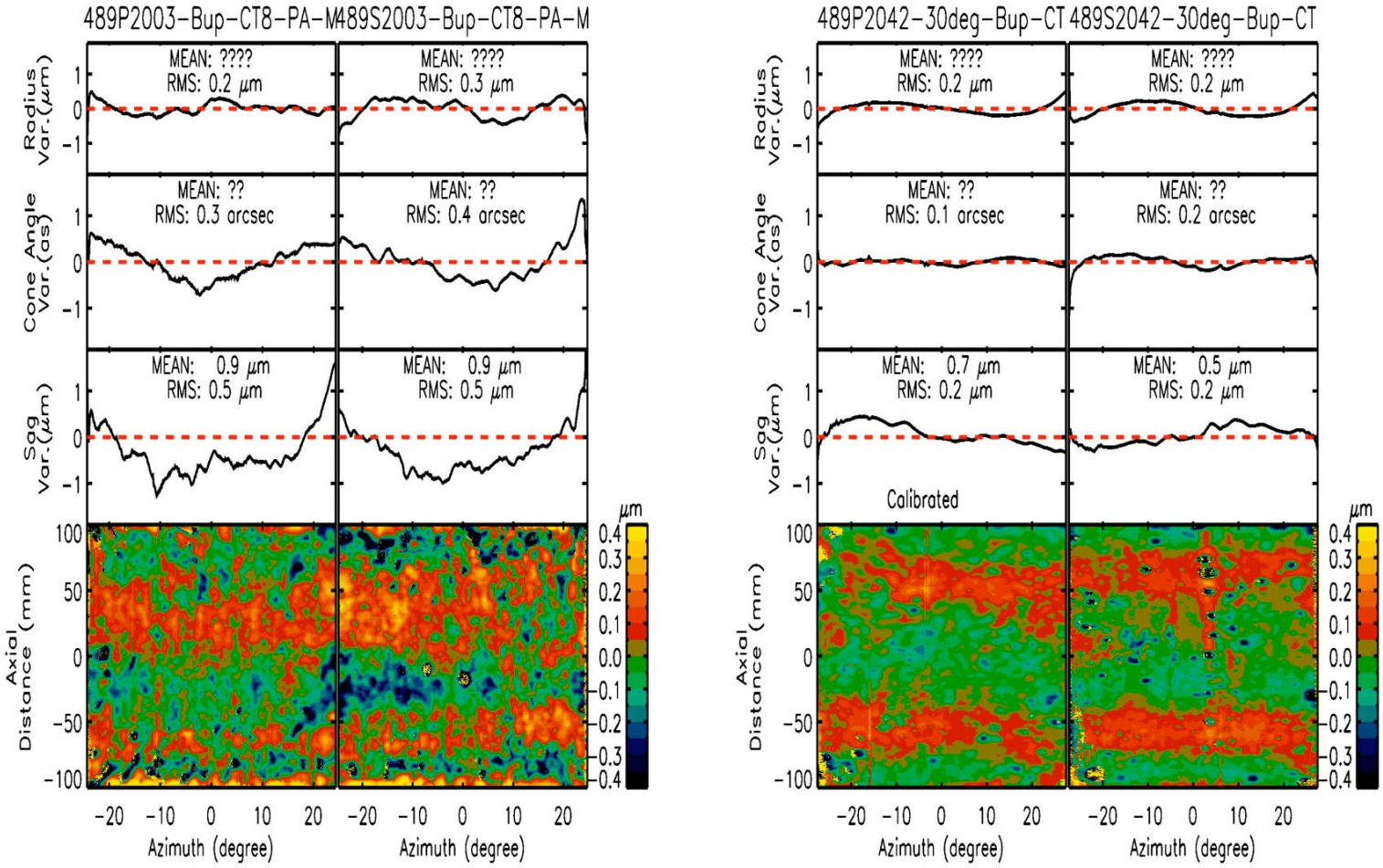
Sag variation: $\Delta s(\phi)$

Average cone angle: θ_0

Remainder: $R(z,\phi)$

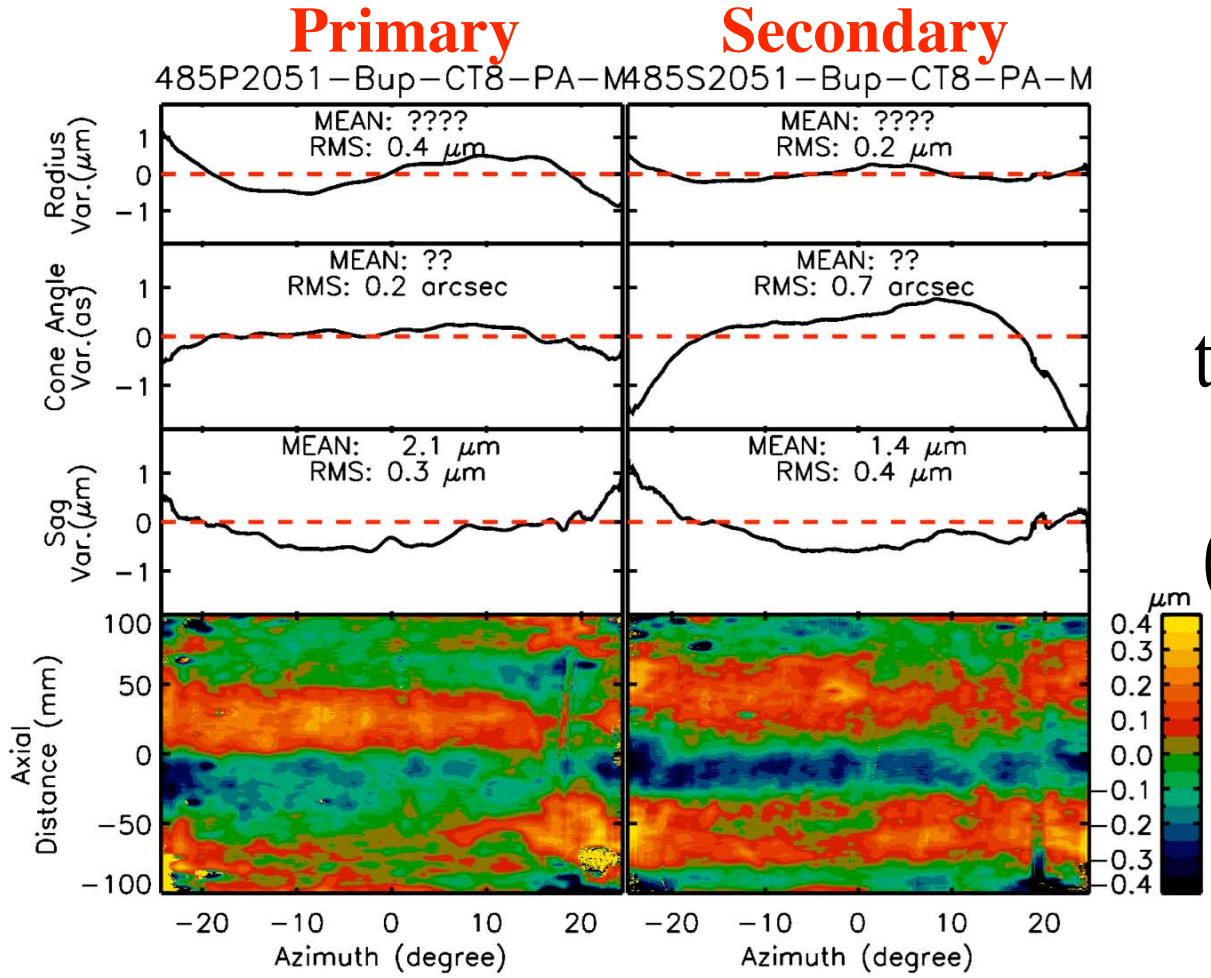
Cone angle variation: $\Delta\theta(\phi)$

Slumping



Mid-frequency error reduction over time

A Typical Pair of Mirror Segments -- 8 months ago

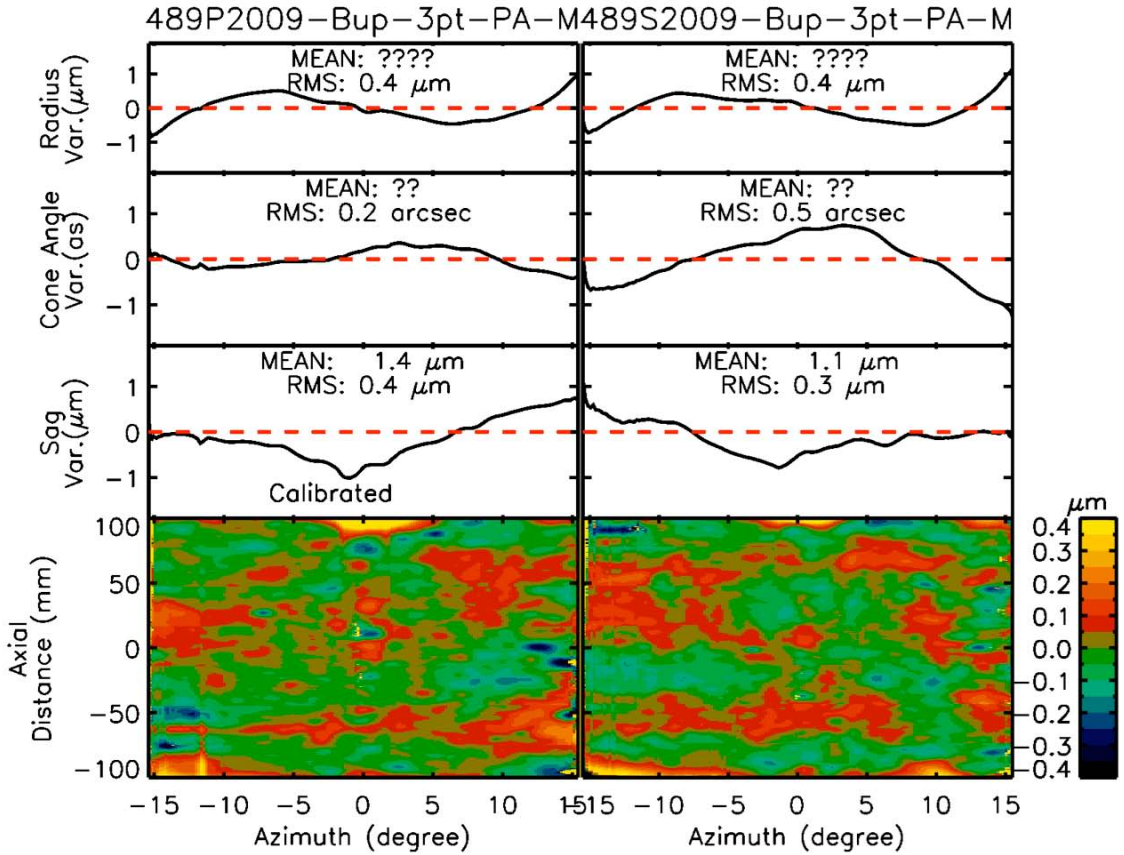


$$\rho_0 + \Delta\rho(\phi) + \tan[\theta_0 + \Delta\theta(\phi)]\bullet z + \left(S_0 + \Delta S(\phi)\right)\bullet\left(\frac{2z}{L}\right)^2 + R(z,\phi)$$

Performance Prediction: 12.5" HPD

A Typical Pair of Mirror Segments -- 4 months ago

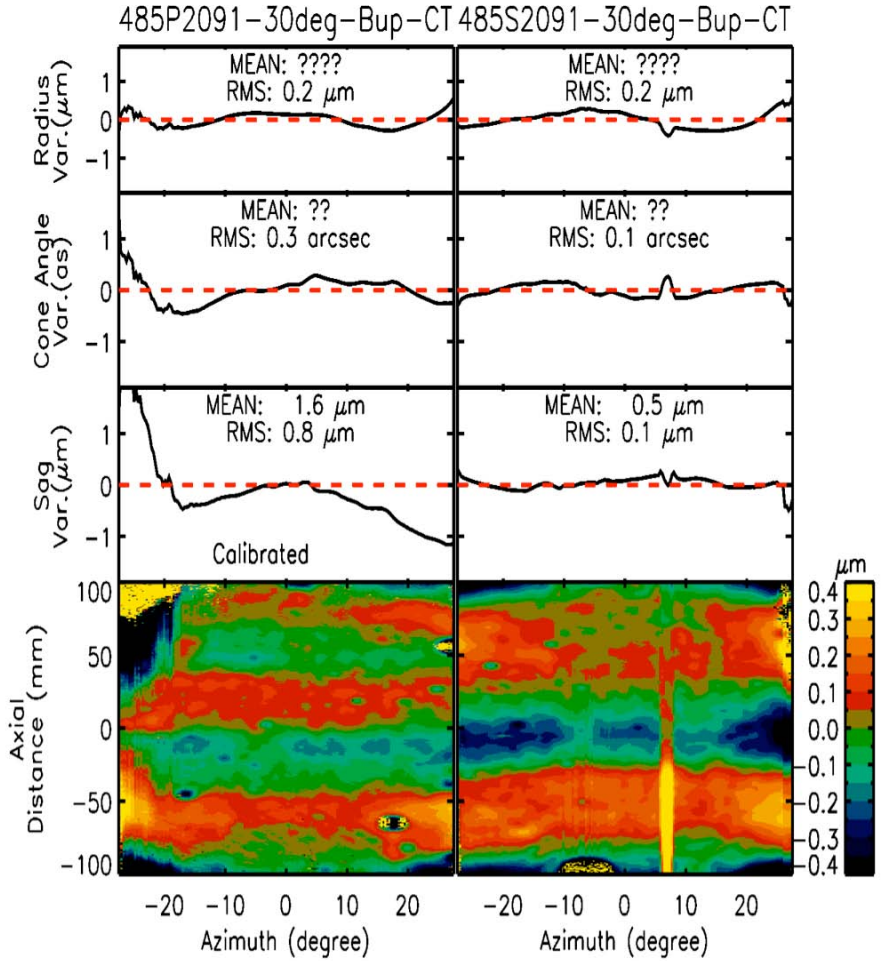
Primary **Secondary**



$$\rho_0 + \Delta\rho(\phi) + \tan[\theta_0 + \Delta\theta(\phi)]\bullet z + \left(S_0 + \Delta S(\phi)\right)\bullet\left(\frac{2z}{L}\right)^2 + R(z,\phi)$$

Performance Prediction: 10.5" HPD

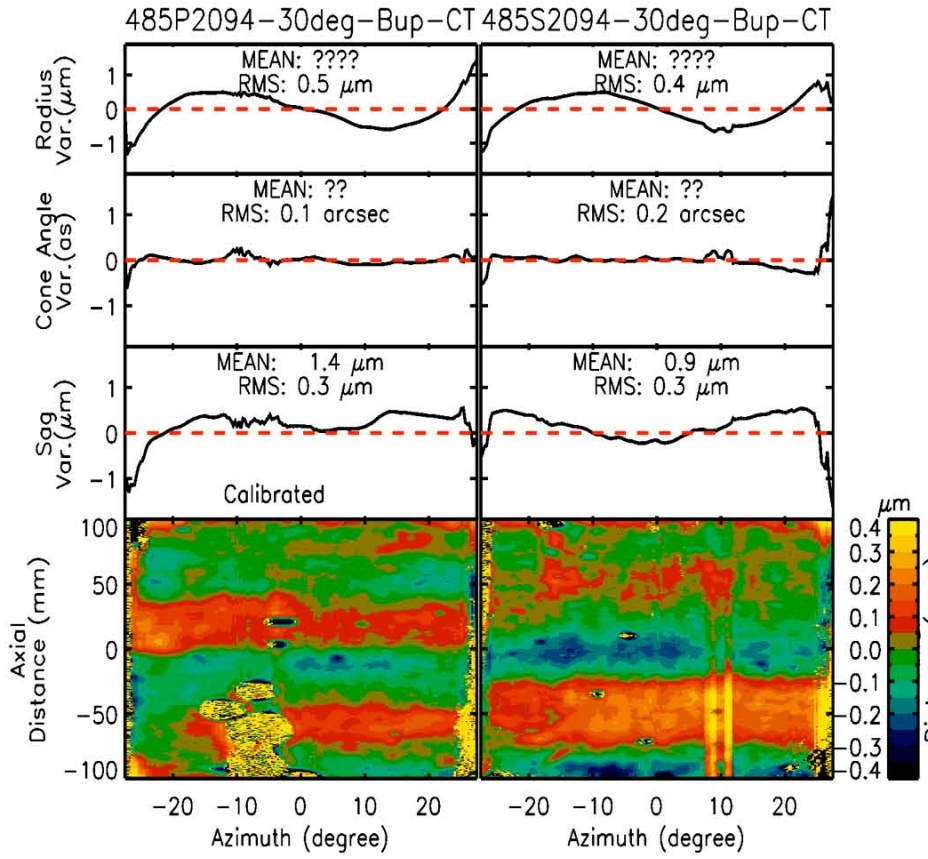
Typical Mirror Segments as of December 2009



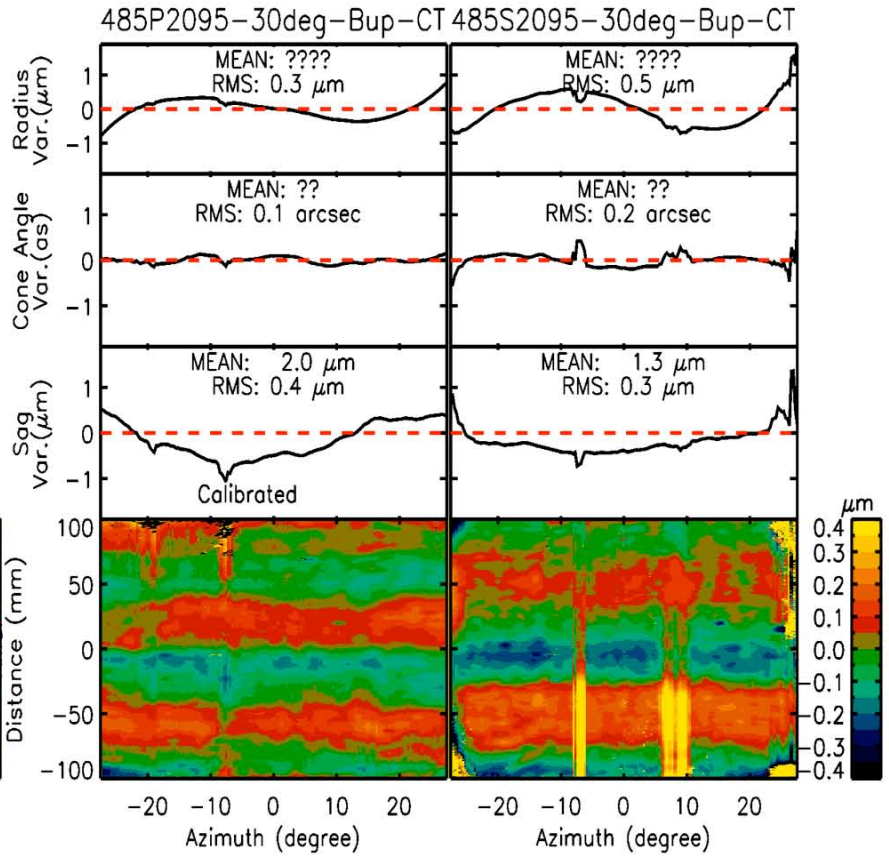
9.5" HPD (two reflections)

- Mandrel surface conditioning is key to making the best mirror possible
- Repeatable and definitive measurement is essential in making further progress toward meeting IXO requirements

Another Two Pairs of Mirror Segments

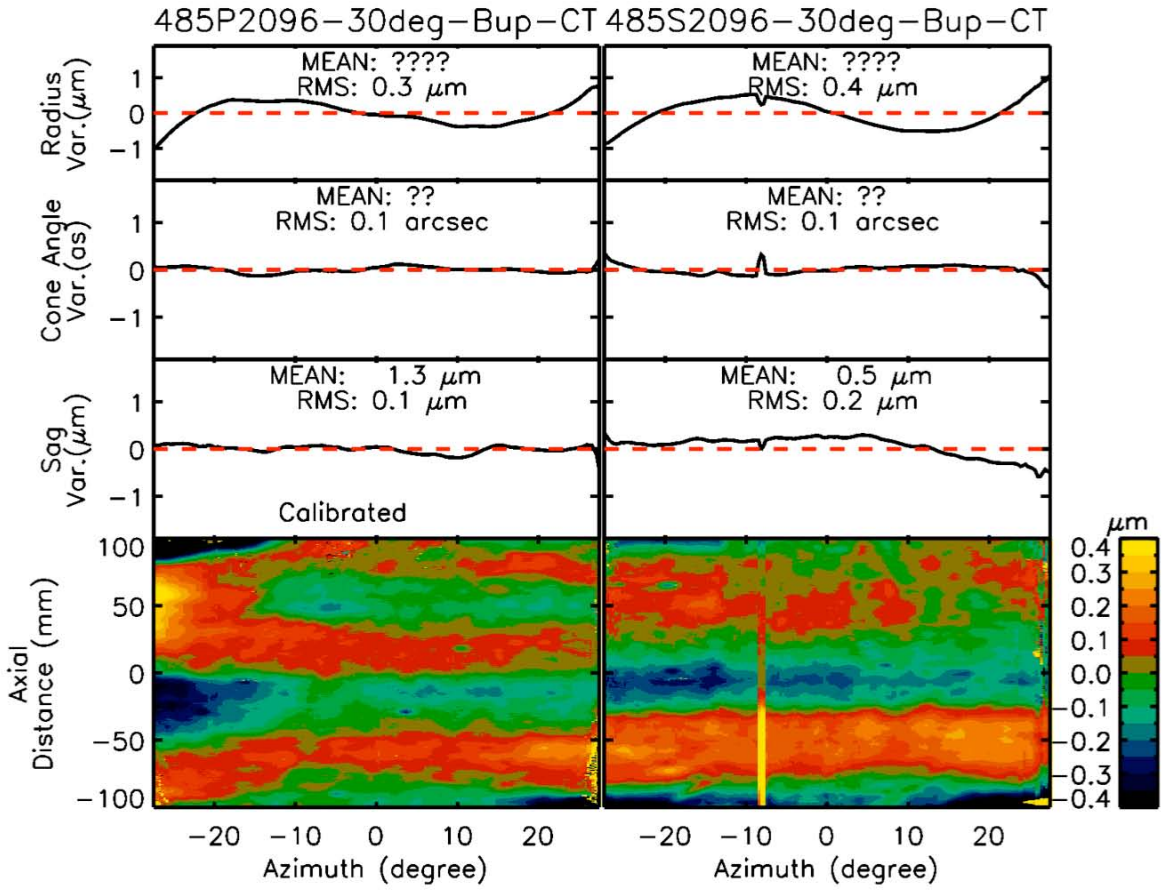


9.5” HPD (two reflections)



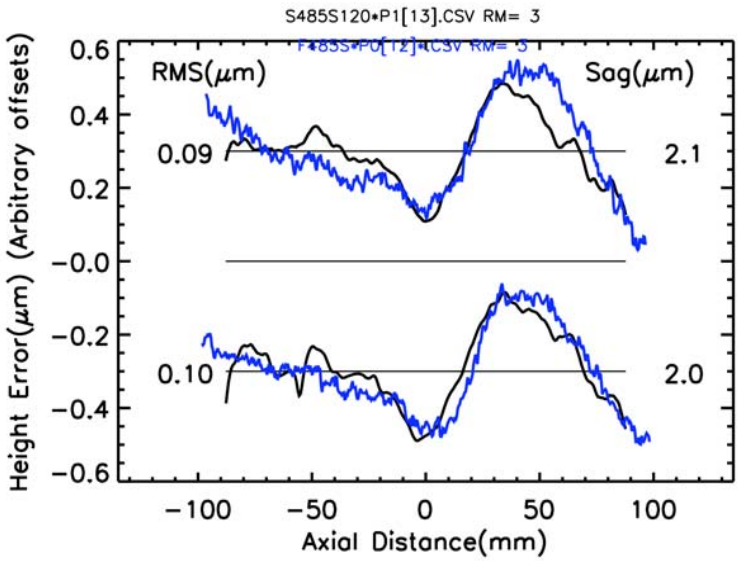
8.5” HPD (two reflections)

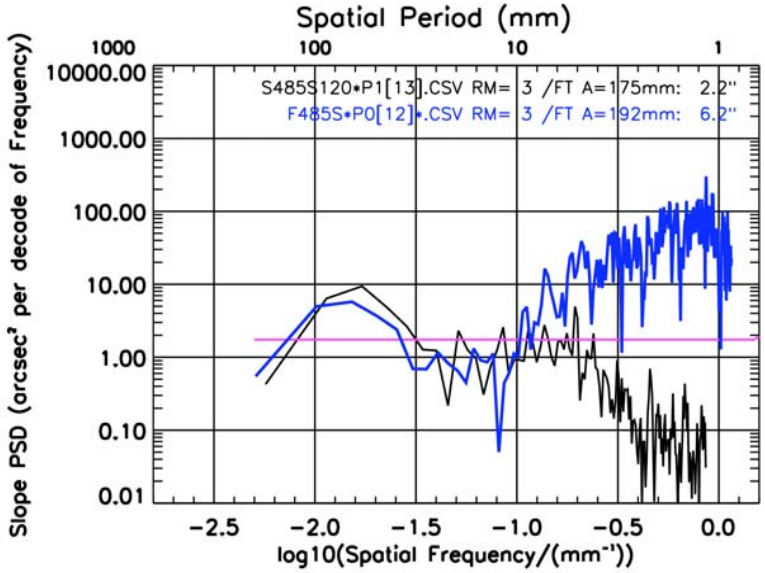
One Latest Pair



8.5” HPD (Two Reflections)

Comparison between Mandrel and Replica





- The difference between mandrel and replica: ~18nm RMS
- Dominant source of error: forming mandrel; Better mandrels are needed to further reduce this error

Status of Mirror Fabrication

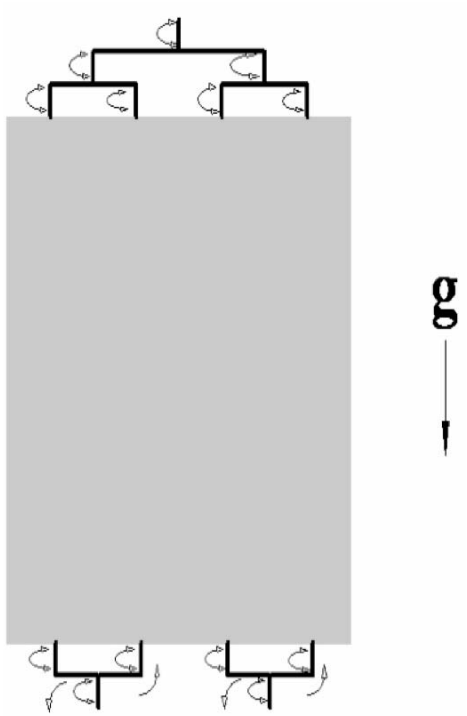
- We are producing very good copies of the forming mandrels. Currently mandrel figure (7.5" HPD) dominates the error of mirror segments
- Better mandrels (2.5" HPD) should enable us to make mirror segments as good as 5" HPD (2010)
- Improvement of slumping process to reduce the 5" to ~3" which is the IXO requirement (2011)

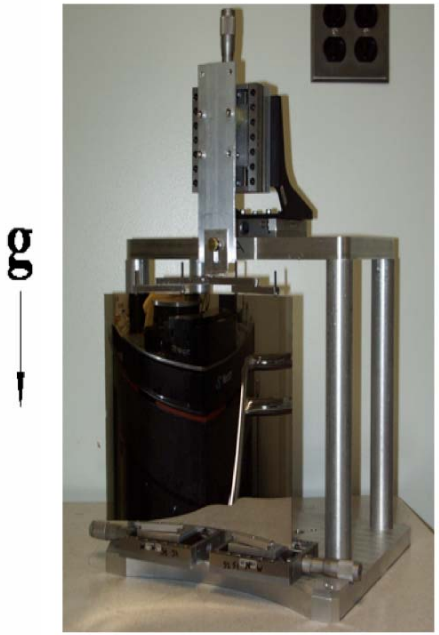
Good metrology is Key to identification and reduction/elimination of the next dominant error

Mirror Segment Metrology

- Requirements
  - Repeatably, accurately, and expeditiously measure each segment and its corresponding mandrel to enable
    - Performance prediction
    - Detailed comparison between mirror and mandrel for process improvement
  - Random and systematic errors should be at least a factor of three smaller than corresponding requirements
- Two Major Components of Metrology
  - Mirror Support
    - Cantor-tree
    - Suspension mount
  - Measurement
    - Normal incidence: Interferometer
    - Grazing incidence: Hartmann test

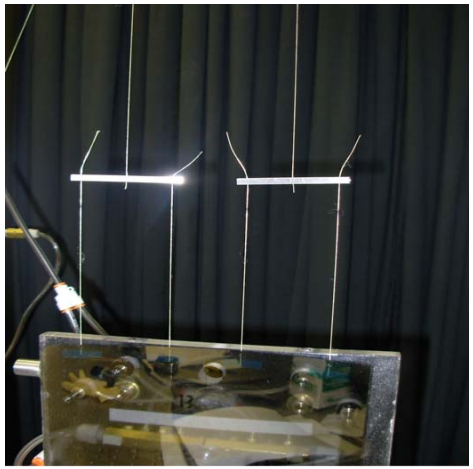
Cantor-Tree Support

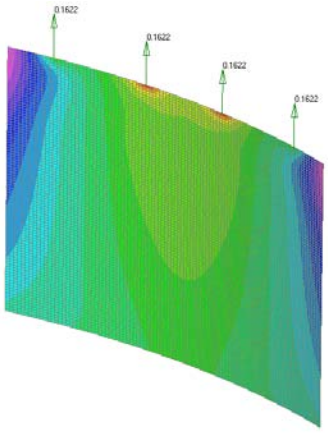




- Relatively good repeatability has been achieved, but not good enough to meet requirements
- Difficult to analyze because the forces are not deterministic
- Being phased out

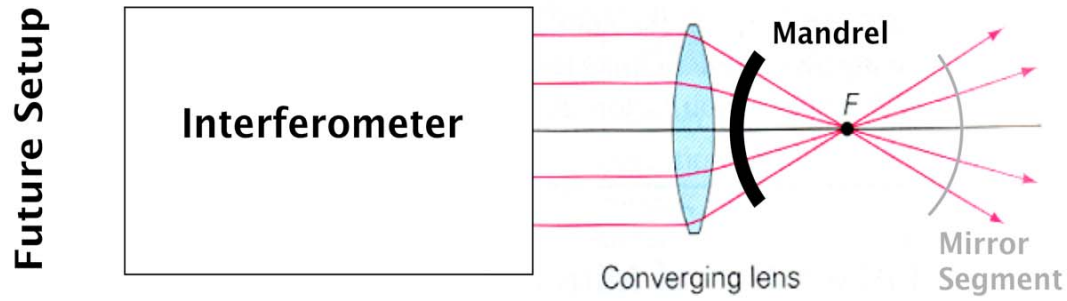
Suspension Mount



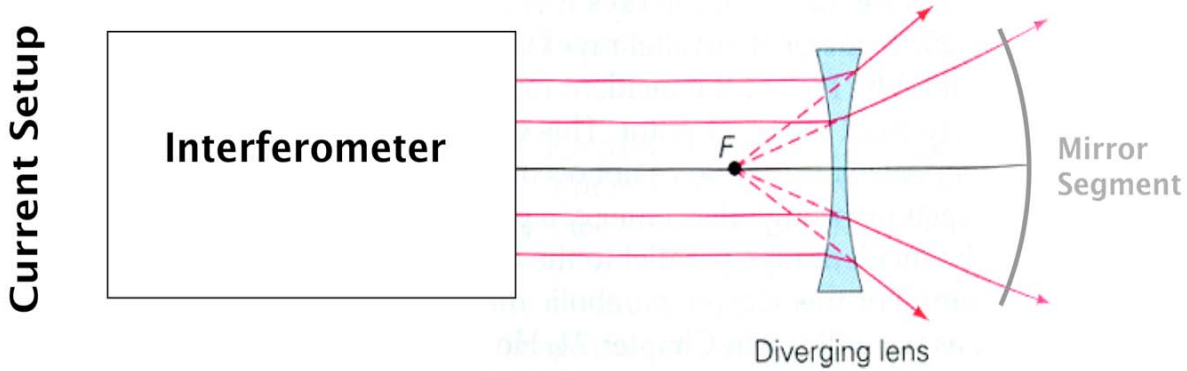


- Use 2 strings, 4 strings or 8 strings
- All forces are deterministic and can be analyzed accurately
- In the worst case scenario, gravity distorts a perfect mirror by 0.4" HPD (one reflection)
- Being actively developed

Measurement System Improvement



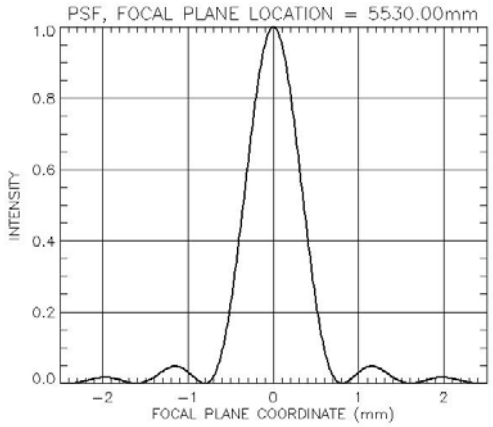
Enabling the measurement of mandrel and mirror on the same wave front

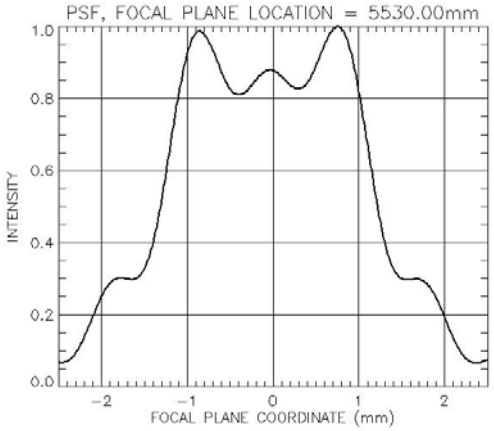


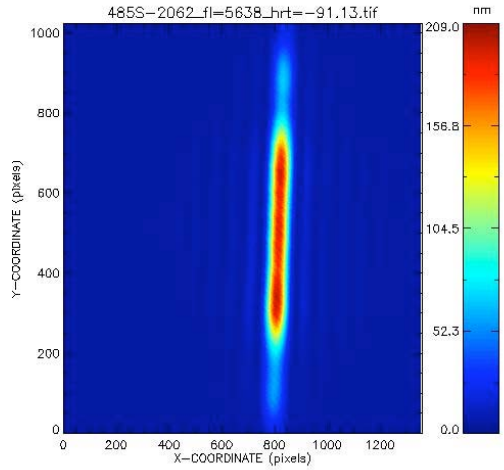
Grazing Incidence Metrology: Hartmann Test

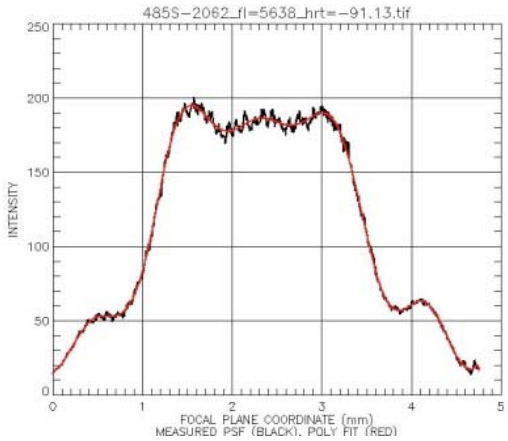
- Measurement of focal length
- Breaking degeneracy of normal incidence metrology where alignment errors and mirror figure errors coincide
- Perform definitive sag and low order figure measurement without using other optics, serving as an absolute check on normal incidence measurement

Measurement of Deviation from Theoretically Expected Profile



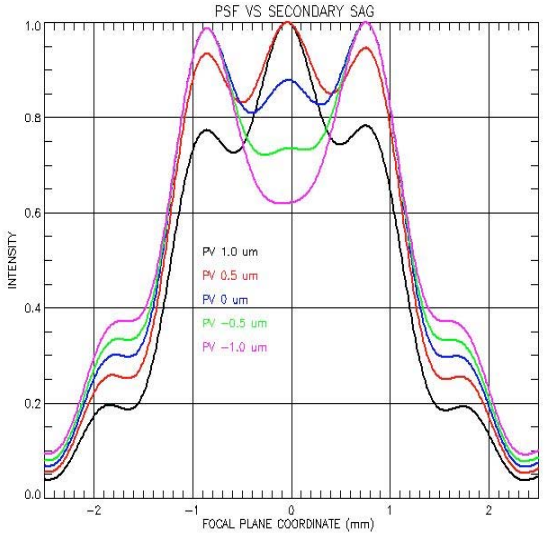


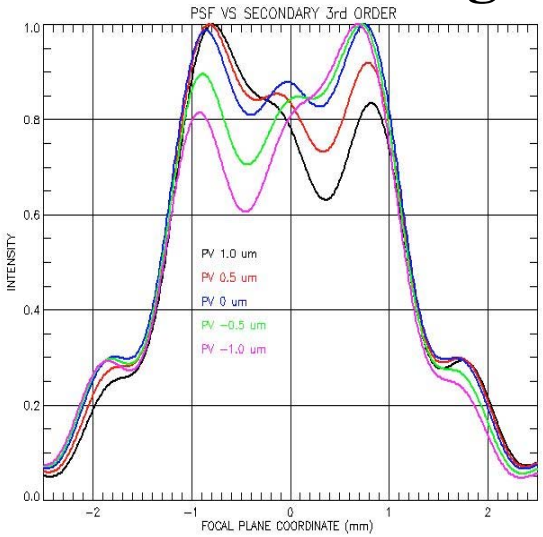




Characteristics of Different Orders of Axial Figure Errors

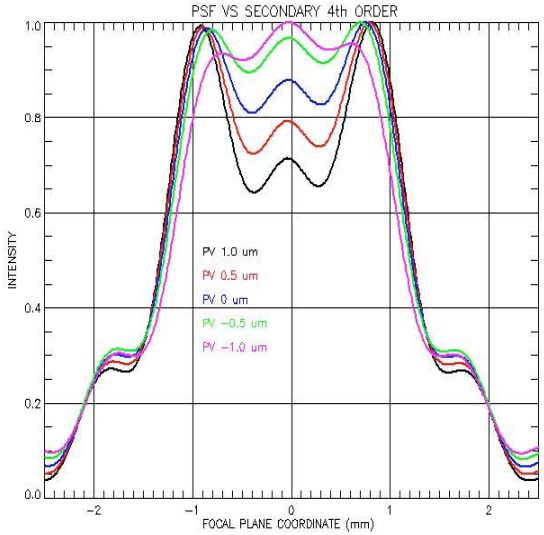
2nd Order Error

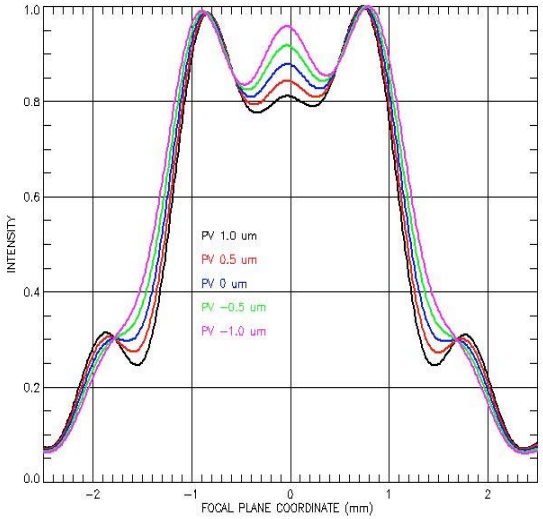




3rd Order Error

4th Order Error





6th Order Error

Complementarity between Grazing and Normal Incidence Metrology

	Normal Incidence	Grazing Incidence
Average Radius	Using a radius gauge	Measuring focal length
Radius Variation	Measuring third orders and up	Not terribly sensitive
Average Cone Angle	Difficult to do because of correlation between pitch and it	Measuring focal length
Cone Angle Variation	Good measurement	Good measurement
Average Sag	Measurement susceptible to systematic error related to other optics	Accurate but may not be precise measurement
Sag Variation	Good measurement	Not terrible sensitive
Axial Figure (Low Frequency)	Good measurement subject to errors of other optics	Accurate but may not be precise enough
Axial Figure (Mid Frequency)	Good measurement, but subject to interferometer noise	No sensitivity

Forming Mandrel Requirement in Context

		Other X-Ray Missions		
Mirror Attributes	IXO	Chandra	XMM	NuSTAR
No. of mirror assemblies	1	1	3	2
Number of Mirror Elements	13896 segments	8 shells	58 shells per assembly	2340 segments per assembly
Manufacture Technology	Glass Slumping	Grinding and Polishing	Nickel electroforming	Glass Slumping
Polished Area (m^2)	60 (721 mandrels)	20	50 (58 mandrels)	18 (75 mandrels)
Total Mirror Area (m^2)	801	20	150	91
Ratio of Total Mirror Area-to-Polished Mirror Area	13.35	1.0	3.00	5.06

Outlook

- Mirror fabrication milestones
  - Consistent at ~5” HPD (two reflections) by end of 2010 once new mandrels are used
  - Consistently meeting requirements (~3” HPD two reflections) by end of 2011 after identifying and removing or reducing “the 4 arcsec error”
- Improvement of metrology to identify and isolate sources of error
  - Metrology mount
  - Upgrade null lens
  - Check for systematic effects
  - Use both normal and grazing incidence measurement

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