Development of X-ray Optics at MSFC

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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.

**HEROES module**

<table>
<thead>
<tr>
<th>Mirror shells per module</th>
<th>14 (6 mod), 13 (2 mod)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner, outer shell diameters</td>
<td>50, 94 mm</td>
</tr>
<tr>
<td>Total shell length</td>
<td>610 mm</td>
</tr>
<tr>
<td>Focal length</td>
<td>6 m</td>
</tr>
<tr>
<td>Coating</td>
<td>Sputtered iridium, ~20 nm thick</td>
</tr>
<tr>
<td>Number of mirror modules</td>
<td>8</td>
</tr>
<tr>
<td>Effective area</td>
<td>~85 cm² at 40 keV, ~40 cm² at 60 keV</td>
</tr>
</tbody>
</table>
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.
Resolution vs off-axis angle for different focal positions

Astronomical Roentgen Telescope ART

<table>
<thead>
<tr>
<th>Module – Spider</th>
<th>On Axis (arcsec)</th>
<th>On Axis (mm)*</th>
<th>15 arcsmin* (arcsec)</th>
<th>15 arcsmin* (mm)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-4</td>
<td>30</td>
<td>0.4</td>
<td>113</td>
<td>1.5</td>
</tr>
<tr>
<td>2-5</td>
<td>32</td>
<td>0.4</td>
<td>115</td>
<td>1.5</td>
</tr>
<tr>
<td>6-8</td>
<td>43</td>
<td>0.6</td>
<td>153</td>
<td>2.1</td>
</tr>
<tr>
<td>7-7</td>
<td>34</td>
<td>0.5</td>
<td>111</td>
<td>1.5</td>
</tr>
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</tr>
</thead>
<tbody>
<tr>
<td>3-2</td>
<td>33</td>
<td>0.43</td>
<td>110</td>
<td>1.44</td>
</tr>
<tr>
<td>4-3</td>
<td>34</td>
<td>0.44</td>
<td>112</td>
<td>1.46</td>
</tr>
<tr>
<td>8-9</td>
<td>35</td>
<td>0.46</td>
<td>114</td>
<td>1.49</td>
</tr>
</tbody>
</table>

*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.

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 cm² at 10 keV
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

• **What**
  • Differential deposition is a technique for correcting figure errors in optics

• **How**
  • Use physical vapor deposition to selectively deposit material on the mirror surface to smooth out figure imperfections

• **Why**
  • 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

1. Surface profile metrology
2. Develop correction profile “Hitmap”
3. Simulations - translation velocity of shell
4. Differential deposition
5. Surface profile metrology
6. X-ray testing
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

Profile pre- & post- correction

Higher-frequencies of profile \( \lambda < 4 \text{ cm} \)

Calculated HPD 2 bounce equivalent

RMS value of higher-order frequencies \( \lambda < 4 \text{ cm} \)
Test coating run # 2: horizontal chamber, 150 mm diameter shell
P-end, pre- and post- 2 stages of correction

Profile pre- & post- correction

Higher-frequencies of profile

Calculated HPD

RMS value of higher-order frequencies

$\lambda < 4 \text{ cm}$
**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.
Methods of optical in-situ film stress measurement:

Multi-beam stress sensor:

- Minimum detectable film stress, \( \Delta(\sigma_{hf}) \):
  - 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 \( \mu \)m thick substrate.

Sensitivity can be enhanced with thinner substrates, \( h \), since:

\[
\sigma_{hf} = (\frac{h}{h_0})^2 (\sigma_{hf})_0
\]

\( \Rightarrow \) 0.007 N/m for 50\( \mu \)m thick substrate which is readily commercially available.

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

Spherometry (our method):
In-Situ Methodology:

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

$$\sigma h_f = \frac{E_S h_S^2}{6(1 - \vartheta s)} \kappa \text{, where } \kappa = \frac{2\delta}{r^2 + \delta^2}$$

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.

\[
\sigma h_f = \frac{4}{3} \frac{E_S}{(1 - \vartheta s)} \left(\frac{h_S}{D_s}\right)^2 \delta
\]
Stress reversal in Cr:

\[ \xi = 22 \text{ nm/min} \]

\[ \xi = 12 \text{ nm/min} \]


Slope at substrate thermal equilibrium is proportional to incremental stress

Also true for other materials such as Ni and Ir

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

Also true for other materials such as Ni and Ir

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)