Development and Calibration of the ART-XC Mirror Modules for the Spectrum Rontgen Gamma Mission

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The Spectrum-Röntgen-Gamma (SRG) mission is a Russian-lead X-ray astrophysical observatory that carries two co-aligned X-ray telescope systems.

The primary instrument is the German-led extended ROentgen Survey with an Imaging Telescope Array (eROSITA), a 7-module X-ray telescope system that covers the energy range from 0.2-12 keV.

The complementary instrument is the Astronomical Roentgen Telescope – X-ray Concentrator (ART-XC or ART), a 7-module X-ray telescope system that provides higher energy coverage, up to 30 keV.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ART</th>
<th>eROSITA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Range</td>
<td>5-30 keV</td>
<td>0.2-12 keV</td>
</tr>
<tr>
<td>Effective Area</td>
<td>455 cm² at 8 keV</td>
<td>2500 cm² at 1 keV</td>
</tr>
<tr>
<td>Field of View</td>
<td>32 arcmin</td>
<td>1 deg</td>
</tr>
<tr>
<td>System Angular Resolution (on axis)</td>
<td>1 arcmin</td>
<td>15 arcsec</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>1.4 keV at 14 keV</td>
<td>130 eV at 6 keV</td>
</tr>
</tbody>
</table>
ART-XC  Optics Configuration

MSFC has designed and is fabricating

- **four** ART x-ray optics modules under an International Reimbursable Agreement between NASA and with IKI (delivery – February 2014)
- **three + one spare** ART modules under Agreement regarding Cooperation on the ART-XC Instrument onboard the SRG Mission between NASA and IKI (delivery – March 2014)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Mirror Modules</td>
<td>7=4+3</td>
</tr>
<tr>
<td>Number of Shells per Module</td>
<td>28</td>
</tr>
<tr>
<td>Shell Coating</td>
<td>&gt; 10 nm of iridium (&gt; 90% bulk density)</td>
</tr>
<tr>
<td>Shell Total Length, inner and outer diameters</td>
<td>580 mm, 50 mm, 150 mm</td>
</tr>
<tr>
<td>Encircled Half Energy Width</td>
<td>Less than 1 mm diameter, center of field of view</td>
</tr>
<tr>
<td></td>
<td>Less than 2.5 mm diameter, 15 arcmin off axis</td>
</tr>
<tr>
<td>Mirror Module Effective Area</td>
<td>≥ 65 cm² at 8 keV (on axis)</td>
</tr>
<tr>
<td>Module Focal Length</td>
<td>2700±1 mm</td>
</tr>
</tbody>
</table>

Schematic representation of the ART-XC instrument
Mechanical Design

- One spider design permits increasing the thickness of outer shells for given weight budget (15 kg / Module)

- Shells are electroformed NiCo, 250 – 325 microns thick
ART-XC Mirror Production
ART-XC Mirror Status

- All shells fabricated for 1st four module
- 75% of shells fabricated for 2nd four modules
- Qualification (engineering) unit tested and delivered to IKI
- 1st flight module undergone extended x-ray calibration
- 2nd module under calibration now
ART-XC: MSFC Test Facility

MSFC STRAY LIGHT FACILITY

• ~ 104 m Beamline
• 1-m diameter main tube
• 3m x 10m instrument chamber

• FOR ART testing:
  • Bell housing for smaller, shorter-focal-length optics
  • Contains Tip, Yaw and linear stages all computer controlled
  • Cu x-ray source system, 50kV, 1 mA, 0.5 mm spot
ART-XC: MSFC Test Facility

**CdTe Detector**
- 5 x 5 x 1 mm
- High rate capability (>105 c/s)
- Series of laser-cut W pinholes

**CCD Cameras**
- 2k x 2k pixels
- 13.5 micron each
- Frame / sec readout capability

![CdTe Detector Image]

![CCD Camera Image]

![Graph of 1mm Thick CdTe Detection Efficiency]
Qualification Unit

✓ Three inner shells (1,2,4)

✓ Three outer shells (25,26,27)

✓ Three mass simulators to replace missing shells (diameters are 74, 101.3 and 126.4 mm)
ART-XC: Qualification Unit

Effective area and resolution of qualification unit measured as follows:

- Initial test
- Post vibration test #1
- Post thermal (survival temperatures) test
- Post acoustic test
- Post module modification (stabilizers added)
- Post vibration test #2
- Final (post shock test)
ART-XC: Qualification Unit X-ray Results

<table>
<thead>
<tr>
<th>Test</th>
<th>Effective Area (cm²)</th>
<th>Error (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>13.56</td>
<td>0.35</td>
</tr>
<tr>
<td>Post vibration test # 1</td>
<td>13.26</td>
<td>0.49</td>
</tr>
<tr>
<td>Post thermal test</td>
<td>13.01</td>
<td>0.47</td>
</tr>
<tr>
<td>Post acoustic test</td>
<td>13.81</td>
<td>0.38</td>
</tr>
<tr>
<td>Post module modification</td>
<td>Not tested</td>
<td></td>
</tr>
<tr>
<td>Post vibration test # 2</td>
<td>13.49</td>
<td>0.38</td>
</tr>
<tr>
<td>Final (post shock)</td>
<td>13.71</td>
<td>0.38</td>
</tr>
</tbody>
</table>

**FWHM Summary vs. Stage of Testing for X Scans, arcsec**

<table>
<thead>
<tr>
<th>Stage</th>
<th>Test Stage</th>
<th>95% CI X Min</th>
<th>95% CI X Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Initial</td>
<td>12.23</td>
<td>14.47</td>
</tr>
<tr>
<td>2</td>
<td>Post Vibe 1</td>
<td>12.18</td>
<td>14.85</td>
</tr>
<tr>
<td>3</td>
<td>Post Thermal</td>
<td>11.99</td>
<td>15.02</td>
</tr>
<tr>
<td>4</td>
<td>Post Acoustic</td>
<td>11.08</td>
<td>13.57</td>
</tr>
<tr>
<td>5</td>
<td>Post Mod</td>
<td>11.64</td>
<td>14.82</td>
</tr>
<tr>
<td>6</td>
<td>Post Vibe 2</td>
<td>12.16</td>
<td>14.45</td>
</tr>
<tr>
<td>7</td>
<td>Final (post shock)</td>
<td>12.62</td>
<td>14.88</td>
</tr>
</tbody>
</table>
Flight Unit X-ray Calibration Requirements

CCD Camera

Point Spread Function (PSF) – FIRST MODULE
Measure the PSF at each focus position and off-axis angle listed below:

Nominal Focus
Offset angles (36 measurements)
Range: -18, -12, -7, -3, 0, 3, 7, 12, 18 arcmin at four different azimuthal angles: 0, 45, 90, 135

Nominal – 7 MM
Offset angles (68 measurements)
Range: -18, -15, -12, -9, -7, -5, -3, -1, 0, 1, 3, 5, 7, 9, 12, 15, 18 arcmin at four different azimuthal angles: 0, 45, 90, 135

Nominal – 15 MM
Offset angles (36 measurements)
Range: -18, -12, -7, -3, 0, 3, 7, 12, 18 arcmin at four different azimuthal angles: 0, 45, 90, 135

Point Spread Function (PSF) – REMAINING MODULES
Measure the PSF at each off-axis angle listed below:

Nominal – 7 MM
Offset angles (68 measurements)
Range: -18, -15, -12, -9, -7, -5, -3, -1, 0, 1, 3, 5, 7, 9, 12, 15, 18 arcmin at four different azimuthal angles: 0, 45, 90, 135
Flight Unit X-ray Calibration (CCD)

- **M1 Half Power Diameter vs. Off-Axis Angle for Several Focus Positions**
  - Field of view with HPD < flight pixel size expands with de-focus
  - 7 mm defocus position is preferred for flight for best survey sensitivity

- **M1 vs. M2 Half Power Diameter vs. Off-Axis Angle at Preferred Focus Position**
  - Modules are very similar
  - Repeatability of calibration results confirmed
Flight Unit X-ray Calibration (CCD)

True-to-scale images at 7mm from focus, as a function of off-axis angle in arcmin.
Flight Unit X-ray Calibration (CCD)

Comparison of on-axis and 18 arcmin off-axis raw images
- Off-axis image shows extended wing structure due to singly reflected x-rays
- Vertical line below on-axis image is an artifact of CCD readout smear -- removed in analysis
- X-rays from 8 keV Cu-K lines
- 1 pixel = 2 arcsec
Flight Unit X-ray Calibration (CCD)

FWHM on axis

PSF on axis
Modeled Stray Light

Modeled stray light reaching the detector on orbit, in terms of brightest pixel. Curves represent (double reflected (black) and singles from the P (blue) and H (red) segments. Straight-throughs are depicted in gray.
Flight Unit X-ray Calibration (CdTe)

On axis measurements
Flight Unit X-ray Calibration (CdTe)

Flight Module 2 measured effective area (104m) compared with (91%) model

On-axis effective area (infinite source) = 68 cm² (requirement = 65cm²)
Flight Unit X-ray Calibration (Comparison)

Reasonably good agreement between CCD and CdTe
ART-XC Flight Module Calibration and data processing has begun

CCD and CdTe data agree well

The first two modules meet effective area requirement (65 cm² / module @ 8 keV) and greatly exceed angular resolution requirement (30 arcsec, defocused, vs ~ 60 arcsec)

Calibration will be concluded by late February / early March 2014
Differential Deposition (K.Kilaru, C. Atkins, D. Broadway)
Stress Measurement in Coatings (D. Broadway)

Methods of In-Situ Stress Measurement: All aim to measure the change in curvature of the substrate from which stress is calculated from the Stoney equation:

$$\sigma_{film} = \frac{E t}{6(1-v)h^2}$$

Our Method: We exploit the known spherical deformation and infer the substrate curvature by measuring the sag of the wafer (just one point).

Figure 1: After R. Abermann, Vacuum 41, 1279 (1990) (left); Measured In-Situ (right). Data matches measured curves from several published experiments.