Development of X-ray Optics at MSFC

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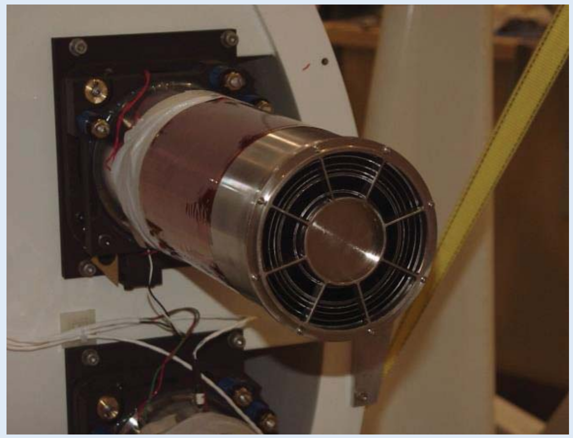
High Energy Replicated Optics to Explore The Sun (HEROES)



HEROES module

Balloon launch

Mirror shells per module	14 (6 mod), 13 (2 mod)
Inner, outer shell diameters	50, 94 mm
Total shell length	610 mm
Focal length	6 m
Coating	Sputtered iridium, ~ 20 nm thick
Number of mirror modules	8
Effective area	~ 85 cm^2 at 40 keV, ~ 40 cm^2 at 60 keV

HEROES,, is a collaborative effort between MSFC & GSFC to modify an existing MSFC-developed balloon-borne hard X-Ray telescope (20-75 keV) to observe the Sun. HEROES will be designed to make both daytime solar and nighttime astrophysical observations with the same balloon flight, and will continue to demonstrate the quality of MSFC-developed optics

Astronomical Roentgen Telescope ART

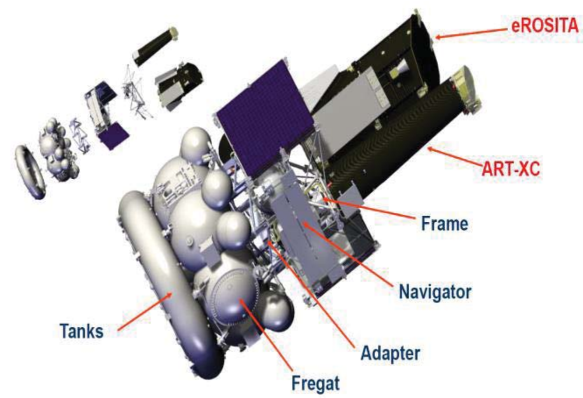
ART-XC is a medium energy x-ray telescope that will fly aboard the Russian Spectrum-Rontgen-Gamma Mission.

ART-XC will fly in 2016 and during its 7-year mission will conduct a 4-year survey of the sky, with an additional 3 years for follow-on studies MSFC will provide x-ray optics modules for the ART-XC instrument.

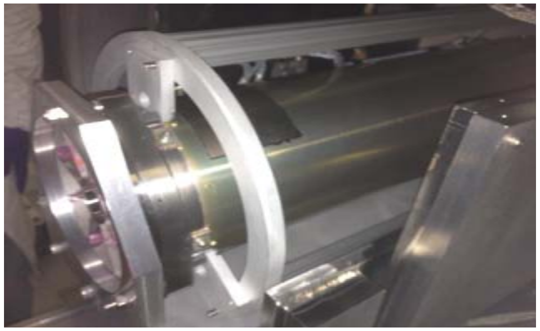
MSFC has developed eight ART x-ray optics modules

ART flight module specifications

Parameter	Value
Number of Shells per Module	28
Shell Coating	> 10 nm of iridium (> 90% bulk density)
Shell Total Length, inner and outer diameters	580 mm, 50 mm, 150 mm
Encircled Half Energy Width	Less than 1 mm diameter, center of field of view Less than 2.5 mm diameter, 15 arcmin off axis
Mirror Module Effective Area	≥ 65 cm^2 at 8 keV (on axis)
Module Focal Length	2700±1 mm
Allowable Total Mass per Module	17 kg including thermal control system
Minimal resonance frequency	40 Hz
Operating Temperature Range	17° C to 23° C



Schematic representation of the SRG payload



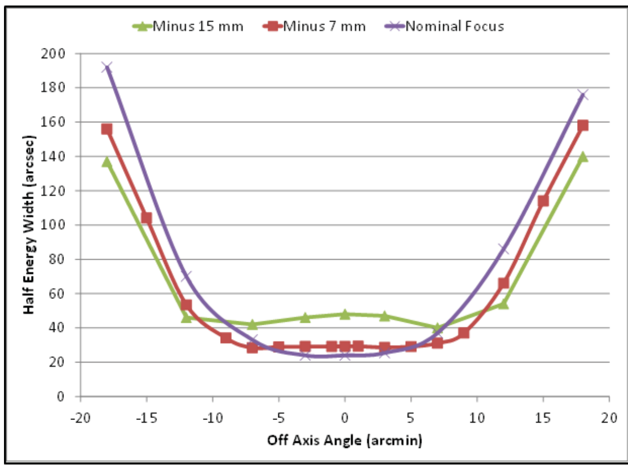
ART module

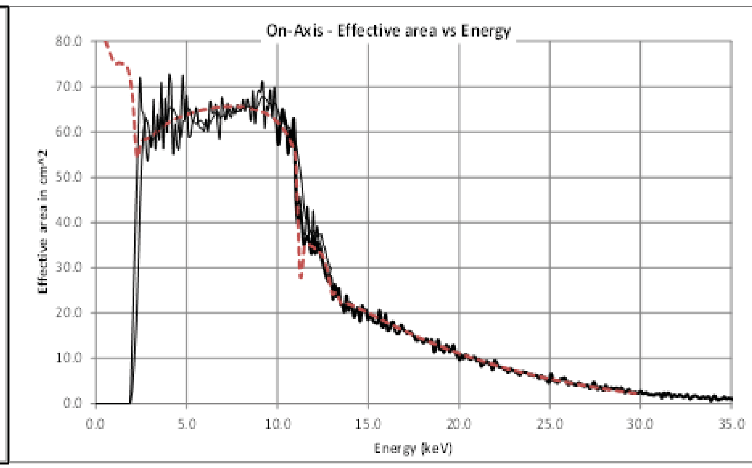
Astronomical Roentgen Telescope ART

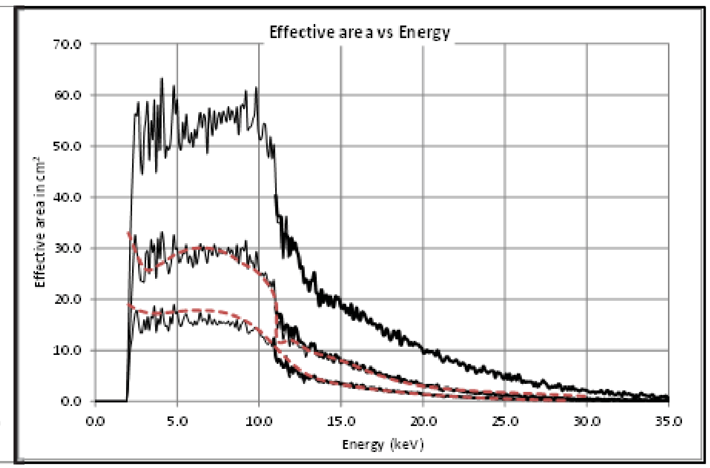
Module – Spider	On Axis (arcsec)	On Axis (mm)$^{+}$	15 arcsmin* (arcsec)	15 arcmin* (mm)$^{+}$
1-4	30	0.4	113	1.5
2-5	32	0.4	115	1.5
6-8	43	0.6	153	2.1
7-7	34	0.5	111	1.5

Module – Spider	On Axis (arcsec)	On Axis (mm)$^{+}$	15 arcsmin* (arcsec)	15 arcmin* (mm)$^{+}$
3-2	33	0.43	110	1.44
4-3	34	0.44	112	1.46
8-9	35	0.46	114	1.49

*average of +/- 15 arcmin and four azimuths (0, 45, 90, 135)
$^{+}$ mm equivalent at 2.765 m
HPD referred to full CCD area (27 mm x 27 mm). Includes single reflections.







Resolution vs off-axis angle for different focal positions

Left: effective area vs energy on axis. Model fit shown as dashed line. Right: effective area at 9 and 18 arcmin off axis. Model fit (dashed line) shown for 9 and 18 arcmin.

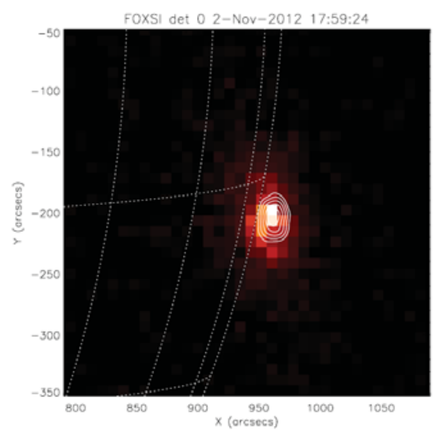
FOXSI

FOXSI is a sounding rocket based payload led by the University of California, Berkeley and consisting of x-ray optics provided by MSFC and focal plane detectors provided by Japan. The goal is to measure weak coronal output against bright footprints, with good angular resolution.

Launch date for FOXSI-2 is December 2014.

- Focal Length: 2 m
- Number of modules: 7
- Number of shells: 7 (10-FOXSI2)
- Shell length: 600 mm.
- Energy range: 4 – 15 keV
- Measured angular resolution 7-8 arcsec FWHM
- Module effective area: 25 cm^2 at 10 keV

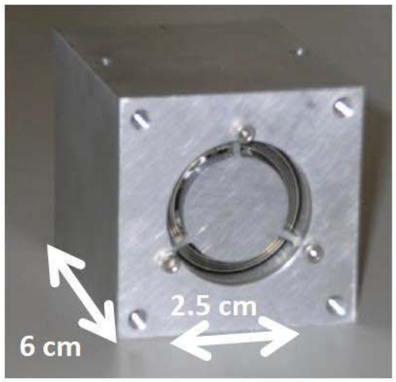
Replicated optics telescope modules (7 shells & 7 mod



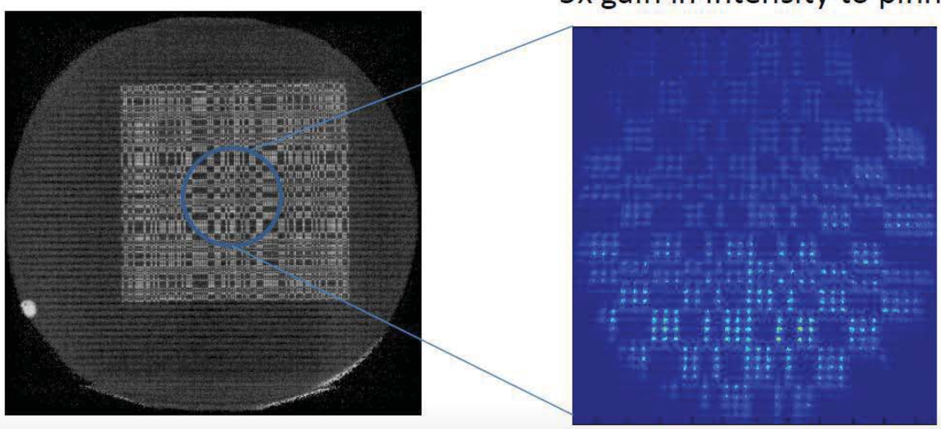
Solar flare image taken by the FOXSI instrument during November 2012 flight

FOXSI rocket during assembly

Demonstration with small prototype microscope



- Built for small mammal x-ray imaging
- Lens composed of ellipsoid and hyperboloid sections
- 3 nested Ni mirrors (nesting increases flux collection)
- Observed Performance:
  - 75 μm spatial resolution
  - 1 cm FOV & 4x magnification
  - 5 mm depth of focus
  - 5x gain in intensity to pinhole

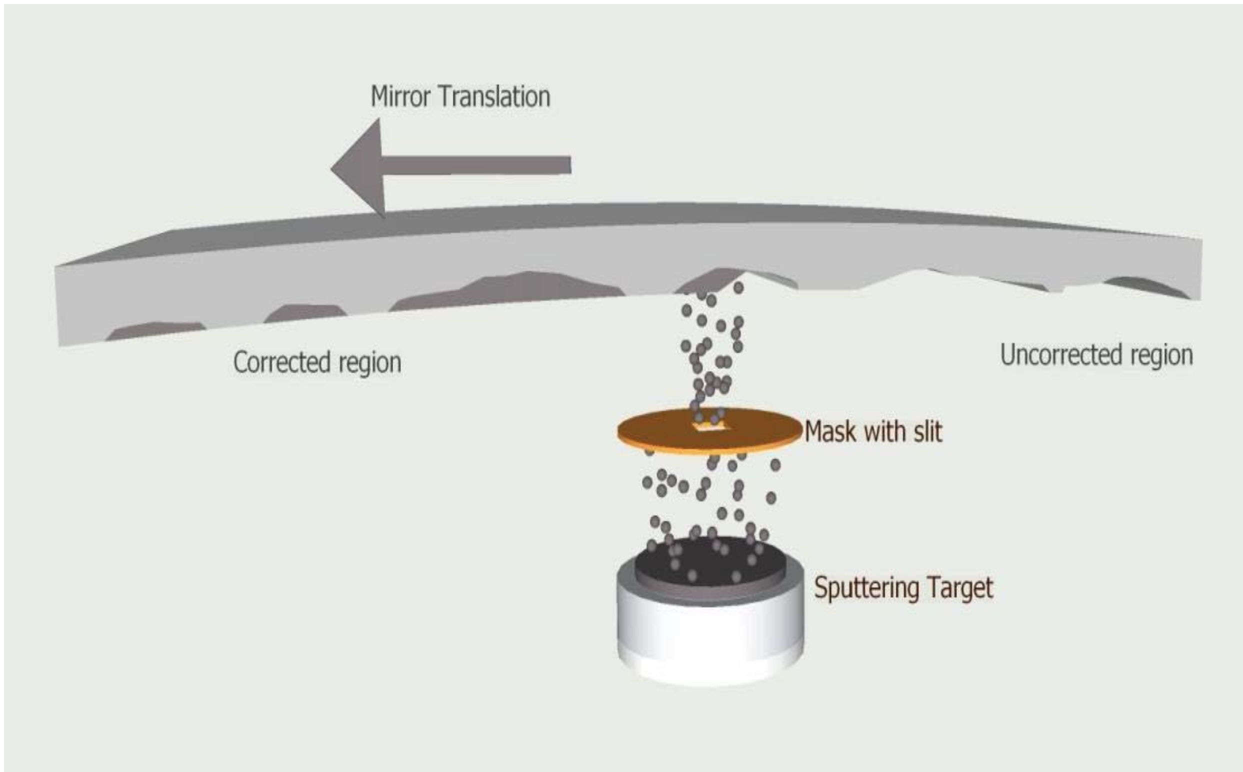


- 2cm x 2cm Pinhole mask, with 0.1 mm diameters on 0.2 mm centers
- Left: Contact Image; Right: Lens Image

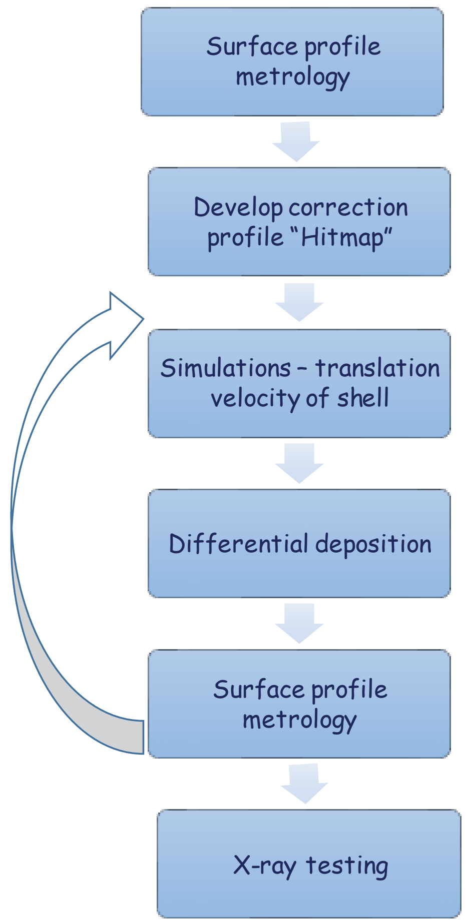
Differential Deposition

- ***<u>What</u>***
  - Differential deposition is a technique for correcting figure errors in optics
- ***<u>How</u>***
  - Use physical vapor deposition to selectively deposit material on the mirror surface to smooth out figure imperfections
- ***<u>Why</u>***
  - Can be used on ***any type*** of optic, full-shell or segmented, mounted or unmounted
  - Can be used to correct a wide range of spatial errors. Could be used in conjunction with other techniques… e.g. active optics.
  - Technique has been used by various groups working on synchrotron optics to achieve sub-μradian-level slope errors

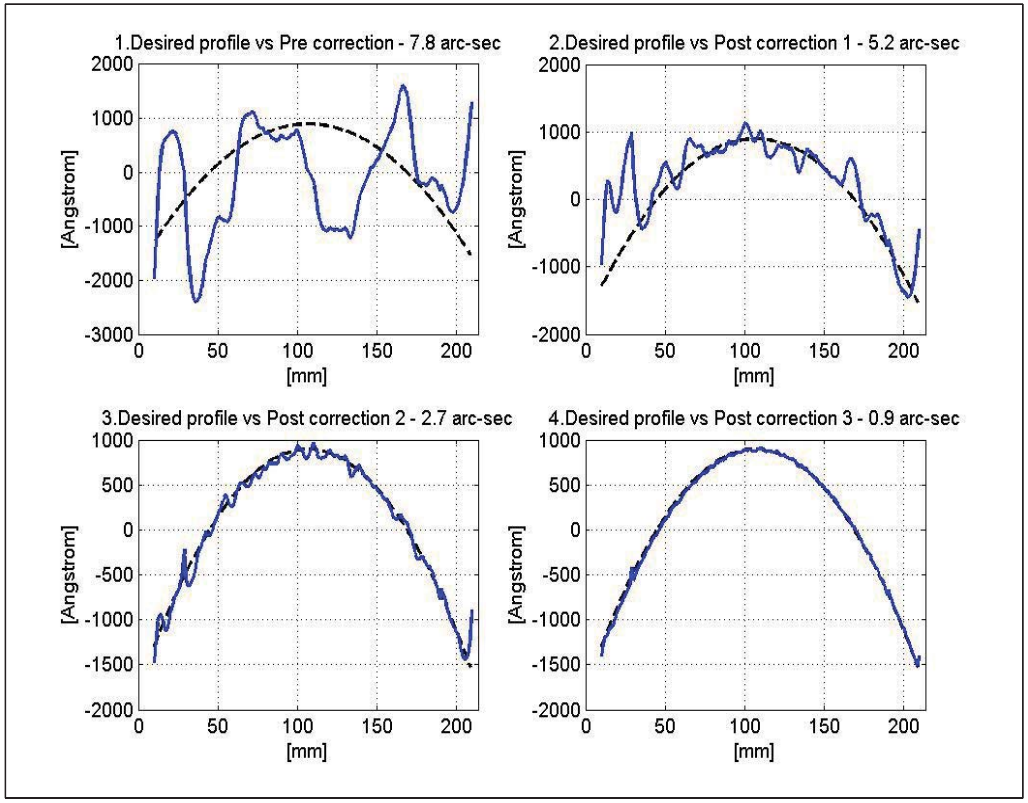
Coating Configuration



Process Sequence - Differential Deposition



Process Sequence – Differential Deposition

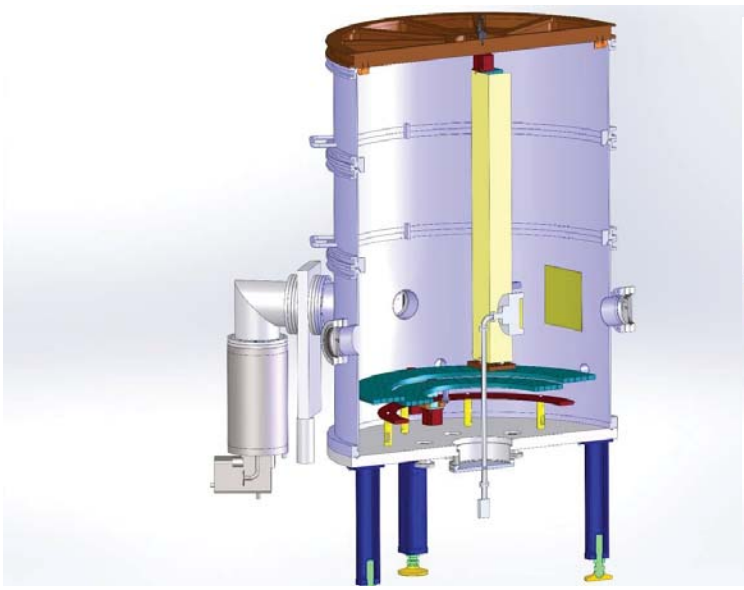


Simulated correction sequence showing parabolic axial figure profile before (top left) and after 3 stages of correction using a beam of FWHM = 14mm, 5.2 mm and 1.7 mm respectively. The dotted line gives the desired figure and the solid line gives the figure obtained at each stage. Overall, resolution improved from 7.8 arcsec to 0.9 arcsec HEW (2 bounce equivalent).

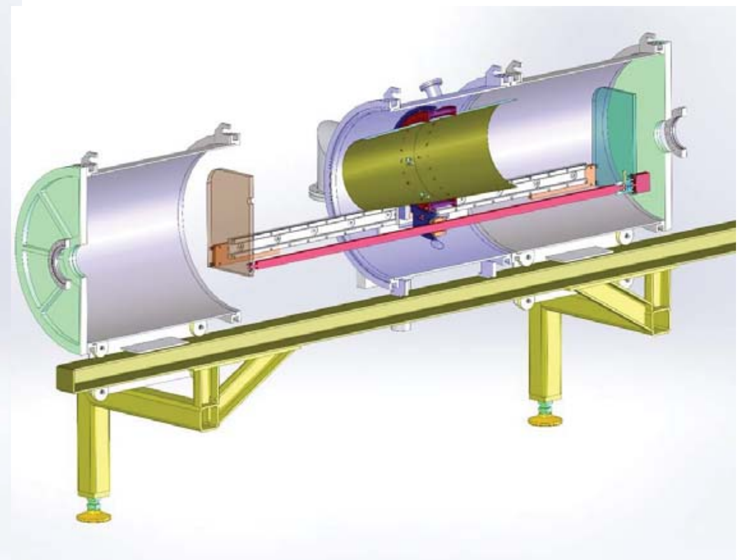
Possible Practical Limitations We Are Addressing

- *Variation of sputtered beam profile along the length of mirror – particularly for short focal length mirrors – Model and correct*
- *Deviation in the simulated sputtered beam profile from actual profile, beam non-uniformities, etc. – Quantify and correct*
- *Positional inaccuracy of the slit with respect to mirror – Model effects to derive requirements*
- *Metrology uncertainty – Upgrade metrology system*
- *Stress effects – Quantify and control stress*

Coating Systems (DC magnetron)



Vertical chamber for segmented optics



Horizontal chamber for 0.25-m-scale full shell optics

Coating Systems

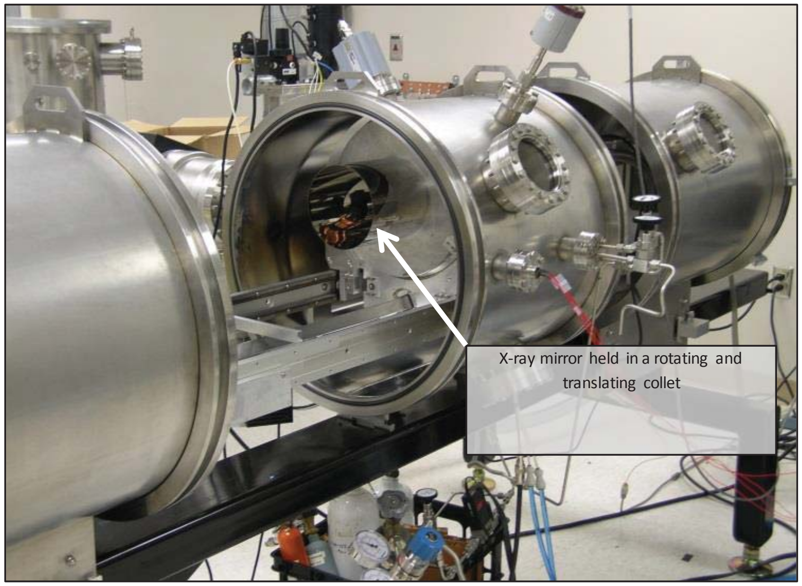


Figure 2: Horizontal differential-deposition chamber

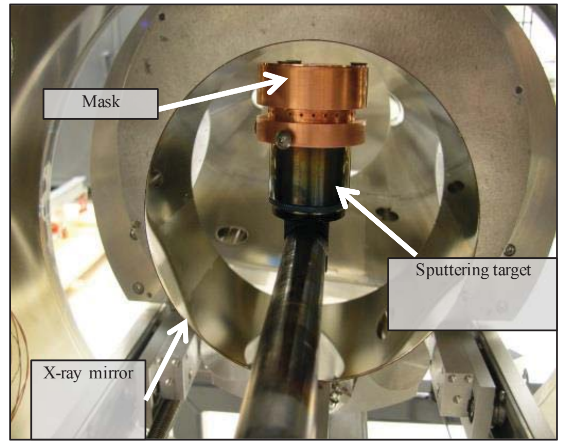
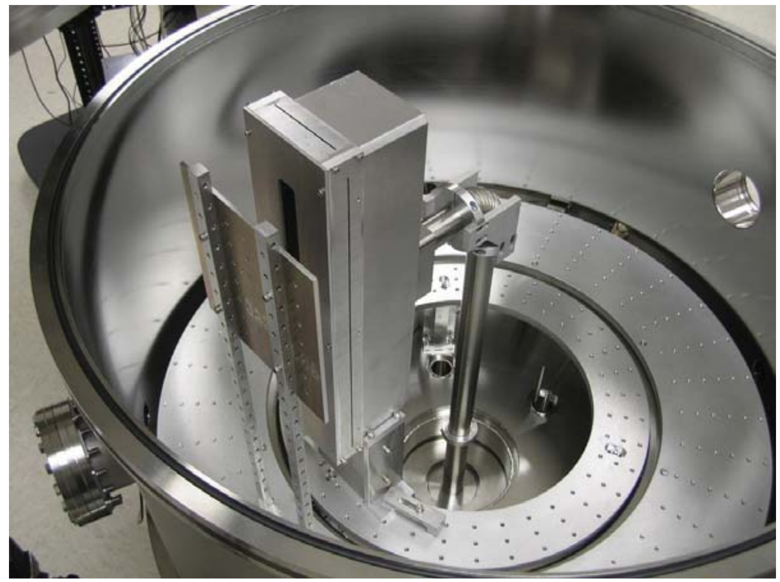


Figure 3: Sputtering head with copper mask positioned inside shell

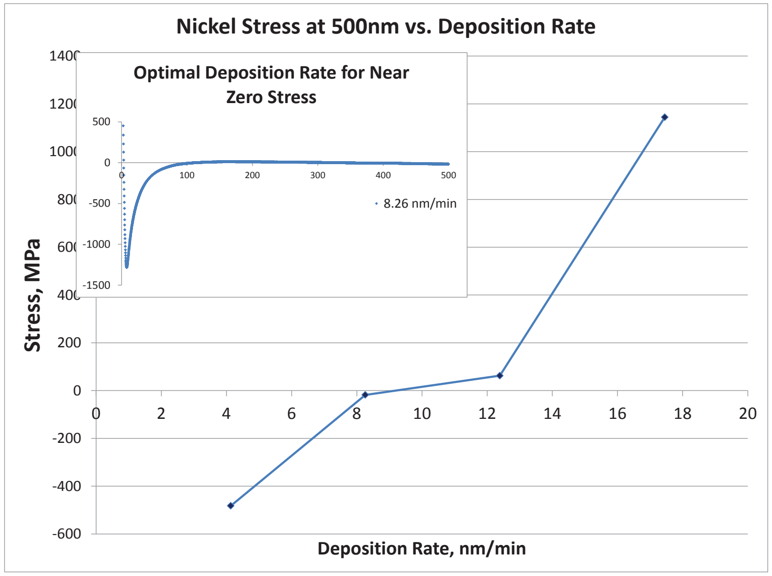
Coating Systems



Vertical deposition chamber

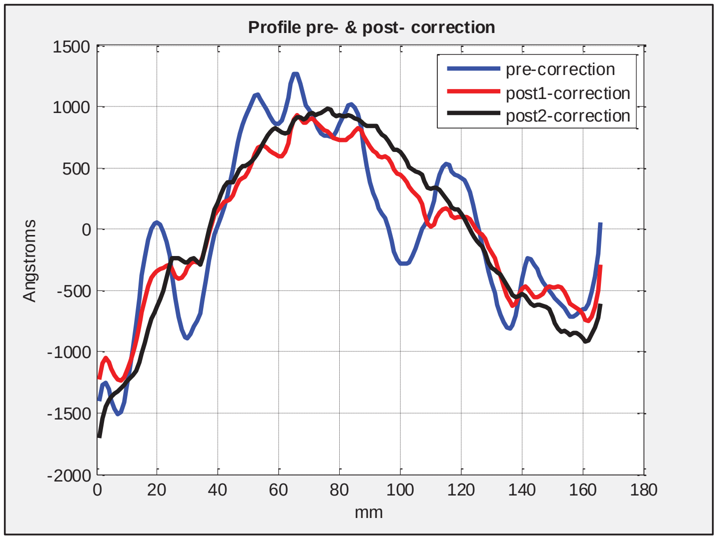
Coating Stress Measurement System

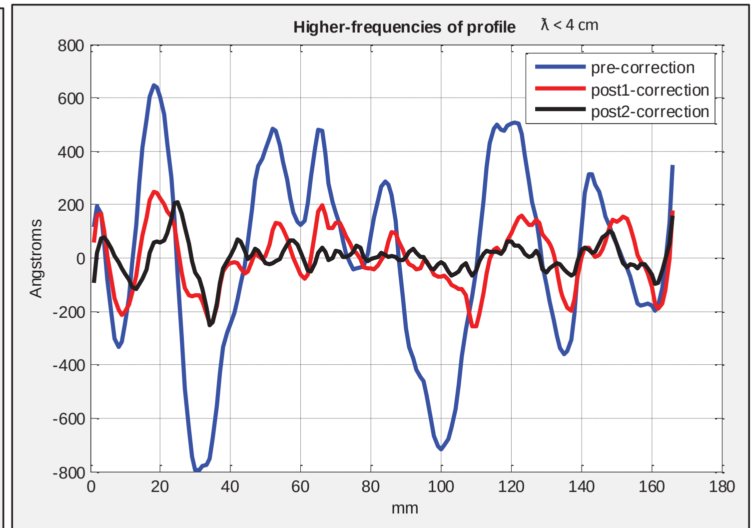
Simulations show that for full shell optic need < 10MPa stress to get < 1 arcsec optic (dominated by longer-wavelength corrections). Set up dedicated system to characterize coating stresses.

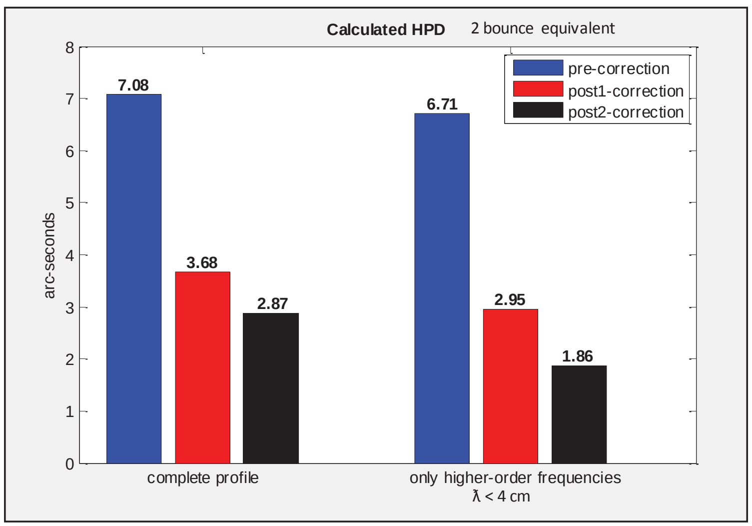


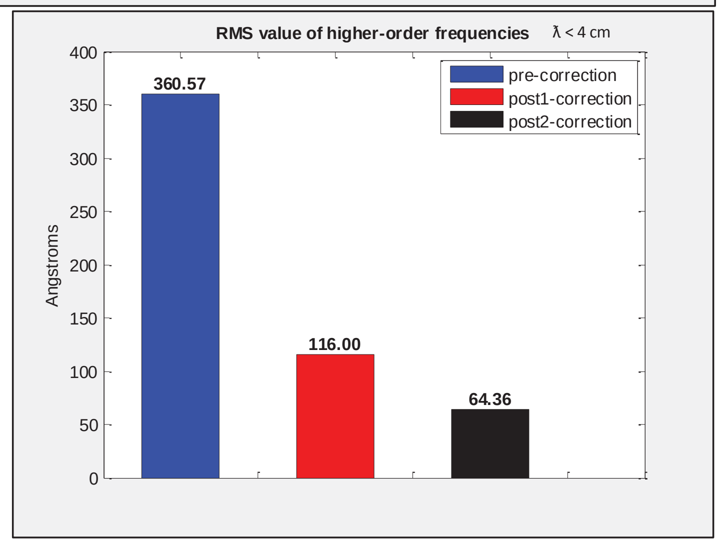
Preliminary measurements showing coating stress versus deposition rate at fixed gas pressure. Inset shows stress versus coating thickness (nm) at fixed deposition rate

Test coating run # 1: horizontal chamber, 150 mm diameter shell
P-end, pre- and post- two stages of correction

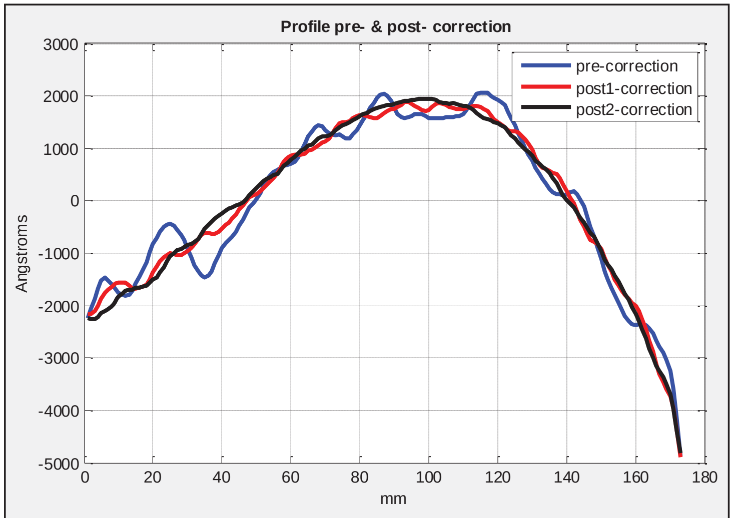


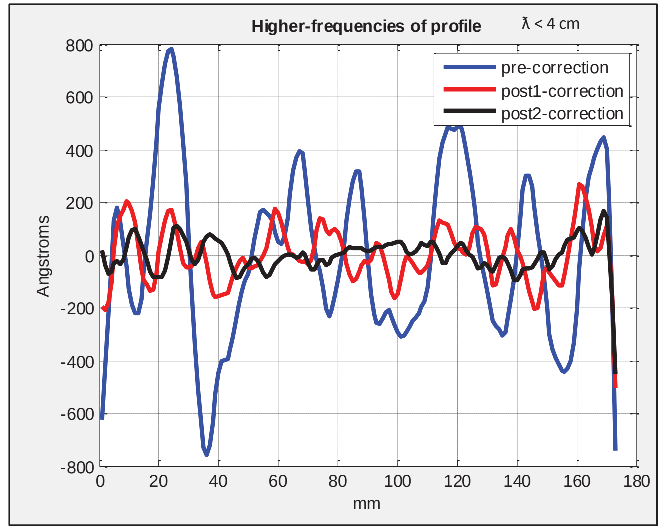


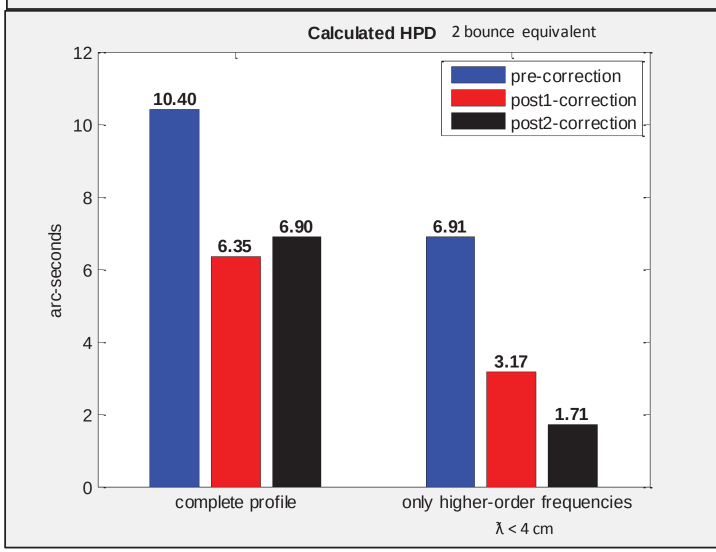


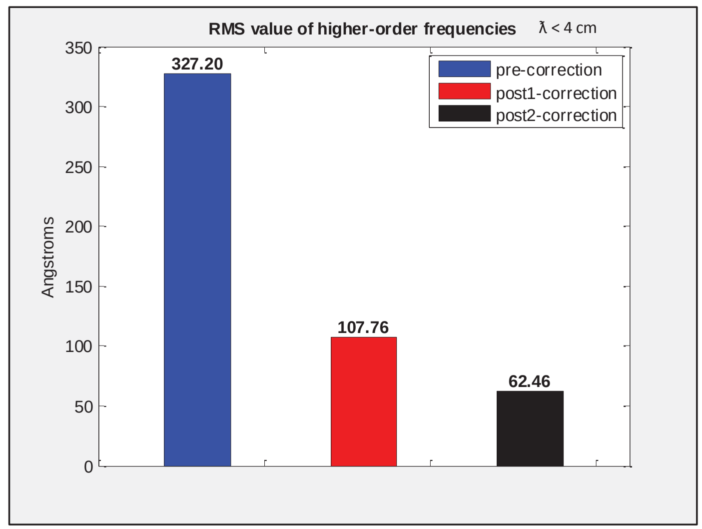


Test coating run # 2: horizontal chamber, 150 mm diameter shell
P-end, pre- and post- 2 stages of correction









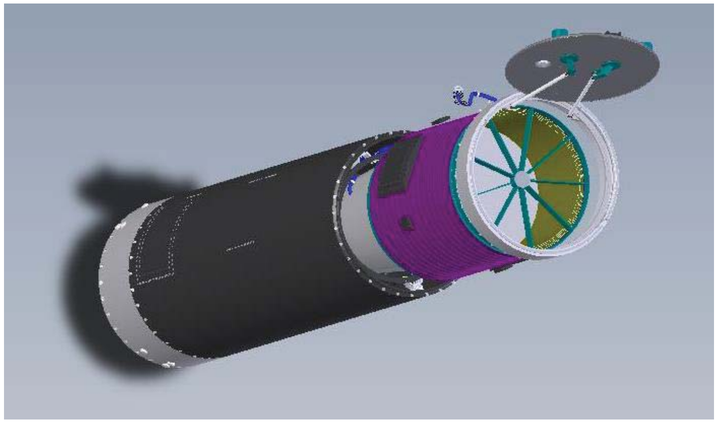
Micro-X

Description:

Micro-X is a sounding rocket based payload consisting of x-ray optics (to be provided by MSFC) and a calorimeter detector led by MIT.

Micro-X will fly with MSFC optics in 2015 and make high-spectral-resolution images of supernova remnants Puppis A and Cas A.

Fabrication of the 0.5-m-diameter Micro-X optics has begun.

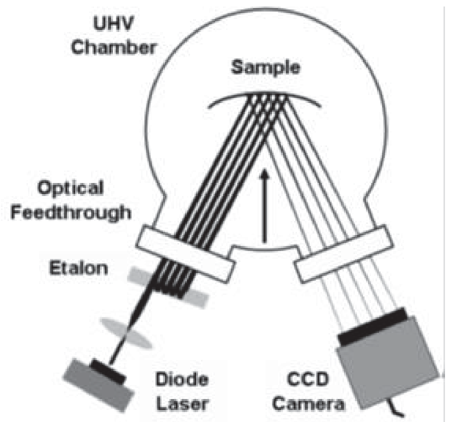


Schematic of the Micro-X telescope

Micro-X mandrel

Methods of optical in-situ film stress measurement:

Multi-beam stress sensor:



<u>Minimum detectable film stress, $\Delta(\sigma h_f)$:</u>

Multi-beam: 0.050 N/m

Micro-cantilever: 0.005-2.5 N/m (depending on technique)

Spherometry (our method): 0.028 N/m for 280 μm thick substrate.

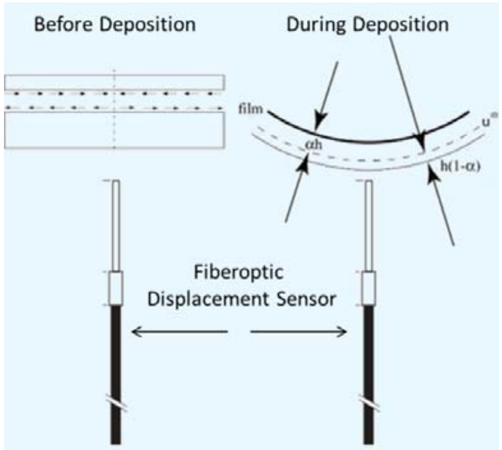
Sensitivity can be enhanced with thinner substrates , h, since:

$$\boxed{\sigma h_f = \left(\frac{h}{h_0}\right)^2 (\sigma h_f)_0}$$

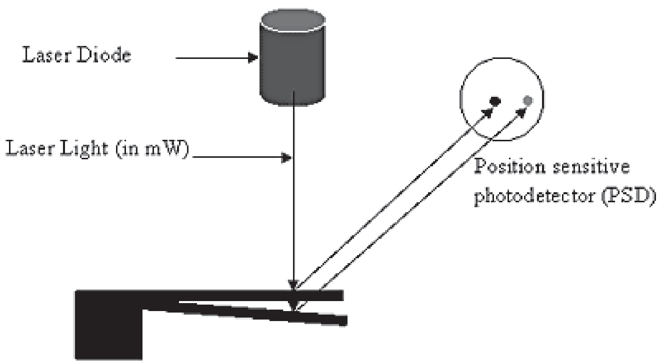
⇒ 0.007 N/m for 50μm thick substrate which is readily commercially available.

Further sensitivity with higher resolution sensor may be possible: 0.0006 N/m

Spherometry (our method):



Micro cantilever:



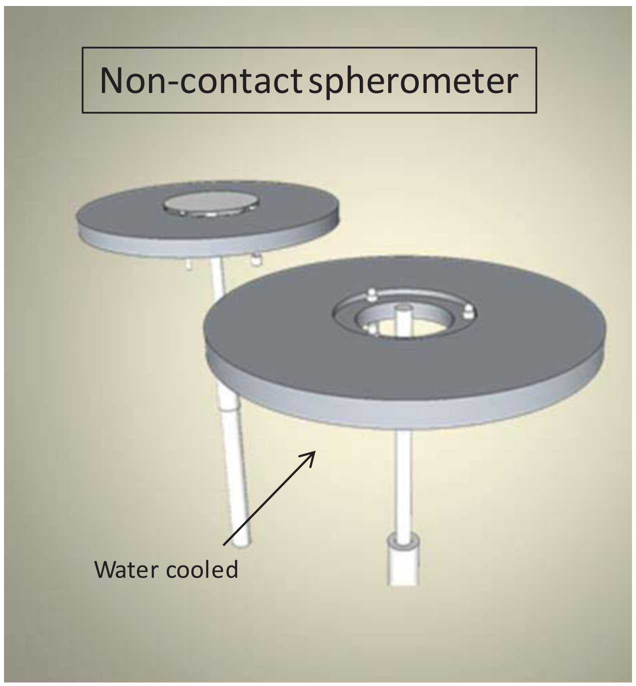
In-Situ Methodology:

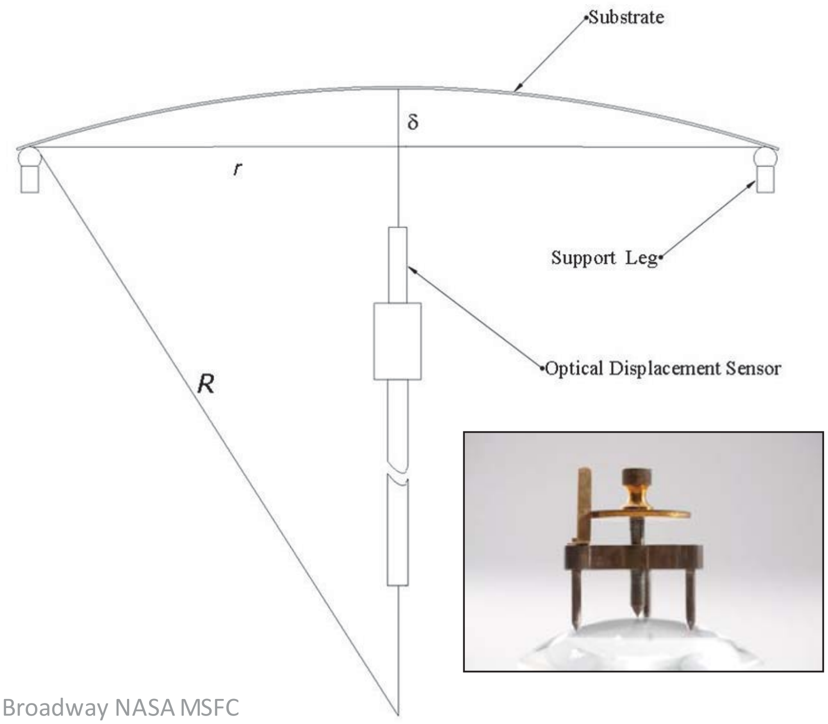
Patent Pending

Since substrate deformation is spherical we need only measure the sagittal, δ, to infer its curvature from which the Stoney equation can be employed:

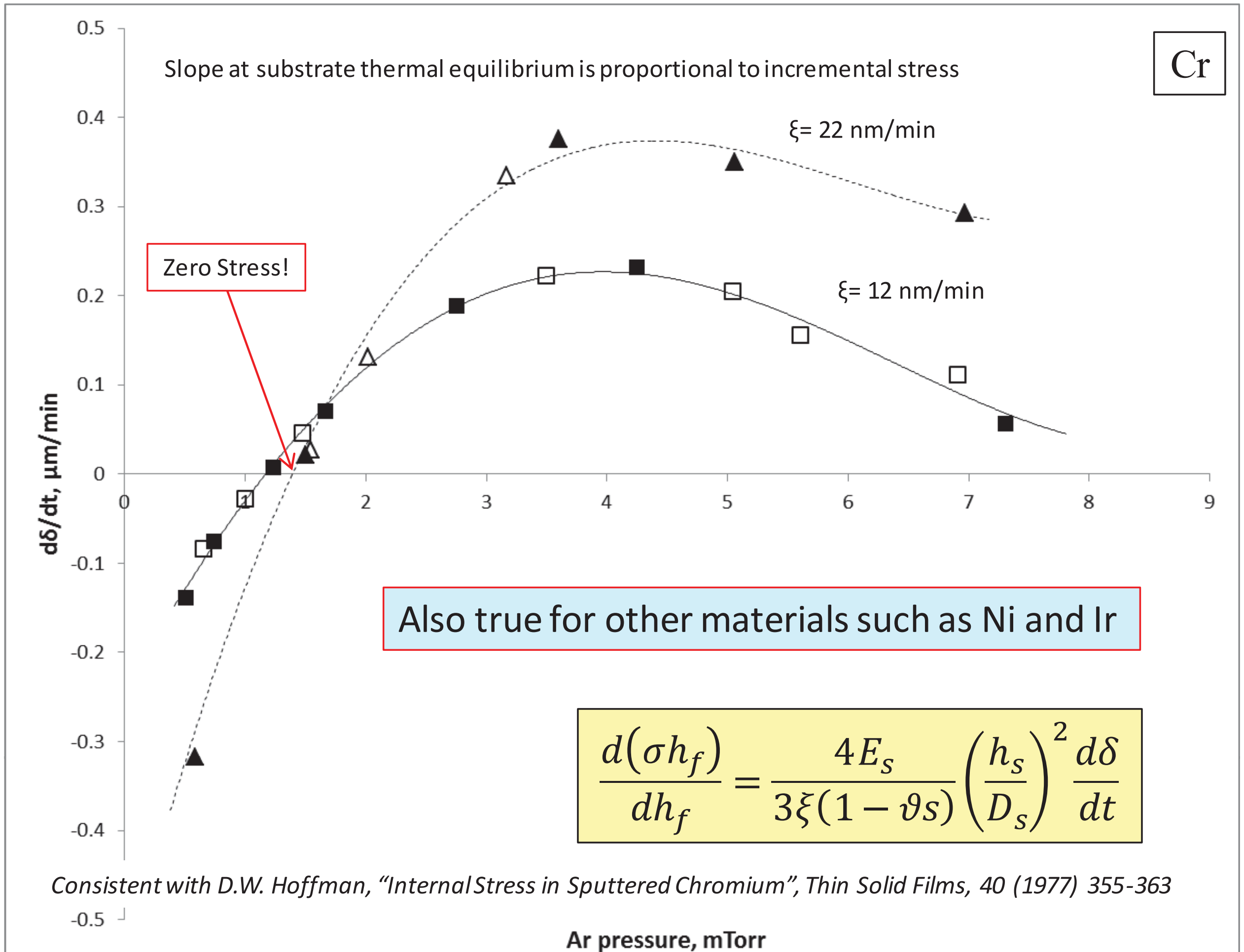
$$\sigma h_f = \frac{E_s h_s^2}{6(1-\vartheta s)}\kappa \quad ,where \quad \kappa = \frac{2\delta}{r^2+\delta^2} \xRightarrow{r \approx \frac{D_s}{2} \gg \delta} \boxed{\sigma h_f = \frac{4}{3}\frac{E_s}{(1-\vartheta s)}\left(\frac{h_s}{D_s}\right)^2 \delta}$$

The curvature measurement is performed during deposition by measuring the backside of a double side polished substrate with a non-contact variation of the classic spherometer using a fiber optic displacement sensor.





Stress reversal in Cr:



Also true for other materials such as Ni and Ir

$$\frac{d(\sigma h_f)}{dh_f} = \frac{4E_s}{3\xi(1-\vartheta s)}\left(\frac{h_s}{D_s}\right)^2 \frac{d\delta}{dt}$$

Consistent with D.W. Hoffman, "Internal Stress in Sputtered Chromium", Thin Solid Films, 40 (1977) 355-363

Full-Shell Direct Fabrication

PLAN

- Demonstrate capability with 'thick' (~ 6 mm) shell first
  - Gain experience with ZEEKO machine (in process)
  - Grind glass shell ready for ZEEKO machine 👍
  - Fabricate fixturing for polishing shell 👍
  - Fabricate fixturing for metrology of shell 👍
- Move to thin shells (2-3 mm)
  - Develop polishing fixtures (in process)
  - Develop metrology fixtures (in process)