The ART-XC Instrument on board the SRG Mission

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ABSTRACT

Spectrum Roentgen Gamma (SRG) is an X-ray astrophysical observatory, developed by Russia in collaboration with Germany. The mission will be launched in 2014 from Baikonur, by a Zenit rocket with a Fregat booster and placed in a 6-month-period halo orbit around L2. The scientific payload consists of two independent telescopes – a soft-x-ray survey instrument, eROSITA, being provided by Germany and a medium-x-ray-energy survey instrument ART-XC being developed by Russia. ART-XC will consist of seven independent, but co-aligned, telescope modules with seven corresponding cadmium-telluride focal plane detectors. Each will operate over the approximate energy range of 6-30 keV, with an angular resolution of <1′, a field of view of ~30′ and an energy resolution about 10% at 14 keV. The NASA Marshall Space Flight Center (MSFC) will fabricate some of the mirror modules, to complement others fabricated by VNIIEF in Russia.

1. SRG Overview

The Spectrum-Roentgen-Gamma (SRG) Mission is a Russian - German X-ray astrophysical observatory. A schematic representation of the SRG satellite is shown in Figure 1. The Max-Planck-Institut für Extraterrestrische Physik (MPE), Germany, is responsible for the development of the first mission instrument – the X-ray grazing-incidence mirror telescope **e**xtended **RO**entgen **S**urvey with an **I**maging **T**elescope **A**rray (eROSITA) [1]. The second instrument is the **A**stronomical **R**oentgen **T**elescope – **X**-ray **C**oncentrator (ART-XC) [2], an X-ray mirror telescope with a harder response than eROSITA. The ART-XC instrument is being developed by the Russian Space Research Institute (IKI) and the All-Russian Scientific Research Institute for Experimental Physics (VNIIEF). The x-ray optics for the ART-XC instrument are to be fabricated by VNIIEF and by the Marshall Space Flight Center (USA).

The scientific payload is housed on the Navigator platform, developed by Lavochkin Association (Russia). Such platforms are now in service on the Elektro-L mission (since January 2011) and the Spektr-R mission (since July 2011). The details of the platform design parameters are presented in Table 1. The Navigator platform has been developed to be a universal medium-class platform for scientific missions planned to be launched to different orbits. The platform has been designed for autonomous operation of scientific payloads and can provide 3-axis stabilization or rotation with variable speed – an important feature to be utilized by the SRG payload during its mission.

Spectrum-RG will be launched in 2014 from Baikonur and delivered to L2 point with use of the Zenit-2SB rocket and Fregat-SB booster.

The SRG observing program is divided into three stages over the 7.5-year mission lifetime. The first ~100 days during the transit to the L2 point will be devoted to initial check-up and in-flight calibrations. The next 4 years will be devoted to the all-sky survey. During this time, the SRG observatory will rotate around the axis pointed approximately to Sun, with a period of about four hours. The final stage of the mission, which will last about 3 years, will be spent on pointed observations of selected objects from the most interesting galaxy clusters, AGNs and galaxy sources. Short (up to one month) pointed observations are possible after each half-year survey period.

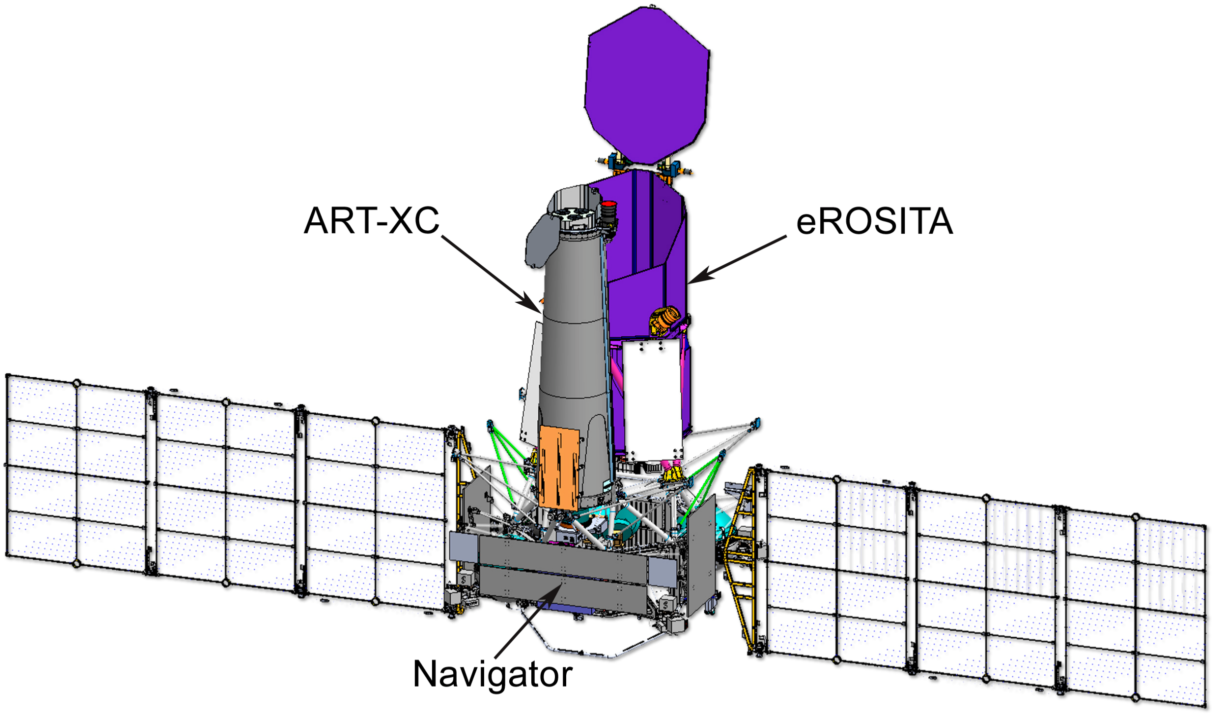

Figure 1. The SRG satellite utilizes the Russian Navigator platform. The eROSITA and the ART-XC telescopes, installed on the platform, are shown in blue and gray, respectively.

Table 1. Key parameters of the Spectrum-Roentgen-Gamma mission

Description	**Value**
Launch date	2014
Launch site	Baikonur
Space Transportation technologies	"Zenit-2SB" LV, "Fregat-SB" upper stage
Operational orbit	Region of libration point L2
Active lifetime	7.5 years
S/C dry mass	2267 kg
Payload mass	1228 kg
S/C wet mass	2647 kg
Radio line frequency range	X band
Science Data Transmission Rate	512 kbit/sec
Payload power consumption	680 W

The mission will conduct an all-sky survey in the 0.5 – 11 keV band with the imaging telescopes eROSITA and ART-XC. It will permit the discovery of all obscured accreting Black Holes in nearby galaxies, many (~millions) new distant AGN, and the detection of all massive clusters of galaxies in the Universe. In addition to the all-sky survey, dedicated sky regions will be observed with higher sensitivity and thereafter follow-on pointed observations of selected sources at energies up to 30 keV will take place in order to investigate the nature of dark matter, dark energy and physics of accretion.

2. ART-XC

2.1. Instrument description

The ART-XC instrument consists of seven co-aligned X-ray mirror modules coupled with seven CdTe doubled sided strip detectors as shown schematically in Figure 2. The mirror modules are installed on an optical bench plate mounted on the top of a carbon fiber optical bench. Each x-ray mirror module is focused onto its own detector and thus seven detectors are installed on the bottom of the optical bench. Table 2 summarizes the overall ART-XC instrument performance specifications.

Table 2. Key parameters of ART-XC.

Energy range	6-30 keV
Field of view	∅32′
On-axis angular resolution	<1′
Energy resolution	10% at 14 keV
Effective area for pointed observations	450 cm^2 @ 8 keV
Grasp for survey	>40 deg^2 cm^2 @ 8 keV
Time resolution	1 ms

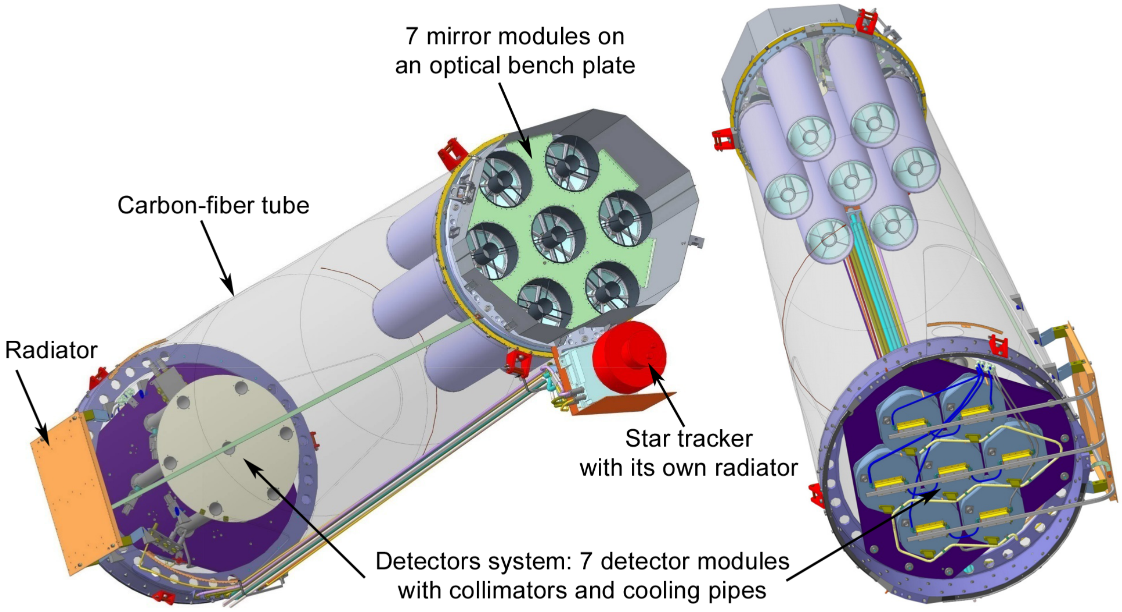

Figure 2. The ART-XC telescope with seven mirror modules and seven focal-plane detectors. The basic structure of ART-XC is the optical bench,- the conical carbon-fiber tube which is equipped with a moveable cover to protect the optics during launch (not shown).The star tracker with its own radiator is installed on the top of this tube. The detector collimators, cooling radiator with cooling pipes and the electronics boxes are visible at the bottom of the tube.

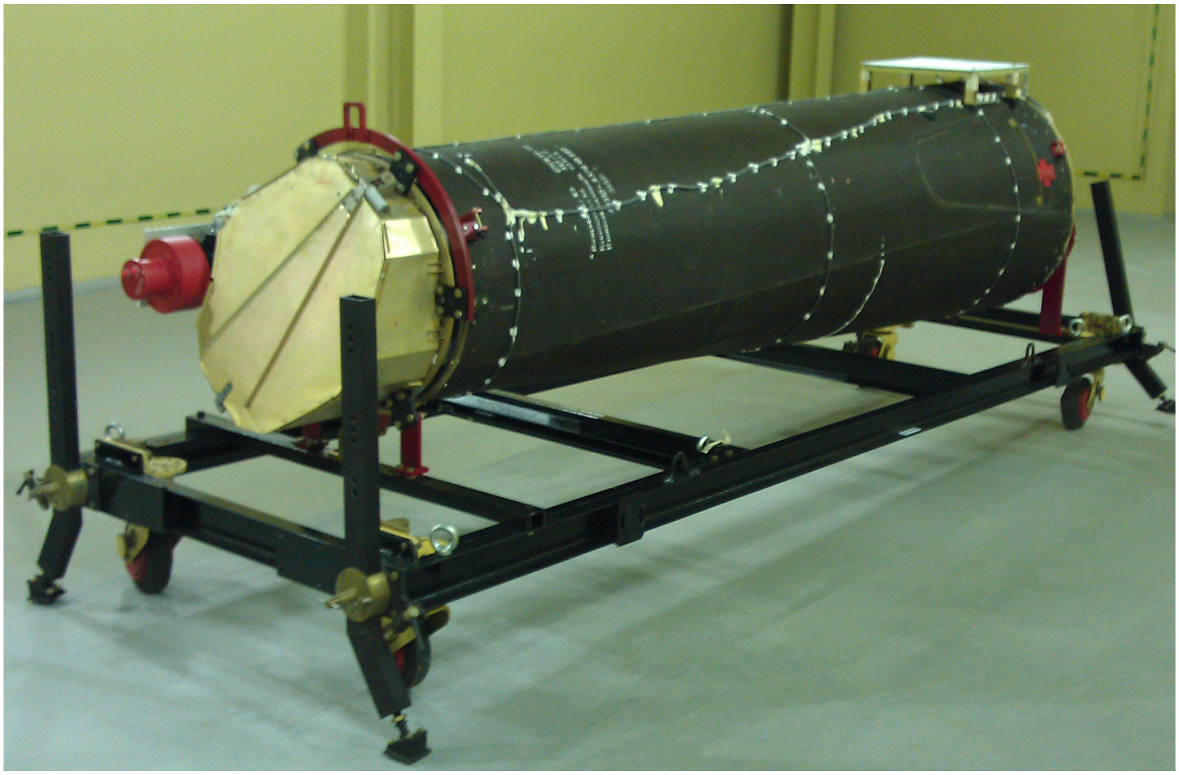

Figure 3. The STM model of the ART-XC telescope. Visible is the carbon-fiber tube, closed by a moveable cover with the star tracker installed nearby. The detector cooling radiator is visible at the top of the rear end of the tube.

2.2. The optical system

A schematic representation of the ART-XC mirror system is shown in the left panel of Figure 4. Each x-ray mirror module contains 28 mirror shells fabricated using an electroformed-nickel-replication technique. The shells are glued in to a supporting spider and the spider is installed onto the optical plate of the instrument. The shell diameters vary from ~ 50 to 150 mm and the focal distance of the mirror system is 2700 mm. In order to extend the energy response to 30 keV the mirror inner surface will be coated with 10-20 nm of iridium. The required *system* angular resolution of better than 1 arc minute necessitates that the shells be figured to a Wolter 1 prescription.

The weight limit for the ART-XC module is 17 kg. The shell thickness varies slightly with radius so the outer shells have larger than nominal thickness to make them stiffer and, hence, to improve the angular resolution of a module.

Table 3. Summary of the mirror system design

Number of mirror systems	7
Number of nested mirror shells	28
Form of shell	Wolter-I
Field of view	∅32′
On-axis angular resolution, HPD	< 40″
Focal length	2700 mm
Length of shell	580 mm
Diameters of mirror shells (intersection)	49 – 145 mm
Material of shells	Ni/Co
Mirror coating materials	Iridium

The production of the modules has been started in two institutions independently. Three modules are to be fabricated by the VNIIEF (Russia). A Reimbursable Agreement has been signed between IKI and NASA at the beginning of 2011 for the Marshall Space Flight Center to fabricate, test, and calibrate the remaining four modules.

Figure 5 shows the expected effective area of a single mirror module (no detector response) for various off-axis angles.

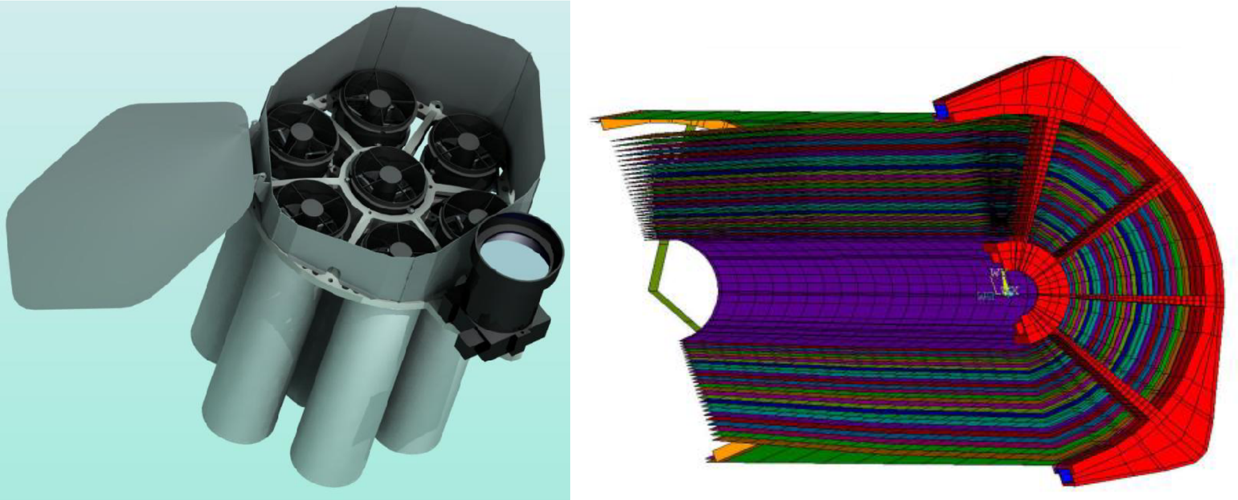

Figure 4. Left: 3D model of the ART-XC mirror system. Seven mirror modules coupled with light restricting pre-collimation system installed on the optical plate. The optical plate is installed on the top of the carbon-fiber optical bench (not shown). Right: A cross section of an ART-XC X-ray mirror module.

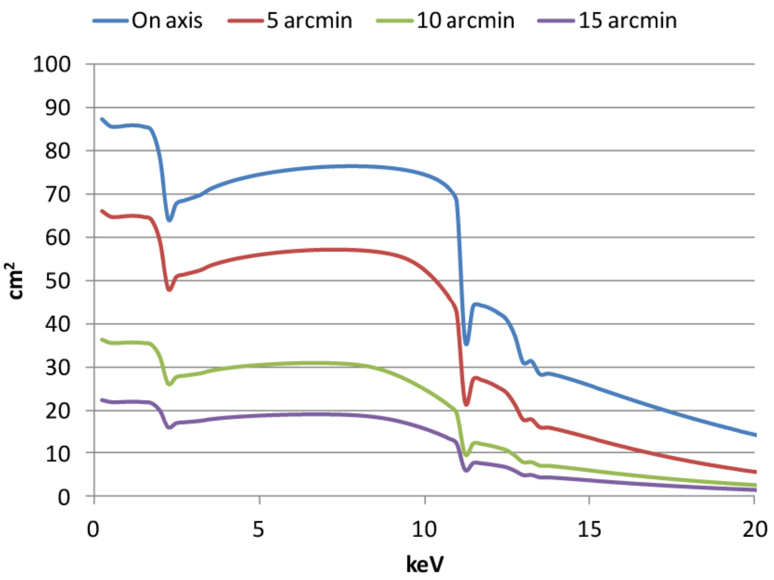

Figure 5. ART-XC single mirror module effective area vs energy for various off-axis angles.

2.3. Focal plane detector system

Each mirror module is aligned with a focal plane detector. Developed by IKI, the ART-XC focal plane uses cadmium-telluride (CdTe) Schottky Diode double-sided strip detectors, read by custom Application Specific Integrated Circuits (ASICs). Each detector has 48×48 read-out strips on a 595 μm pitch giving a field of view of about 36×36 arcmin^2. Combining the detector's spatial resolution with the mirror module's angular resolution results in an expected system resolution of around 1 arcmin. The ASIC system has relatively low noise and a low-energy threshold of 5 keV is now being achieved in flight development units. The expected energy resolution is 1.4 keV at 14 keV. Table 4 shows the ART-XC detector parameters.

To reduce polarization effects, the detector crystal is cooled to −30°C. A thin (100 μm) beryllium window seals a vacuum-tight housing that prevents condensation onto crystal surface during ground tests (see Figure 6). The ground tests utilize a built-in Peltier cooler; flight operations will use a passive system of thermal tubing and an external radiator.

A cylindrical collimator of height 380 mm and inside diameter 40 mm limits the diffuse background reaching the detector. This collimator is fitted with graded shielding: the bottom half with tin, copper, and aluminum; the top half with just copper and aluminum. The collimator base incorporates a moveable Am^{241} source for in-flight calibration.

Figure 7 show the configuration of the seven flight detectors with associated cooling pipes, while protoflight hardware undergoing bench tests is shown in Figure 8.

Using a set of radioactive sources (e.g. Am^{241}, Cd^{109}, Fe^{55}, etc.), tests were carried out with the detector prototype under different conditions (in air, in vacuum enclosure, etc.), and with different detector parameters (varying high voltage from 100 V to 450 V and detector temperature from +20°C to −30°C) and it was confirmed that the detector operates stably under fixed conditions. As an example of detector performance, Figure 9 shows two spectra collected over ~10 ks under different conditions. In both, we can clearly see all the main Am^{241} lines (26.3 keV and 59.5 keV), Np^{237} lines (13.9 keV, 17.7 keV and 20.7 keV) and lines caused by K_α escapes from Cd and Te elements (32.06 keV and 36.36 keV). In the spectrum of Am^{241}+Fe^{55} we also detect a blend of iron lines around 6 keV. These data confirm that we can achieve a low-energy threshold of about 5 keV and 12% FWHM energy resolution at 14 keV.

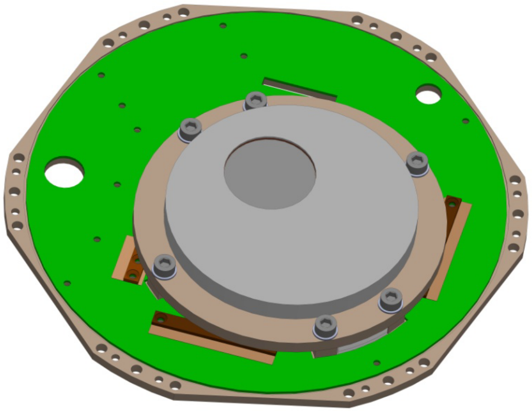

Figure 6. Bottom part of the ART-XC detector module showing the protective vacuum-tight box with beryllium window below which the CdTe crystal is installed. This box is filled with nitrogen to prevent condensation onto the Peltier-cooled crystal surface during ground tests.

Table 4. The ART-XC detector parameters

Detector type	CdTe Schottky Diode double sided strip (ACRORAD, Japan)
Size of CdTe crystal	30 × 30 × 1 mm
Working area	28.56 × 28.56 mm
Strip width	520 µm
Inter-strip distance	75 µm
Number of strips	48 × 48
ASIC	VA64TA
Energy range	5-80 keV
Energy resolution	10% at 14 keV
Operating temperature	−30°C
Operating voltage	−300 V
Be window thickness	100 µm

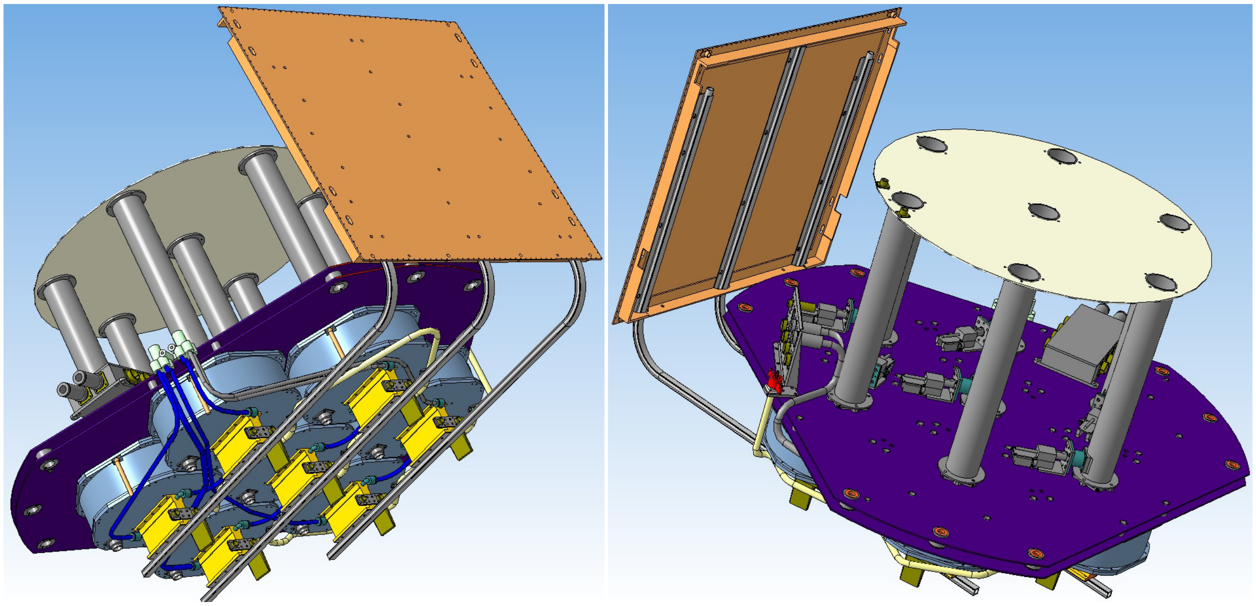

Figure 7. Seven detectors with front end electronics are placed on the ART-XC detector platform. Cylindrical housings are shown together with the cooling pipes and the radiator of the passive detector cooling system. The detector precollimator tubes are also visible.

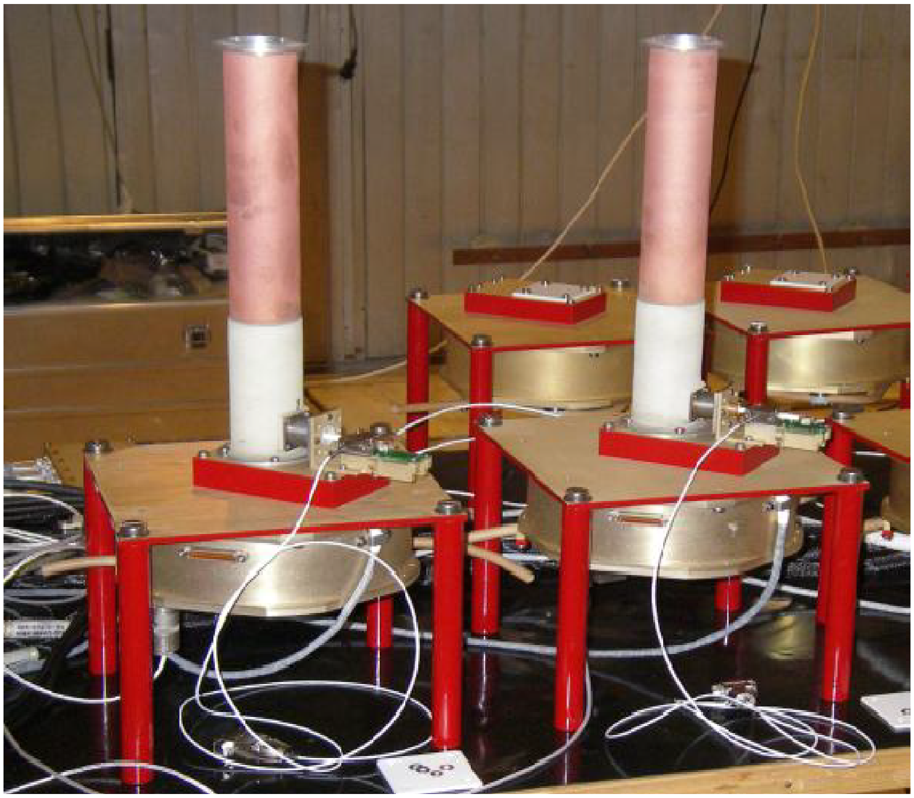

Figure 8. ART-XC protoflight detector units undergoing laboratory tests.

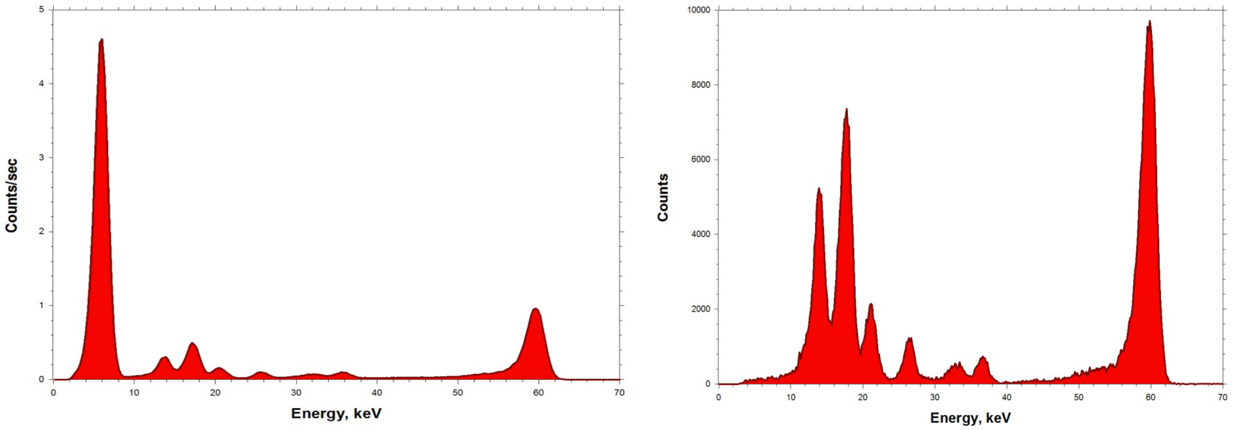

Figure 9. Energy spectrum measured with ART-XC CdTe detector prototype. Left: Fe^{55} + Am^{241} at T = 6°C, U = −300 V; Right: Am^{241} at T = −32°C, U = −450 V. These data confirm that we can achieve a low-energy threshold of better than 5 keV and 12% FWHM energy resolution at 14 keV.

3. Science with ART-XC

The scientific goals of the SRG mission are to study the large-scale structure of the Universe and explore the evolution of supermassive black holes. To achieve these goals SRG will survey the sky in the low and mid-energy band with unprecedented sensitivity, discovering a very large number of galaxy clusters and AGN.

ART-XC's role is to extend the energy range of the eROSITA instrument, significantly enhancing the sensitivity of the SRG mission at and above the critical iron-K region and facilitating the x-ray detection of heavily obscured cosmic sources, especially local Active Galactic Nuclei.

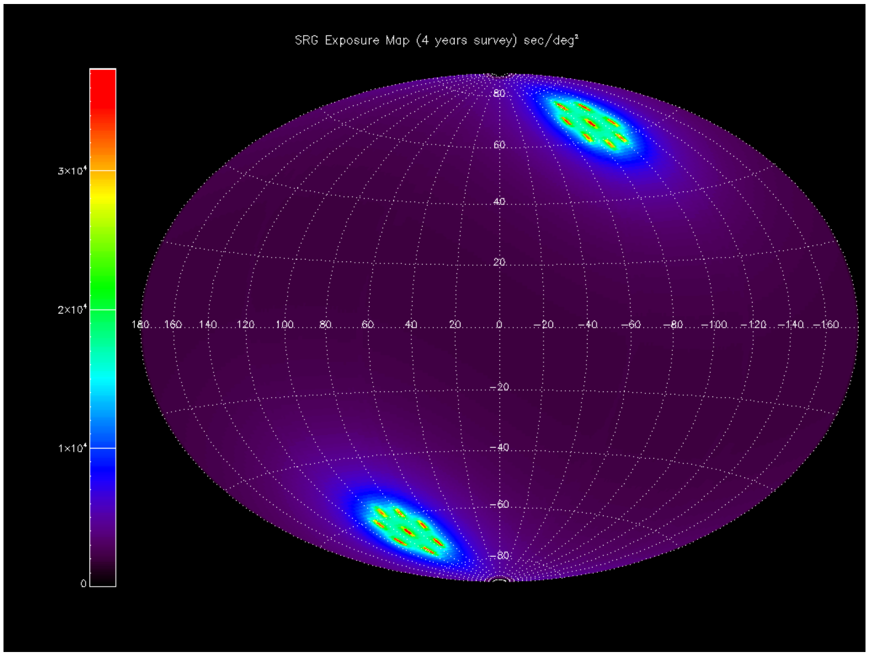

Figure 10. Exposure map (equatorial coordinates) for the 4-year survey of SRG in units of seconds/ square degree. During the first 6 months of the survey the spacecraft rotation axis will be pointed towards the Sun. For the next 7 half-year survey periods, to avoid confusion around the survey poles, it is planned to offset the scan poles by 8 degrees in different directions from the Ecliptic pole.

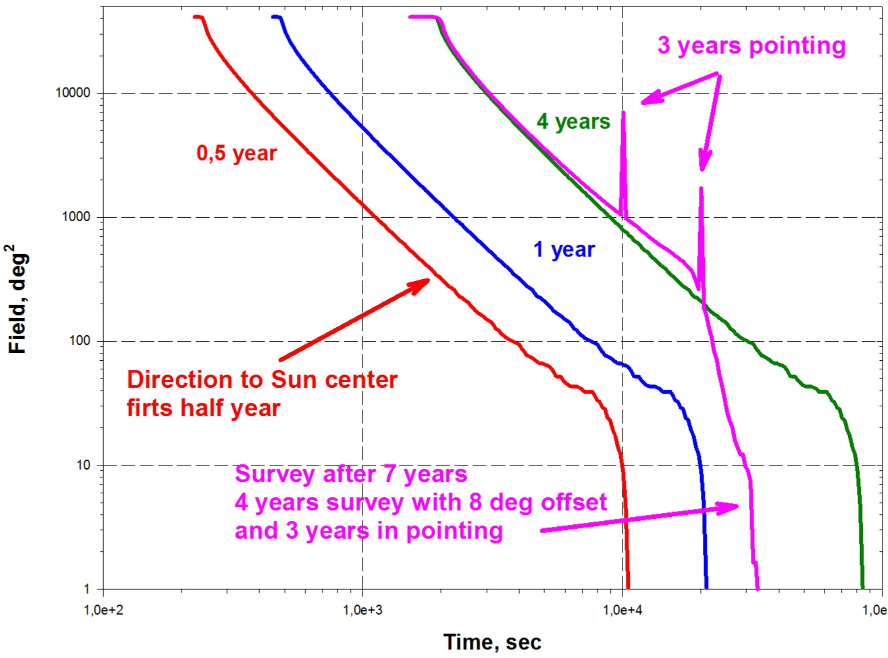

Figure 11. Cumulative function of the SRG survey. Red line – half year survey with the spacecraft rotation axis pointed towards the Sun. Blue and green lines – the same, but the duration of the surveys is 1 year and 4 year respectively. Purple line – the sum of the cumulative function of 4 year all sky survey in case of semiannally offset scan poles by 8 degrees in different equatorial directions from the Ecliptic pole and 3 year pointing mode (~6000 points with 10^4 and ~1500 points with 2×10^4 sec).

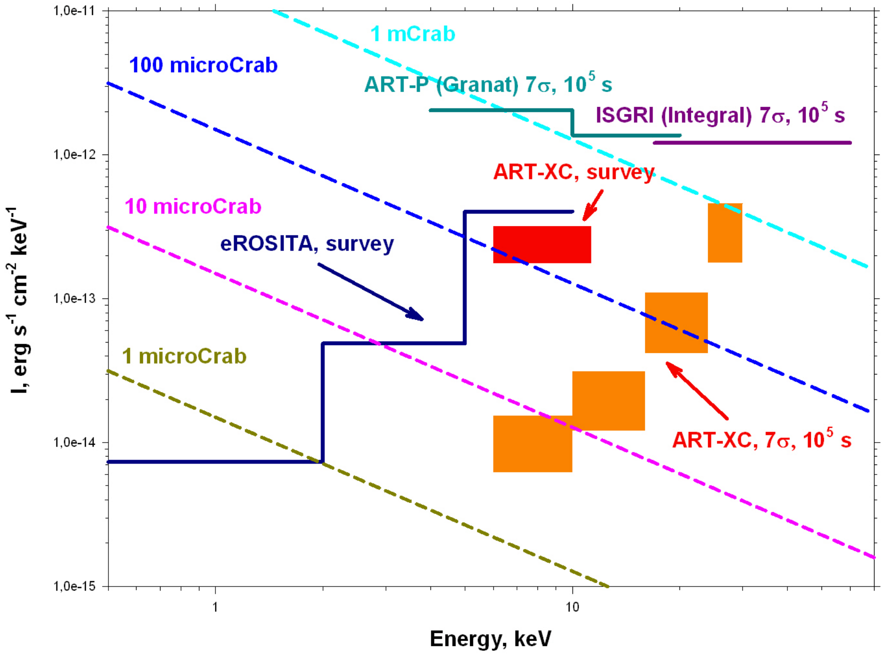

Figure 12. Sensitivity of ART-XC and eRosita in survey mode (4 years) and ART-XC in pointing mode (10^5 seconds). The actual sensitivity level (inside boxes) depends on contemporary background level from 10^{-2} counts s^{-1} cm^{-2} keV^{-1} to 10^{-3} counts s^{-1} cm^{-2} keV^{-1}. The sensitivity limits of two coded-mask telescopes ART-P (Granat) and ISGRI (Integral) are given for comparison.

As mentioned above, during the all-sky survey SRG will observe the whole sky every half year due to the Earth's rotation around the Sun. It is planned, that during the first 6 months of the survey the spacecraft rotation axis will be pointed towards the Sun, which will bring the survey poles coincident to the Ecliptic poles. For the next 7 half-year survey periods in order to avoid confusion around the survey poles, it is planned to offset the scan poles by 8 degrees in different equatorial directions from the Ecliptic pole. The final 3 years of mission will be spent on pointed observations of selected objects from the most interesting objects found. Therefore the SRG mission will effectively perform three surveys – the all sky survey, a concurrent order-of-magnitude deeper survey near the ecliptic poles and an even deeper 'blank-field' survey during long pointed observations (see Figure 10 and 11).

During these we can expect several thousands of sources to be detected by ART-XC, with about a thousand of these providing enough photons for detailed study. In the critical 6-7 keV region, the eROSITA + ART-XC ensemble has twice the effective area of eROSITA alone, more than tripling the number of AGN amenable to study.

The harder response of ART-XC relative to eROSITA also facilitates the x-ray detection of obscured AGN. The combination of eROSITA + ART-XC enables the detection of some hundreds of heavily obscured AGN, a key population that accounts for over half of all AGN.

In the all-sky survey, eROSITA will also detect over 10^5 clusters of galaxies. Although ART-XC is less sensitive to the relatively soft spectra of clusters, it will extend the SRG spectral energy range for the brighter low-redshift clusters to aid in detecting cluster temperatures, a key to estimating their mass. The sensitivity of ART-XC and eRosita in survey mode and ART-XC in pointing mode is shown in Figure 12.

Finally, during the mission's pointing phase, the ART-XC instrument will study the spectra of heavily obscured galactic X-ray binary systems and will study the broad-band spectra of various Galactic objects including binary systems, anomalous pulsars and supernova remnants up to 30 keV with sufficient good spectroscopy and timing. Further, ART-XC can study the non-thermal component in the galactic diffuse emission and perform searches for cyclotron line features in the spectra of X-ray pulsars.

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