Development of Mirror Modules for the ART-XC Instrument aboard the Spectrum-Roentgen-Gamma Mission

M. Gubarev[1*], B. Ramsey[1], S.L. O'Dell[1], R. Elsner[1], K. Kilaru[1], J. McCracken[1],

M. Pavlinsky[2], A. Tkachenko[2], I. Lapshov[2]

C. Atkins [1, 3] V. Zavlin [1, 4]

[1]NASA Marshall Space Flight Ctr., Huntsville, AL USA
[2]Space Research Institute, Moscow, Russia
[3]University of Alabama in Huntsville, Huntsville, AL USA
[4]Universities Space Research Association, Huntsville, AL USA

ABSTRACT

The Marshall Space Flight Center (MSFC) is developing x-ray mirror modules for the ART-XC instrument on board the Spectrum-Roentgen Gamma Mission. Four of those modules are being fabricated under a Reimbursable Agreement between NASA and the Russian Space Research Institute (IKI.) An additional three flight modules and one spare for the ART-XC Instrument are produced under a Cooperative Agreement between NASA and IKI. The instrument will consist of seven co-aligned x-ray mirror modules with seven corresponding CdTe focal plane detectors. Each module consists of 28 nested thin Ni/Co shells giving an effective area of 65 cm^2 at 8 keV, response out to 30 keV, and an angular resolution of 45 arcsec or better HPD. Delivery of the first four modules is scheduled for November 2013, while the remaining three modules will be delivered to IKI in January 2014. We present a status of the ART x-ray module development at MSFC.

1. SRG Overview

The Spectrum-Röntgen-Gamma (SRG) mission is a Russian-led X-ray astrophysical observatory that carries two co-aligned X-ray telescope systems. SRG's primary mission is to perform the most sensitive X-ray all-sky survey, over a 4 year period, to be followed with pointed observations for an additional 3 years.The primary instrument is the **e**xtended **RO**entgen **S**urvey with an **I**maging **T**elescope **A**rray (eROSITA)[1], a 7-module X-ray telescope system with soft x-ray response. The complementary instrument is the **A**stronomical **R**oentgen **T**elescope – **X**-ray **C**oncentrator (ART-XC or ART)[2], a 7-module X-ray telescope system that provides higher energy coverage. Key performance characteristics of the eROSITA and ART telescope systems are compared in Table 1 and Figure 1.

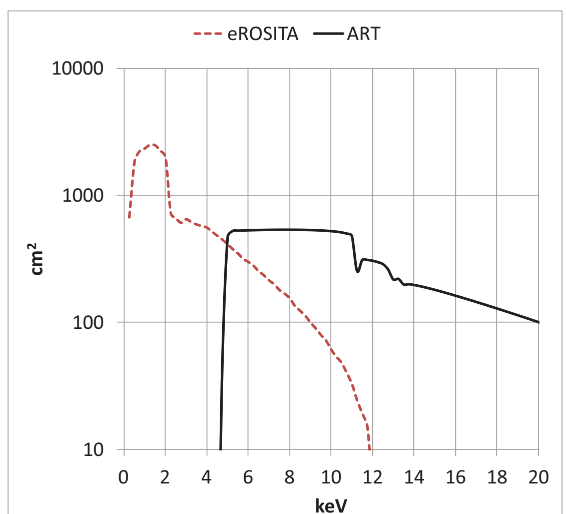

Figure 1. A comparison of the net (optics with detector) on-axis effective area $A_{eff}(E, 0)$ of the eROSITA and the ART telescope systems aboard SRG.

The SRG observatory will be launched into a low-Earth orbit from Baikonur and then delivered to a 6-month-period halo orbit around the outer Lagrange point (L2) via a Zenit rocket and Fregat booster. To optimize the final

*Mikhail.V.Gubarev@nasa.gov; Phone: 1 256 544-7816; FAX 1 256 544-2659

orbital parameters, a gravitational maneuver around the Moon will be performed.

Table 1. Performance characteristics of the ART and eROSITA instruments aboard the SRG mission.

Parameter	ART	eROSITA
Energy Range	**5-30 keV**	**0.2-12 keV**
Effective Area	**455 cm^2 at 8 keV**	**2500 cm^2 at 1 keV**
Field of View	**32 arcmin**	**1 deg**
System Angular Resolution (on axis)	**1 arcmin**	**15 arcsec**
Energy Resolution	**1.4 keV at 14 keV**	**130 eV at 6 keV**

The ART instrument comprises seven independent, co-aligned telescopes (x-ray mirror modules and detectors) sharing a carbon-fiber optical bench. The schematic representation of the ART-XC instrument is shown in Figure 2. There are two thermal control systems for the ART-XC instrument; an active control system maintains the mirror modules at near-room-temperature and a passive system keeps the focal-plane detectors at their required temperature. The radiator for the passive system is shown at the bottom left of Figure 2.

2. ART-XC Mirror Modules

The x-ray mirror modules for the ART-XC instrument are designed and being fabricated at MSFC. Four flight modules are produced under an International Reimbursable Agreement between NASA and IKI. The delivery date for these modules is November 2013. The remaining three flight modules and one spare unit are fabricated under a Cooperative Agreement between NASA and IKI. The remaining three flight modules are scheduled to be delivered in January 2014. MSFC will hold the spare flight unit for the ART-XC instrument.

The science-derived effective area requirement for the mirror module is > 65 cm^2 at 8 keV on axis. Figure 3 shows the expected effective area of a single mirror module (no detector response or thermal insulation) for various off-axis angles. Table 2 lists other requirements, generated by IKI, for the mirror module.

MSFC has designed the ART-XC x-ray optics modules. Figure 3 displays a sectional schematic of an ART mirror-module assembly. Each module comprises 28 concentrically nested shell mirrors, fabricated from a nickel-cobalt alloy. For each mirror module, a single spider holds the mirror shells at one end only through combs glued onto the spider legs. A thin aluminum thermal insulator tube with heaters maintains the module within the desired ±3°C operational temperature range. Three attachment lugs on the periphery of the spider secure each module to the support plate on the top of the optical bench.

Table 2. ART flight mirror module parameters

Parameter	*Value*
Number of Mirror Modules	7=4+3
Number of Shells per Module	28
Shell Coating	> 10 nm of iridium (> 90% bulk density)
Shell Total Length	580 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 from mirror intersection plane
Allowable Total Mass per Module	17 kg including thermal control system
Operating Temperature Range	17^o C to 23^o C

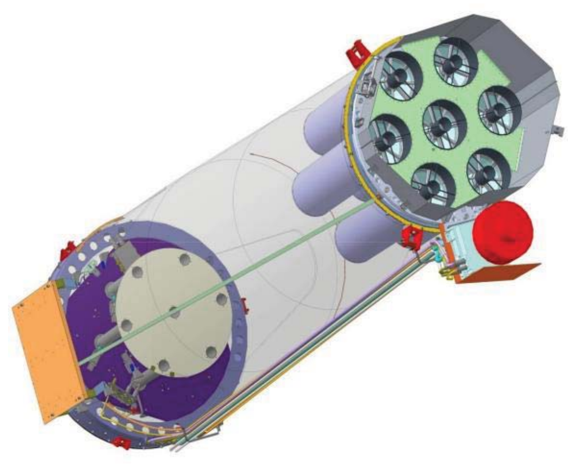

Figure 2. The ART Instrument with seven mirror modules and seven focal-plane detectors.

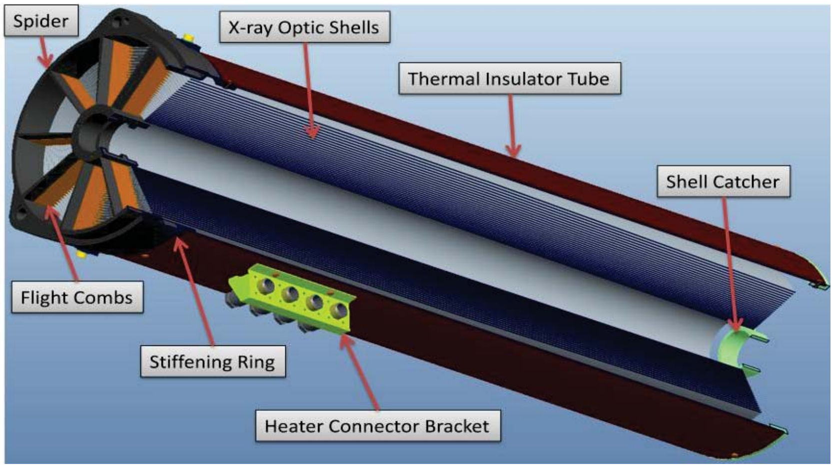

Figure 3. A cross section of an ART X-ray mirror module. The inner baffle and the heaters are not shown

The ART-XC shell mirrors are fabricated using the electroform-nickel replication technique[3, 4]. In this process a thin nickel or nickel-alloy mirror shell is electroformed onto a figured and super-polished electroless-nickel-plated aluminum mandrel, from which it is subsequently separated in chilled water by differential thermal contraction. The shells vary in diameter from about 50 mm to 150 mm and range in thickness from 250 μm (inner) to 350 μm (outer). The total length (primary and secondary mirror surfaces combined) is 580 mm. A thin coating (> 100 nm) of near-bulk-density iridium sputtered onto the inner surfaces enhances the high-energy reflectivity.

MSFC has expanded its capability to accommodate the increased workload and aggressive production schedule of the ART mirror module development[5]. Five polishing stations were assembled to ensure completion of the 28 ART mandrels on schedule. Also MSFC constructed an additional electroforming bath reaching a total capacity of 8-10 shells per week. Two custom radio-frequency (RF) sputtering chambers were developed to coat a thin (10 nm) layer of iridium inside shells. To enable multiple modules to be assembled as shells become available, five alignment and assembly stations have been fabricated.

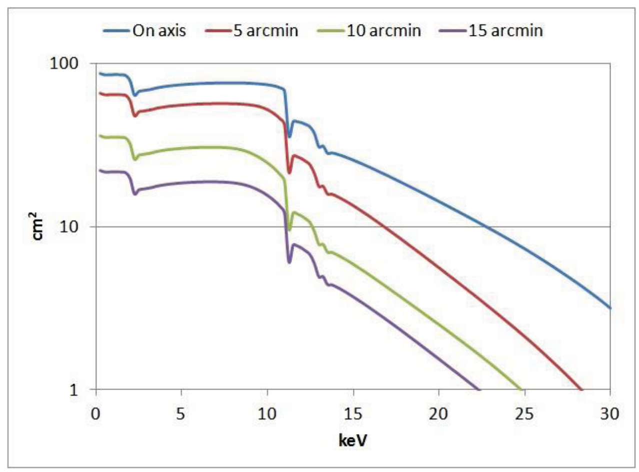

Figure 3. ART single mirror module effective area vs energy for various off-axis angles.

3. ART-XC Engineering mirror module

The ART-XC engineering qualification mirror module consists of 6 flight-grade x-ray mirror shells plus a system of three mass simulators (diameters are 74, 101.3 and 126.4 mm) designed to provide the principal resonant frequencies, and masses, of the missing 22 shells. The schematic representation of the ART-XC qualification mirror module is shown in Figure 4. The remaining module components: spider, protective housing, heaters and cables, and interior baffle system, are identical to the flight units. The flight-grade mirrors included in the module are inner three shells (1^{st}, 2^{nd} and 4^{th}) and outer three shells (25^{th}, 26^{th} and 27^{th}.) The ART-XC qualification module in its handling fixture is shown in Figure 5.

After the qualification mirror module was assembled a series of the environmental tests were performed. The ART-XC module was x-ray tested before, during and after environmental testing. The x-ray measurements were performed at MSFC's 104 meter Stray Light Facility. The measurements of on-axis effective area and point spread function were taken before any environmental testing, and then after each of the thermal, acoustic, vibration and shock tests. In addition, after the final test, a more comprehensive set of calibration data were taken.

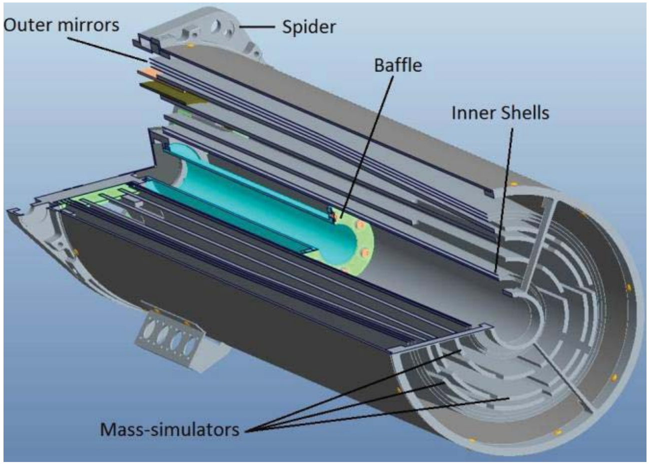

Figure 4. A cross section of ART-XC qualification mirror module. The heaters are not shown.

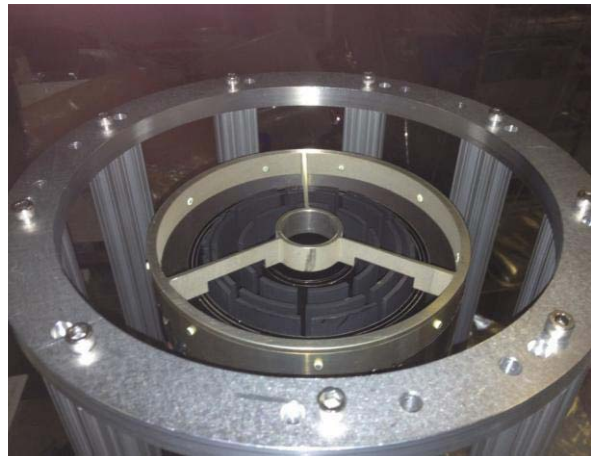

Figure 5. The ART-XC qualification module in the handling fixture.

The results of the effective area tests are summarized in the Table 3. These measurements show that there is no statistically significant change in effective area that would indicate mechanical changes in the module. The measured 13.5 cm^2 effective area of the qualification module is consistent with the requirement of 65 cm^2 effective area for the flight modules at 8 keV. The effective area was also measured for series of off-axis angles. An example of the measured effective area of the ART-XC qualification mirror module as a function of x-ray energy is shown in Figure 6. Overall the shape of the effective area curves are roughly as expected and the off axis responses are consistent with the models.

Table 3. Results of the qualification module effective area measurements at each stage of testing for 7-9 keV energy range

Test	Effective Area (cm^2)	Error (cm^2)
Initial	13.56	0.35
Post thermal test	13.01	0.47
Post acoustic test	13.81	0.38
Post vibration test	13.49	0.38
Final (post shock)	13.71	0.38

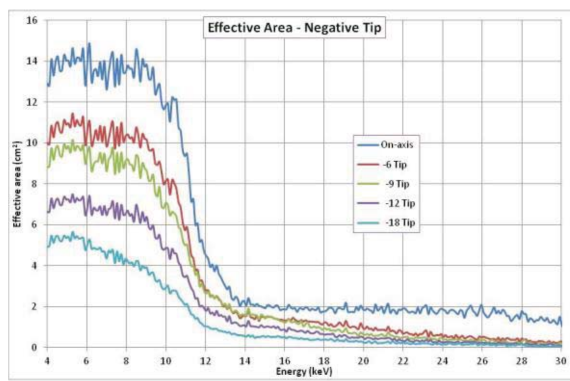

Figure 6. Qualification test article effective area versus energy for negative TIP off-axis angles

The point spread functions of the engineering unit were measured at each x-ray test and were compared against each other. The data show that there are no significant changes in the FWHM of the PSFs that would indicate mechanical changes in the module. Small changes are expected due to slight misalignments of the detector system, relative to the true focal position, when the scans are set up. The module HPD was calculated at each stage of test and the results varied between 31 and 33 arcsec with no statistically significant change or trend. The full module HPD requirement is < 1mm diameter at the center of the field of view. As 33 arcsec corresponds to 0.44 mm, the measured resolution exceeds requirements by a factor of two. Furthermore, the effect of gravity sag in the optic contributes around 21 arcsec to the measured HPD according to simulations. Thus the true (zero-g) resolution is probably nearer 25 arcsec, when gravity effects are subtracted in quadrature.

The measured focal length of the qualification module at the 104 m source to optics distance was measured to be 2773 mm (nominal 2772 mm).

After completion of the tests in April 2013 the ART-XC qualification mirror module was shipped to IKI for cross-calibration and for the qualification tests of the ART-XC instrument as a whole.

4. Flight Modules Fabrication Status

After successful completion of the ART-XC qualification mirror module tests we proceeded with assembly and alignment of the flight modules. Prior to the integration into a module, each ART-XC mirror shell coated with iridium undergoes an acceptance x-ray test. The test is performed to ensure the mirror meets the angular resolution and effective area requirements. To the date 172 ART-XC shells have been accepted for integration into the flight modules and 103 shells are already integrated. An image of an ART-XC module with 28 mirrors integrated is shown in Figure 7. Three flight modules are fully populated with the mirror shells and fourth module has 25 mirror shells installed. The flight modules installed on the alignment systems are shown in Figure 8.

Figure 7. 28 mirror shells installed into the ART-XC flight module

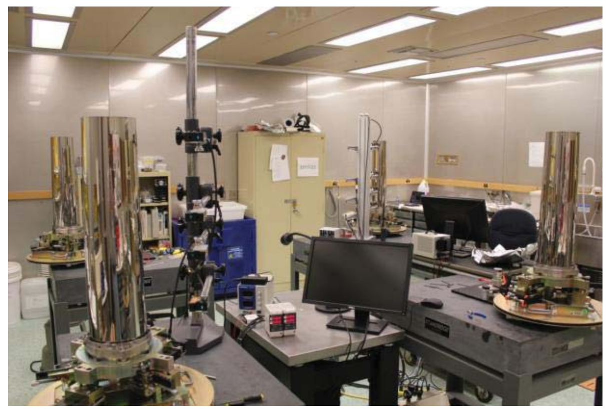

Figure 8. Four ART-XC flight units installed on the alignment systems

The mirror module heaters have been recently provided by IKI and are being installed on the protective housings fabricated at MSFC. After the housings are installed on the flight modules, MSFC will vibration test them, in its environmental test facility, to acceptance levels provided by IKI. Upon completion of vibration testing, four mirror modules will be X-ray tested and calibrated in the Stray Light Facility, prior to shipment to Russia in November 2013. In parallel with the x-ray tests and calibrations, the assembly of the next four modules scheduled to be delivered to IKI in January 2014 will start.

5. Conclusions

MSFC is developing x-ray mirror modules for the ART-XC instrument on board the SRG Mission. Four mirror modules are being fabricated under an International Reimbursable Agreement between NASA and IKI. Delivery of these modules to IKI is scheduled for November 2013. The remaining three flight and one spare module for the ART-XC Instrument are being produced under a Cooperative Agreement between NASA and IKI and are scheduled to be delivered in January 2014.

To verify the optical and mechanical performance of the ART-XC modules MSFC has developed a qualification mirror module on which a series of acoustical, thermal, vibration and shock tests were performed. X-ray measurements were taken before and during these tests. The measured effective area of the qualification unit is consistent with the requirement of 65 cm^2 at 8 keV for the flight module, while the angular resolution measured surpasses the angular resolution requirement for the flight modules. The series of measurements taken during the tests show that there is no statistically significant change in effective area or in the angular resolution that would indicate mechanical changes in the module. The ART-XC qualification mirror module has been delivered to IKI.

Four mirror modules are being integrated. Upon completion of vibration testing, these four modules will be X-ray tested and calibrated, prior to shipment to IKI in November 2013. The assembly of next four modules, scheduled to be delivered to IKI in January 2014, will be performed in parallel with the x-ray tests and calibrations of the first four modules.

6. References

[1] Predehl P., et al., "eROSITA on SRG", Proc. SPIE 7732, 77320U (2010).

[2] Pavlinsky M., et al. "The ART-XC Instrument on board the SRG Mission", Proc. SPIE 8147, 814706-814706-6 (2011).

[3] BD Ramsey, RF Elsner, D Engelhaupt, MV Gubarev, JJ Kolodziejczak, SL ODell, et al. “The development of hard X-ray optics at MSFC”, Proc. of SPIE. 4851, 631-638 (2003).

[4] BD Ramsey, “Replicated Nickel Optics for the Hard-X-Ray Region”, Exp. Astron. 20, 85-92 (2005)

[5] M. Gubarev, B. Ramsey, S.L. O’Dell, R. Elsner, K. Kilaru, J. McCracken, M. Pavlinsky, A. Tkachenko, I. Lapshov “The Marshall Space Flight Center Development of Mirror Modules for the ART-XC Instrument aboard the Spectrum-Roentgen-Gamma Mission”, Proc. SPIE 8443, 84431U (2012)