ART-XC/SRG: Status of the x-ray optics development

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ABSTRACT

The Astronomical Roentgen Telescope (ART) instrument is a hard-x-ray instrument with energy response up to 30 keV that is to be launched on board of the Spectrum Roentgen Gamma (SRG) Mission. The instrument consists of seven identical mirror modules coupled with seven CdTe strip focal-plane detectors. The mirror modules are being developed at the Marshall Space Flight Center (MSFC.) Each module has ~65 sq. cm effective area and an on-axis angular resolution of 30 arcseconds half power diameter (HPD) at 8 keV. The current status of the mirror module development and testing will be presented.

Keywords: Spectrum-Röntgen-Gamma, **A**stronomical **R**oentgen **T**elescope – **X**-ray **C**oncentrator, x-ray optics

1. SRG Overview

The Spectrum-Röntgen-Gamma (SRG) mission is an X-ray astrophysical observatory that carries two co-aligned X-ray telescope systems. SRG's primary goal is to perform the most sensitive X-ray all-sky survey to date, to be followed with pointed observations. 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. Performance characteristics of the eROSITA and ART telescope systems as required

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**

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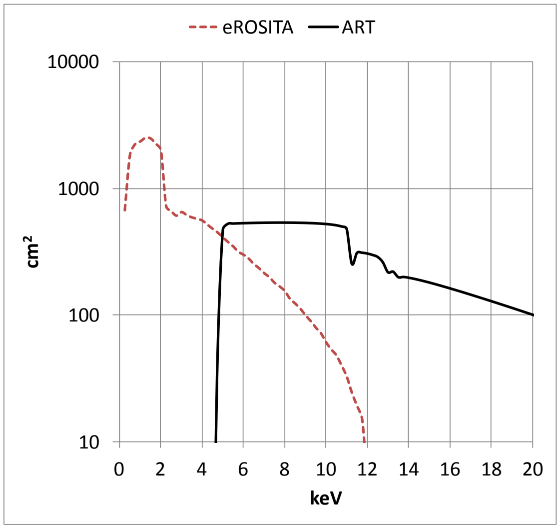

Figure 1. A comparison of the net (optics with detector) on-axis effective area $A_{eff}(E, 0)$ of the eROSITA and the ART telescope are compared in Table 1 and Figure 1.

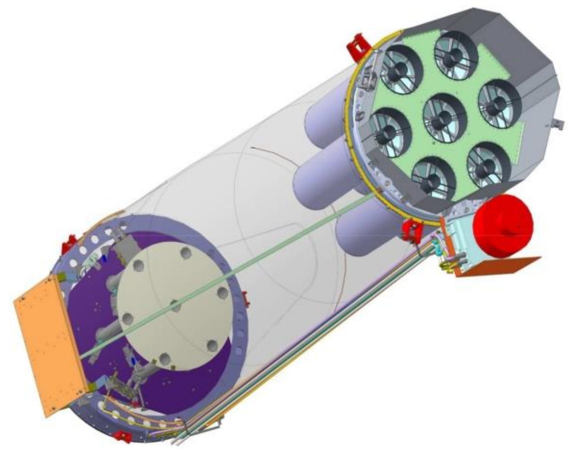

Figure 2. The ART Instrument with seven mirror modules and seven focal-plane detectors.

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. The first ~100 days, during the transit to the L2 point, will be used for initial check-out and in-flight calibrations. The next 4 years will be devoted to an all-sky survey, during which time the spacecraft rotates about an axis that points, initially, directly towards the sun. Thus, the overlapping point of the great scan circles gives a deep survey region at each ecliptic pole. During the survey, the SRG observatory will rotate around the axis pointed approximately between the Sun and the Earth, with a period of about four hours. SRG will observe the whole sky every half year due to Earth's revolution around the Sun. The final stage of the mission, which will last about 3 years, will be spent on pointed observations.

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	$\geq$ 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
Lowest Resonance Frequency, Hz	40
Operating Temperature Range	17^0 C to 23^0 C

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 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.

MSFC has designed the ART mirror module and is fabricating four ART x-ray optics modules under an International Reimbursable Agreement between NASA and with IKI[3]. The delivery date for these modules is September 2014. The remaining three flight modules, to be delivered in September-October 2014, and an additional spare unit are being fabricated under a Cooperative Agreement between NASA and IKI. MSFC will hold the spare flight unit for the ART-XC instrument. MSFC has obtained export licenses from the US State Department for shipment of the qualification and four flight units fabricated under the International Reimbursable Agreement, three flight units fabricated under Cooperative Agreement, and the supporting data to Russia.

Table 2 shows the requirements for the ART x-ray optics and Figure 3 displays a sectional schematic of the ART mirror-module assembly designed by MSFC. Each module comprises 28 concentrically nested shells, fabricated from a nickel-cobalt alloy. The shells vary in thickness from 250 µm (inner) to 350 µm (outer) and range in diameter from about 50 mm to 150 mm. 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.

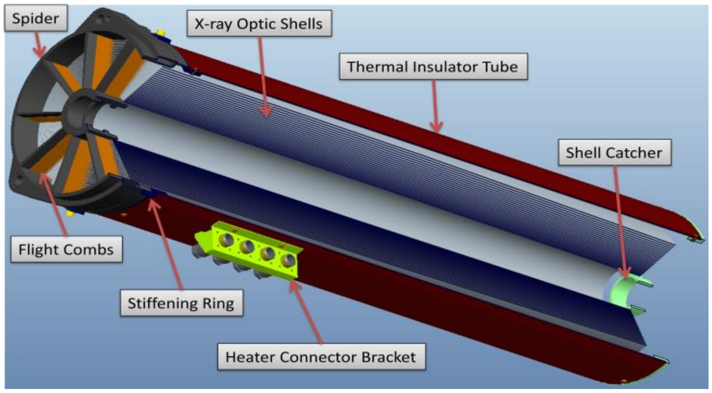

Figure 3. A cross section of an ART X-ray mirror module. An inner baffle tube (to reduce stray light) and the module heaters are not shown

2. Fabrication and Calibration Status

The ART-XC shell mirrors are fabricated using the electroform-nickel replication technique[4, 5]. 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. To date fabrication of 28 ART mandrels has been completed. All mirrors for engineering mirror module unit as well as for eight flight units have been electroformed, replicated, coated with iridium and tested.

The ART engineering unit which imitates the flight module resonance frequencies but with only six mirror shells and mass-simulators, has been designed and fabricated (see Figure 4)[6]. The engineering unit has been checked via x-ray measurements, environmentally tested (vibration, shock, acoustic and thermal), and then fully characterized in x rays. X-

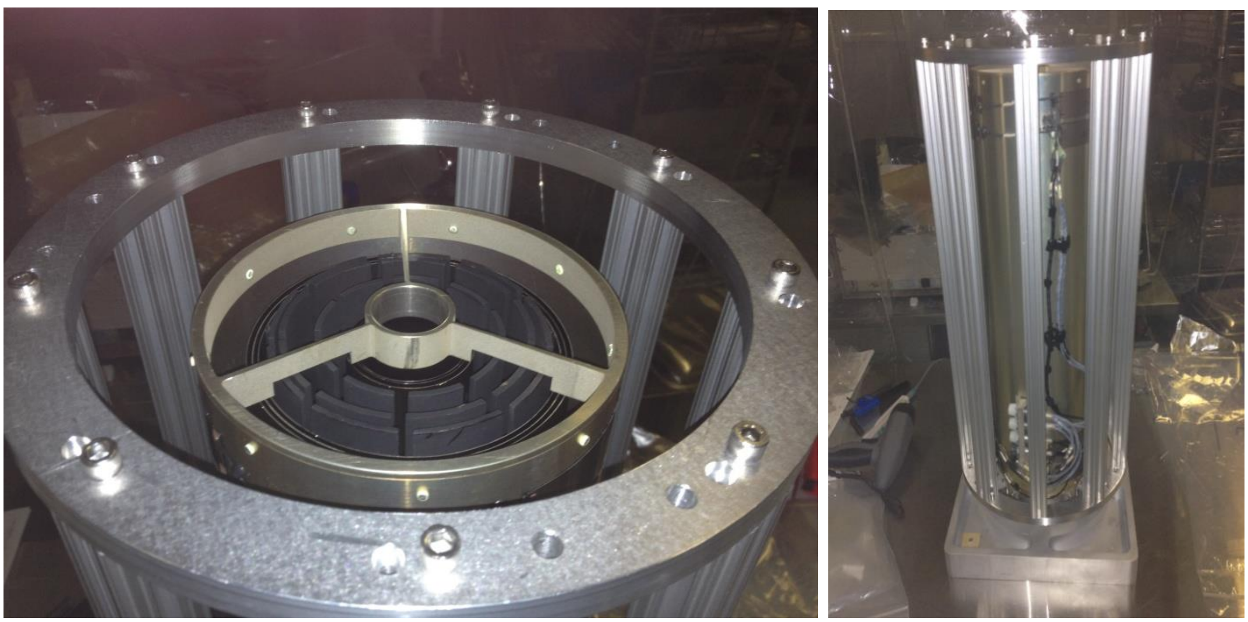

Figure 4. The ART-XC qualification module in the handling fixture mounted on the shipping base. The unit contains three inner shells, three mass-simulators painted black and three outer shells.

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. 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.

To date four ART flight mirror modules have been assembled. Two of these modules passed the vibration tests performed in accordance with the vibration test program summarized in Table 3. The lowest resonant frequency for the flight units was measured to be above 65 Hz, compared to the 40 Hz requirement. These two modules have been calibrated at MSFC's 104-m Stray Light Facility (SLF). The flight unit installed in the bell housing of the SLF is shown in Figure 5. The next two assembled modules are in line for the vibration tests and calibrations and the assembly of the next four mirror modules (three flight and one spare) is in progress.

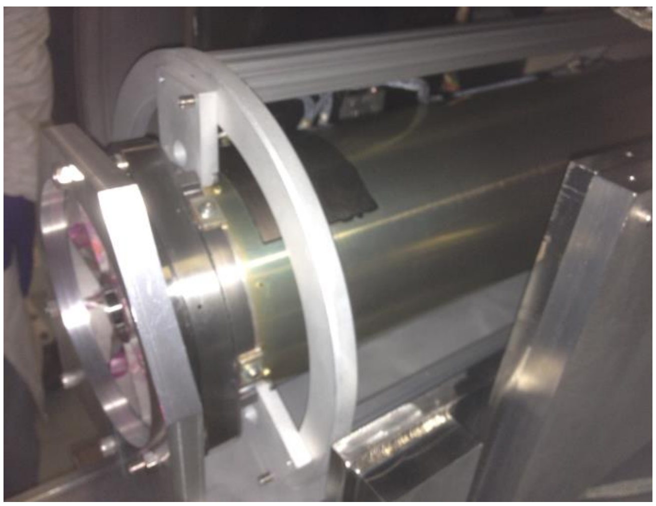

Figure 5. ART mirror module installed into a handling fixture (left)

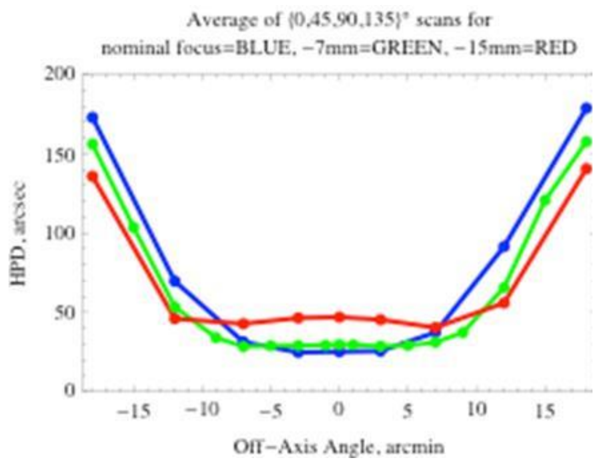

Figure 6. Angular resolution of an ART mirror module for three focal distances.

The angular resolution and effective area of the mirror nodules was measured on axis and off-axis using both an iKon-L 936 ANDOR CCD camera and an Amptek XR-100T CdTe detector (5 mm × 5 mm) with a set of pinholes. The CCD camera has limited response above 10 keV, so the calibration for the energy range between 10 and 30 kev was performed with the CdTe detector only. It was found the results of the calibration performed by the camera and detector are in close agreement for 8 keV x-rays.

Table 3. Vibration test, Random vibration requirements. Before the test listed below, a low-level sine sweep is performed on a flight mirror module to verify that the lowest resonant frequency is above 40 Hz.

Test #	Test Duration (sec)	Frequency Range (Hz)					
		20-50	50-100	100-200	200-500	500-1000	1000-2000
		Power Spectral Density. g^2/Hz					
1a	60	0.01	0.01	0.01-0.025	0.025	0.025-0.0125	0.0125-0.0065
1b	240	0.01	0.01	0.01	0.01-0.004	0.004-0.002	0.002-0.001
2	675	0.002	0.002	0.002	0.002	0.002	0.002-0.001

The first ART mirror module was subjected to series of the tests in order to optimize the calibration strategy for all ART mirror modules. In order to find an optimal focal distance a series of angular resolution measurements was performed. It was found that the defocusing a module by 7 mm provides more uniform angular resolution across the field of view compared to the resolution at the nominal focal distance. Figure 6 illustrates the effect of defocusing on off-axis resolution of the ART mirror module.

The angular resolution, the effective area and point spread functions were measured on axis and for number of off-axis angles. The Half Power Diameter (HPD) angular resolution of the ART mirror modules was measured to be less than 30 arc seconds. Analysis to remove the effects of the gravitational sag of the ART mirrors during the testing is underway. The on axis effective area measured for the two ART modules tested so far (65 and 68 sq.cm. at 8 keV) meets the requirements outlined in Table 2. The measured on axis effective area dependence on the x-ray energy for an ART mirror module is shown in Figure 7. More detailed results of the ART mirror modules calibration are presented in Gubarev, et al. "Calibration of the ART-XC/SRG x-ray mirror modules" in the proceedings of this conference.

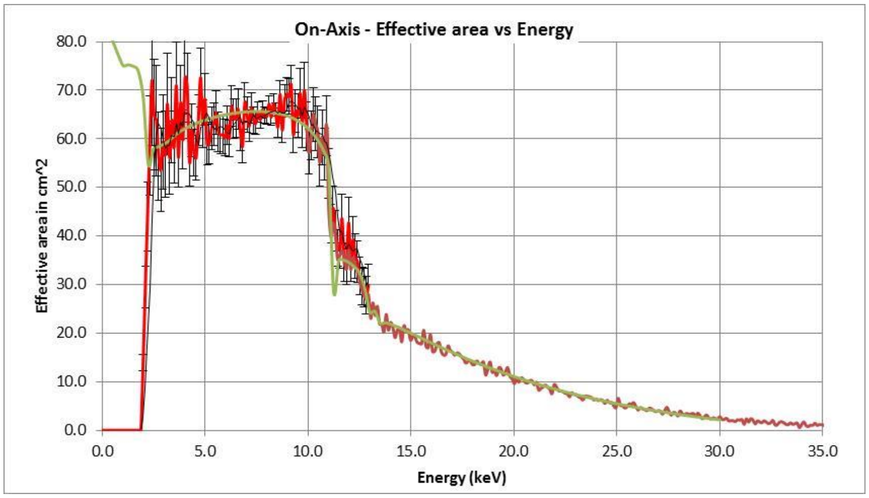

Figure 7. Measured on axis effective area of an ART module as a function of x-ray energy.

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 August 2014. To date four these modules have been assembled and two of them have been calibrated. The angular resolution and the effective area measured so far meet the ART performance requirements.

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 September-October 2014. The assembly of these mirror modules is underway.

MSFC has obtained export licenses from the US State Department for shipment of the mirror module flight units under both Agreements, as well as the supporting data to Russia.

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