Abstract :

This document describes the Spectrum-RG mission in general and the eROSITA instrument in particular. This document serves as basis for the planning and development of eROSITA.

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CONTENTS

1 SCOPE

This document describes the Spectrum-RG mission in general and the eROSITA instrument in particular.

A medium size satellite called "Spectrum-Roentgen-Gamma" (Spectrum-RG or SRG) will be launched in 2011 timeframe into a 600 km orbit from Baikonur. The payload includes eROSITA (extended ROentgen Survey with an Imaging Telescope Array, MPE-led consortium, Germany) with 7 Wolter-type modules, the wide field X-ray monitor Lobster (LU, UK), the X-ray concentrator based on Kumakhov optics ART ("Astronomical Roentgen Telescope", IKI, Russia) and a GRB detector (Russian consortium). High particle background on high apogee orbits severely affects the capabilities of X-ray telescopes to study diffuse emission. For the baseline configuration of the SRG mission a low earth orbit was selected to circumvent this limitation. The mission will conduct the first all-sky survey with an imaging telescope in the 2-12 keV band with the main goal to detect 100 thousand clusters of galaxies and thereafter to do follow-up pointed observations of selected sources, in order to investigate the nature of Dark Matter and Dark Energy. But also the old ABRIXAS goal is maintained, namely to discover the hidden population of several hundred thousand obscured supermassive black holes and the first all-sky imaging X-ray time variability survey. The SRG mission would thus be a highly significant scientific and technological step beyond Chandra/XMM-Newton and would provide important and timely inputs for the next generation of giant X-ray observatories like XEUS/Con-X planned for the 2015-2025 horizon.

2 REFERENCES

Applicable Documents

- SPECTRUM-RG/eROSITA/LOBSTER MISSION DEFINITION DOCUMENT

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Acronyms

- see eRO-MPE-LI-11-02_1

3 MISSION OVERVIEW

The Spectrum-RG/eROSITA/Lobster is based on a free flight mission (Russian Federal Space Program 2006-2015) with the X-ray instruments ROSITA and Lobster which were originally proposed for ISS Europe segment. The baseline configuration of the Spectrum-RG mission is defined to be as following:

- Launch in the 2011 using a Soyus-2 rocket from Baikonur into 600 km circular orbit, 28° inclination
- Medium class platform based on Navigator (Lavochkin Association, Russia).
- Payload:
  - eROSITA (MPE-led consortium, Germany), X-ray mirror telescopes;
  - Lobster (LU-led consortium, UK), wide field X-ray monitor;
  - ART (IKI, Russia), X-ray concentrator based on Kumakhov optics
  - SXC (SRON/NL, GSFC/USA, ISAS/J), X-ray Calorimeter

The mission will conduct the first all-sky survey with an imaging telescope in the 2-12 keV band to detect up to 100 thousand clusters of galaxies and thereafter to do follow-up pointed observations of selected sources in order to investigate the nature of Dark Matter and Dark Energy. A secondary (and old ABRXAS) goal is to discover the hidden population of several hundred thousand obscured supermassive black holes and the first all-sky imaging X-ray time variability survey. In addition to the all-sky surveys it is foreseen to observe dedicated sky regions with high sensitivity The proposed orbit provides an order of magnitude lower particle background than those of Chandra and XMM-Newton, which will allow the detailed study of diffuse objects with low surface brightness.

Both ROSITA and Lobster were previously studied and endorsed by ESA for the International Space Station. Their accommodation on a dedicated free flyer would provide a significantly higher scientific output. The eROSITA telescopes are based on the existing design launched on the ABRIXAS mission, and flight-ready CCDs have already been fabricated, which guarantee the high sensitivity required for the broad band all-sky survey. In order to optimize eROSITA for the additional science goal of the Dark Energy study, we increased the grasp and improved the angular resolution of the X-ray telescopes. The improved capabilities would respond to scientific developments of the last years; e.g., they match well the goals set out (By NASA, DOE, ESA, ESO and others) in the recent call for ideas on Dark Energy observations. LOBSTER will be the first imaging X-ray all-sky monitor (ASM), based on the lobster-eye wide-field-of-view telescope geometry using square-pore microchannel plates. With the advantage of focusing optics, LOBSTER will have an order of magnitude better sensitivity than previous non-imaging ASMs. LOBSTER will improve source location accuracy from a few degrees to a few arcminutes and open up the soft X-ray band (0.1-4.0 keV) to continuous monitoring for the first time. With an instantaneous field of view 162°×22.5°, it will cover almost the entire X-ray sky once per ~96 minute spacecraft orbit.

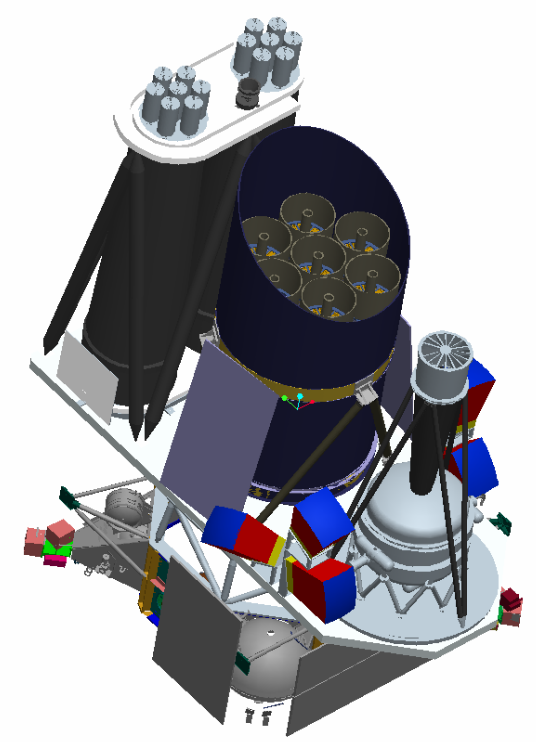


Figure 1: Preliminary SRG/eROSITA/Lobster/ART-XC/SXC spacecraft on (without solar panels.

The ART-XC is an X-ray concentrator with very narrow field of view based on glass polycapillary semi–lens (Kumakhov optics). It has no true imaging capabilities, but due to high signal to noise ratio provides an opportunity to sufficiently increase the sensitivity of the project at high energies (>10 keV). It would be very useful for follow up observations of obscured AGNs and heavily absorbed Galactic sources discovered by eROSITA during the all-sky survey phase of the mission.

SXC is a microcalorimeter operating at 50mK, and providing 6eV energy resolution. In the survey phase it will investigate the various contributions to the hot interstellar medium, in the pointed phase it is intended to to complimentary studies on clusters of galaxies.

4 SCIENTIFIC PAYLOAD

The scientific payload consists of the following instruments:

- eROSITA (MPE, Germany), Wolter-telescope, 7 mirror modules – 35 cm diameter, energy range 0.2 - 12 keV, PSF < 20 arcsec FOV averaged and < 15 arcsec on axis (at 1,5 keV) + 7 framestore pn-CCD cameras - 50msec time resolution, energy resolution FWHM 138 eV at 6 keV, effective area 2500 cm^2, a grasp of >700 cm^2 deg^2 at 1 keV; FoV = ~1° diameter.
- Lobster (LU, UK), wide field x-ray monitor, 6 modules, FOV 22.5°×162°, energy range 0.1 - 4.0 keV (TBD), angular resolution arcmin (FWHM), energy resolution ΔE/E <20%, a grasp of >104 cm^2 deg^2 at 1 keV, and a daily sensitivity better than 15 mCrab
- ART-XC – Astronomical Roentgen Telescope – X-ray Concentrator (IKI, Russia), X-ray concentrator, consist of 6 units with 6 concentrators. Energy range 5-80 keV (goal), FOV 10° × 10°, effective area >103 cm2 at 30 keV, energy resolution <1 keV at 60 keV, a grasp of 150 cm^2 deg^2 at 10 keV;

SXC – Spektr-RG X-ray Calorimeter (SRON/NL, GSFC/USA, ISAS/J), consists of 1 eROSITA Mirror Module and a microcalorimeter. Energy range 0,1 – 10 keV, energy resolution 6 eV 6 keV, 10 arcmin field of view, 350 cm^2 effective area @ 1keV.

PL mass – 1850 kg, power consumption – 1200 W.

eROSITA

eROSITA will be explained in greater detail in chapters 5 and 6.

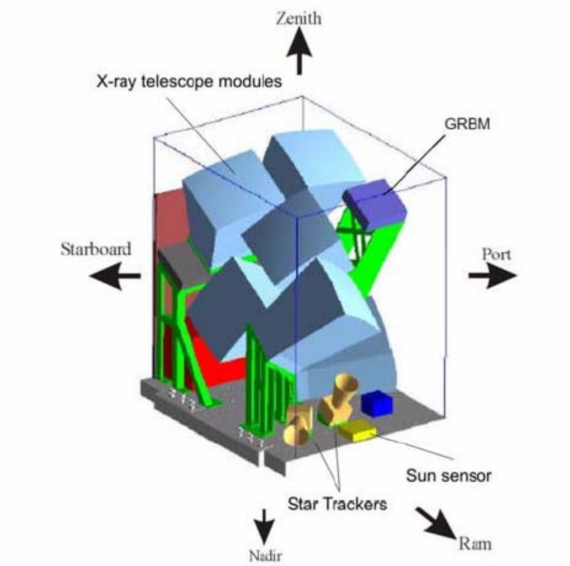
Lobster

4.1.1 Science case

The goal of Lobster, as for any ASM, is to approach the limit of "all the sky, all the time". The instrument consists of six «lobster eye» MCP telescopes, collectively providing wide angle (22.5º×162º) X-ray imaging in the 0.1-3.5 keV energy band, covering almost the entire X-ray sky once per ~96 minute spacecraft orbit. For comparison, the instantaneous fields-of-view of XMM-Newton and Chandra are less than 1 degree diameter. All-sky coverage is provided in a straightforward way by the motion of the spacecraft, whose orbital period is synchronous with the period of rotation about its axis tilted with respect to the Sun direction by 30°. The goal of the mission is to address the variability of the X-ray sky with order-of-magnitude better sensitivity (~0.15 mCrab in one day, 5σ) and angular resolution than any previous (or indeed feasible) non-imaging ASM. The scientific impact of Lobster spans all of astronomy - from studies of the X-ray emission of comets to stars and quasars, from regular X-ray binaries to erratic stellar transients (~4,000 per year at a flux level of 10^{-10} erg cm^{-2} s^{-1} and ~36,000 at 10^{-11} erg cm^{-2} s^{-1}), from the energetically gentle fluctuations in the hot outer regions of stars to the catastrophic events of supernova and the enigmatic gamma-ray bursts (GRBs - more than 1,000 GRBs per year out to $z \sim 4$). Most importantly, about 400 bright AGN will be monitored at the 20% level on a daily basis for the duration of the mission, providing the first true census of X-ray time variability in active galaxies, and providing a definitive answer as to whether characteristic timescales exist in such sources. About 30 AGN are bright enough at any given time to allow daily monitoring with Lobster to ~5% accuracy, forming a «core sample» which is ideal for multiwavelength monitoring campaigns. An important secondary function of Lobster data analysis, as with any X-ray ASM, will be to alert contemporary narrow-field-of-view X-ray observatories. The final Lobster catalogue will contain some ~250,000 sources.

4.1.2 Instrument

Lobster is an all-sky X-ray monitor comprising of six telescope modules, each consisting of approximately 60 Micro Channel Plate (MCP) optics, tiled to produce the required field of view and geometrical area. Each telescope module has a Microwell array proportional counter detector in the focal plane. Lead-glass plates of the MCP X-ray optics containing a square array of square cross-section holes or channels. The square sides are 40 mm long and the plate thickness is 1 mm. X-rays may be reflected at grazing incidence, from the inside surfaces of these channels; the reflectivity of these channel walls will be enhanced by the deposition of a nickel, gold or iridium coating. The plates, initially flat, are curved or «slumped» to a 0.75 m radius spherical figure. In this way X-rays from a distant object can be focused to a point. Each optic module is a 6×8 square array of MCP tiles and forms the top surface of a telescope module. The structure and basic parameters of Lobster are shown in Figure 2. Note that both figure and table describe the original configuration of Lobster, which was a design for deployment on the International Space Station. Final Lobster module accommodation will be optimized for deployment on a free flyer. The six telescope modules are aligned to produce a single, contiguous field of view of 22.5°×165°. The motion of the spacecraft platform sweeps this FOV around the sky once per orbit to build up the all-sky map.



Number of telescope modules	6
Number of MCP optic tiles	~60 per module
Angular resolution (FWHM)	4′
Field of view (1 module)	27.5°×22°
Energy range	0.1 – 4.0 keV
Focal length	375 mm
Reflectivity coating	Gold or Iridium
Detector principle	Microwell array
Size	20×20 cm^2
Pixelsize	200 μm diameter
Read out speed	0.1 sec
Energy resolution	~1.2 keV
Instrument mass	120 kg
Instrument Power	145 W
Data volume	~5.6 Gbit/day

Figure 2: view of the Lobster instrument and its characteristics in the original configuration designed for the ISS.

Art-XC

4.1.3 Science

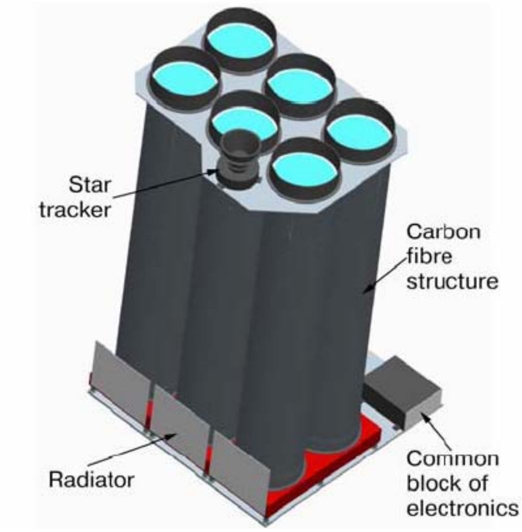
The ART-XC instrument is designed for the following tasks:

- Extend the energy coverage of the SRG observatory up to 80 keV;
- Search for heavily absorbed/Compton thick sources (both extragalactic and Galactic);
- Provide a necessary high energy extension of AGN spectra to allow detailed modeling of their spectra, including reflection component especially for AGNs discovered at survey phase of eROSITA observations;
- Provide the information on the hard tails in the spectra of galaxy clusters to constrain the strength of the magnetic fields in the inter cluster medium;
- Study broad band spectra of Galactic objects (including binary systems, anomalous pulsars, supernova remnants);
- Study non-thermal component in the Galaxy diffuse emission.

4.1.4 Instrument

ART-XC instrument is an X-ray concentrator with a very narrow field of view based on glass poly-capillary semi-lens (Kumakhov optics). Even though an X-ray concentrator has no true imaging capabilities and therefore cannot compete with grazing incident mirror instruments (which, by the way, don't work easily at high energies), it will be quite useful for pointing and survey observations. The instrument, equipped with a large area poly-capillary glass concentrator combined with a small CZT detector sensitive in the 5-80 keV energy range, would significantly improve the faint point sources spectroscopy in hard X-rays. This is of particular interest due to the recent INTEGRAL and Swift discovery of the large number of obscured AGNs and comparison of their spectra with the spectrum of the cosmic hard X-ray background. The other important areas to be explored are detection of the Ti-44 line in the supernova remnants and detailed study of high-energy cyclotron lines in the spectra of X-ray pulsars. The expected parameters of the instrument show that it could be an order of

magnitude more sensitive compared to standard coded aperture telescopes. The structure of ART-XC and its basic parameters are shown in
Figure 3. We would like to note that though glass poly-capillary lenses have been widely used in on-ground application for X-rays, there was not yet experience with space-qualified concentrators, operating at hard X-ray energies up to 80 keV. To minimize risks we are considering as fallback option a set of four coded mask telescopes based on Si and/or CZT (Cadmium-Zinc-Telluride) detectors



Number of modules	6
Concentrator	glass poly-capillary semi-lens
Field of view	46′ at 5 keV 2.8′ at 80 keV
Focal length	~1.4 m (TBC)
Effective area of optics	~1100 cm^2 at 30 keV
Detector	CZT
Energy range	5 – 80 keV (goal)
Energy resolution	≤1 keV at 60 keV
Total area of 6 detectors	≤ 4 cm^2
Total weight of instrument	280 kg
Instrument Power	180 W

Figure 3: Schematic view and basic parameters of the ART-XC instrument. It has 6 poly-capillary glass concentrators and an embedded startracker.

SXC

- The Calorimeter will provide spectral studies with unprecedented energy resolution in X-rays. In the survey phase it will concentrate on the the Hot Interstellar Medium and will be able to separate the contribution from the Local Bubble, the Disk and the Halo. In the pointed phase, it will study in great spectral details cluster of galaxies with respect to turbulences, but also densities, temperatures and element abundances.

5 eROSITA SCIENCE CASE

Dark Energy

One way to test cosmological models and to assess the origin, geometry, and dynamics of our Universe is through the study of the large-scale structure in the matter distribution and its growth with time. Galaxy clusters are ideal tracers of the large-scale structure. The galaxy cluster population provides information on the cosmological parameters in several complementary ways:

1. The cluster mass function in the local Universe mainly depends on the matter density Ω_m and the amplitude of the primordial power spectrum σ_8.
2. The evolution of the mass function f(M,z) is directly determined by the growth of structure in the Universe and therefore gives sensitive constraints on Dark Matter and Dark Energy.
3. The amplitude and shape of the cluster power spectrum, P(k) and its growth with time, depend sensitively on Dark Matter and Dark Energy.
4. Baryonic wiggles due to the acoustic oscillations at the time of recombination are still imprinted on the large scale distribution of clusters and thus can give tight constraints on the curvature of space at different epochs.

The constraints provided by the different cosmological tests with clusters are complementary in such a way, that degeneracies in the parameter constraints in any of the tests can be broken by combinations. The simultaneous constraint of Ω_m and σ_8 by combining method 1 and 3 above is one such example (Schuecker et al. 2003). In addition the combination of several tests provides important consistency checks as explained below. In addition to the above applications, galaxy clusters have been used as cosmological standard candles to probe absolute distances, analogous to the cosmological tests with supernovae type Ia:

- The assumption that the cluster baryon fraction is constant with time combined with observations of this quantity provides constraints on Dark Matter and Dark Energy (e.g. Allen et al. 2004).
- In a very similar way, combined X-ray and Sunyaev-Zeldovich-measurements provide a means for absolute distance measurements and constraints of the geometry of the Universe (e.g. Molnar et al. 2005).
- Large, well defined and statistically complete samples of galaxy clusters (which are dynamically well evolved and for which masses are approximately known) are obvious prerequisites for such studies. Substantial progress in the field requires samples of tens to hundreds of thousands of clusters. Surveys in several wavelength regions are used or planned to be used to achieve this goal.
- In X-ray surveys, galaxy clusters are detected by the radiation of the hot intracluster medium. X-ray observations are up to date still the most efficient means to provide cluster samples with these qualities, (i) since X-ray luminosity is tightly correlated to the gravitational mass (Reiprich & Böhringer 2002), (ii) because bright X-ray emission is only observed when the cluster is well evolved showing a very deep gravitational potential well, and (iii) because the X-ray emission is highly peaked, minimizing projection effects. Therefore most cosmological studies involving galaxy clusters are based on X-ray surveys (e.g. Henry 2000, 2004, Böhringer et al. 2000, 2004, Vikhlinin 2003).

The eROSITA Cluster Survey

The eROSITA flux limit of the survey in the 0.5 to 2 keV band will be ~4×10^{-14} erg s^{-1} cm^{-2} (an order of magnitude deeper than the ROSAT Survey, Figure 4) over most of the sky and about ten times deeper in the poles of the survey scan pattern. At this flux the X-ray sky is dominated by clusters and AGN, which can be separated with an angular resolution of 25". The number–flux relationship is well known to the proposed depth (Gioia et al. 2001; Rosati et al. 2002). The proposed survey will identify ~100,000 clusters. Multi-band optical surveys to provide the required photometric redshifts are already in the planning stages, and will be contemporaneous with or precede the X-ray survey. The cluster population will essentially cover the redshift range z = 0–1.5 and will reveal all evolved galaxy clusters with masses above 3.5×10^{14} h^{-1} M_{sun} up to redshifts of 2. Above this mass threshold the tight correlations between X-ray observables and mass allow direct interpretation of the data.

This sample size is necessary for example to precisely characterize the cluster mass function and power spectrum in at least ten redshift bins, to follow the growth of structure with time.

It is also needed to study in detail the biasing of the cluster power spectrum as a function of the cluster mass in order to obtain a better understanding and confirmation of the cluster mass calibration. The biasing describes the ratio of the amplitude of the density fluctuations in the galaxy cluster versus the matter distribution. This parameter can be determined theoretically as a function of mass and the comparison with observations will serve as an important calibration check.

A statistics of at least 50,000 to 100,000 clusters is necessary to reveal the baryonic oscillations in the cluster distribution power spectrum (Angulo et al. 2005).

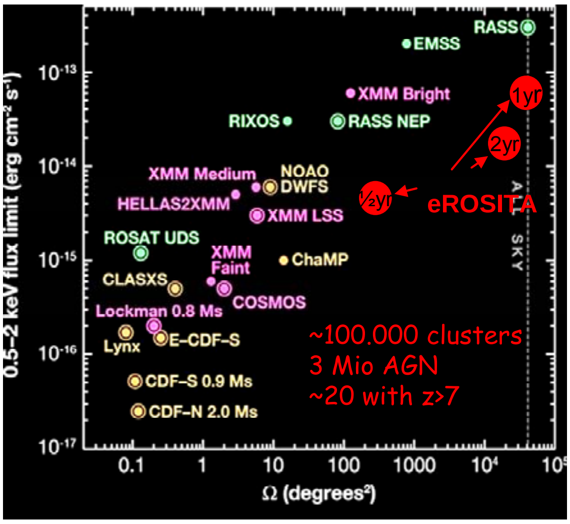


Figure 4: Sensitivity of the eROSITA galaxy cluster survey (red dots) in comparison with previous surveys.

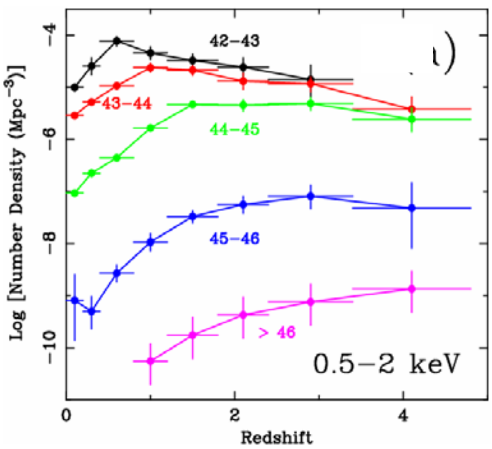


Figure 5: The luminosity function of AGN shows that low luminosity AGN occur later in the evolution of the Universe than high luminosity quasars.

Obscured AGN

The detection of all (including obscured) AGN in the local Universe was the primary goal of ABRIXAS and ROSITA before the existence of Dark Energy was realized. This is still one of the main goals of the new eROSITA mission. Deep surveys in the hard X-ray range with Chandra and XMM-Newton, in the mid-infrared with ISO and in the sub-mm with the SCUBA and MAMBO bolometers, together with population synthesis models, have shown that both the cosmic star forming rate and the black hole feeding rate were about two orders of magnitude higher in the early Universe than today (Brandt & Hasinger, 2005, Figure 5). The decline of this activity occurred at a surprisingly recent stage in cosmic history and is as yet not understood. Many hidden, but still very active black holes should be lurking in rather nearby galaxies, waiting to be detected by a hard X-ray survey.

Other scientific goals

Among many other interesting science targets are:

- Tidal disruption of a star when approaching a supermassive black hole causes a bright X-ray flare in an otherwise dull galaxy. The decay time of this flare is of the order of years.
- GRBs: According to the scan geometry, every source in the sky will be seen every half year at least 10 times in consecutive orbits for about 10 s per orbit. With a sensitivity of 40µCrab per 10 s, the GRB afterglow will be observable for two days. We expect to detect 600 afterglows during the four years of the all-sky survey.
- Large scale diffuse emission: With 30 times better sensitivity and much superior energy resolution, eROSITA will be able to perform detailed spectroscopic studies where ROSAT could yield only a four-band photometry.
- Dust scattering halos have diameters up to several degrees. eROSITA combines the advantage of ROSAT (unlimited field of view) with that of XMM-Newton (energy resolution) and provides in addition a substantially reduced pile up which hampers the observation of halos because bright central sources are needed for this kind of studies on interstellar dust.
- Recent surveys with Chandra, XMM-Newton, XTE and Integral have uncovered a large population of low-luminosity galactic X-ray sources whose nature is not yet known. eROSITA will he the definite mission to build and identify complete samples by combining X-ray variability and X-ray spectral information with specially designed optical identification programs.
- ROSAT has uncovered a small group of X-ray dim isolated neutron stars with currently seven members only. These stars are of utmost importance to constrain the equation of state in ultradense matter since they allow direct inspection of a neutron star's atmosphere. eROSITA will significantly enlarge the sample and thus provide excellent targets for detailed spectroscopy with future X-ray missions (XEUS).
- Stellar Coronae: The source population at low galactic latitudes is dominated by stars. We expect to identify these by their relatively soft spectrum. Subjects for eROSITA are, e.g. time variability on short, intermediate and long timescales, which can be assessed only by means of an all-sky survey.
- X-ray Binaries: This class contains the brightest X-ray sources in the sky.
- Supernova Remnants: The advantage of an all-sky survey is its unlimited FoV which allows the precise mapping of large objects, as e.g. Supernova remnants.

6 INSTRUMENTAL CONCEPT

eROSITA X-ray optics

The mirror replication technique was developed for XMM-Newton (an ESA Cornerstone Mission launched in 1999) and has then been applied to ABRIXAS, which had scaled the

XMM-Newton telescopes down by a factor of about 4. The ABRIXAS optical design and manufacturing process are adopted for eROSITA partially because the inner 27 mirror shells and therefore the focal length are kept the same. The mirror system consists of 7 mirror modules with 54 mirror shells each and a baffle in front of each module. Unlike on ABRIXAS, the seven optical axes are co-aligned (Figure 7). Compared to a large single mirror system, the advantages of a multiple mirror system are: shorter focal length (reduced instrumental background), smaller mirror shells (easier to handle), and reduced pileup when observing bright sources. This configuration allows a more compact telescope and multiple but identical cameras which automatically provides a 7-fold redundancy.

The mirror shells are manufactured by replication from super-polished mandrels. The reflective layers of gold copy the surface of the mandrel to get the required X-ray optical quality. The carrier material of the reflecting surface is electroformed nickel. The wall thickness of the mirror shells varies between 0.25 and 0.45 mm. All shells are adjusted and bonded to a supporting spider wheel. The capabilities of the X-ray mirror system are described by effective area, vignetting function, and PSF. Since the entire FOV is used for the surveys, the measure for sensitivity is the product of the FOV-averaged effective area and the solid angle of the FOV ("grasp"). The characteristics are described in Table 1.

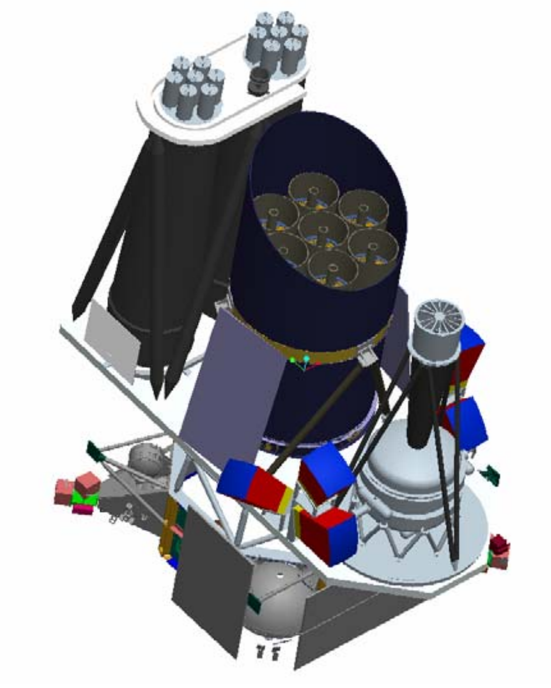


Figure 6: Spectrum-RG with the Navigator-spacecraft and the payload comsisting of ART-XC, eROSITA, SXC (from left to right) and 5 modules of LOBSTER.

Figure 7: The seven mirror modules with the baffles in front and the seven cameras at the rear end of the optical bench. Total length of the telescope is <2,600 mm, the diameter is ~1,300mm.

Table 1: Telescope parameters

mirror modules	7
mirror shells per module	54
energy range	0.2 < E < 12 keV
angular resolution @ 1,5 keV	< 15'' on-axis

grazing angles	16' < α < 96'
wall thickness	0.2 – 0.45 mm
microroughness	< 0.5 nm RMS
mirror coating	Au (> 50 nm)

outer diameter	356 mm
inner diameter	76 mm
length of shells	300 mm

focal length	1,600 mm
weight of mirror module	< 50 kg
material of shell	Nickel

A stray light preventing system has to be developed including telescope baffles and the 100 nm aluminium blocking filter on the CCD. The worst case analysis indicated the visible photon background was 1×10^{-2} photons/s/pixel. This provides a margin of 5×10^{4} during the worst case observations in a direction only 13 degrees to the illuminated Earth limb. Scattered light due to solar illumination of the baffle interior was significantly lower. Less than about 180 mm of the outer part of the baffle is illuminated by the Sun in the worst case (60° to the telescope axis). The baffle tubes are thermally isolated from the temperature controlled mirror modules by GFRP isolations, preventing distortion from solar heating. An additional X-ray baffle (cylindrical shells) will reduce the amount of single reflections from the rear end of the hyperboloid, if a bright source is just outside the field of view. The mirror system must be maintained at 20 ±2 °C during operation to avoid deformation and image degradation.

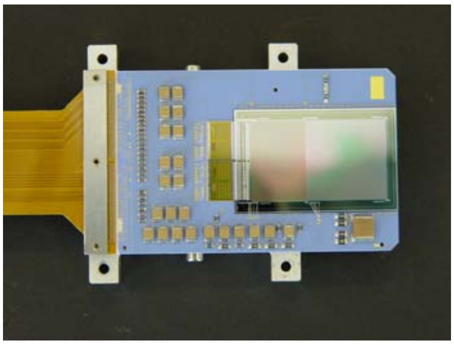


Figure 8: eROSITA CCD-Module. The CCD with its image area (3×3 cm^2) and the slightly smaller frame store area (left) is connected via 384 bond wires with three CAMEX read out chips. They are mounted, together with the (passive) front end electronics, on a ceramic printed circuit board (blue). The flexlead on the left connects the CCD-Module with the experiment electronics. Shown is the older 3×3 cm^2 version with 256×256 pixel.

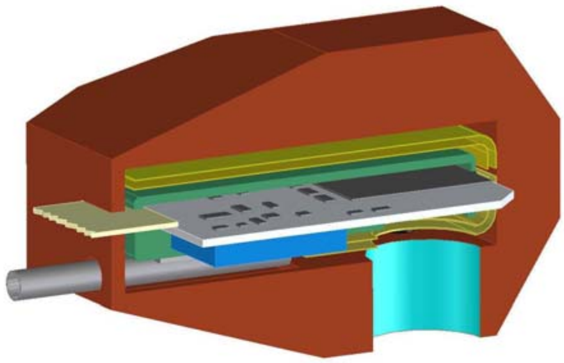


Figure 9: Schematic representation of the eROSITA Camera with the (warm) Cu-proton shield (brown), the thermal insulation (yellow), the housing (cold, green), and the CCD-Module (grey) which is thermall connected to heatpipes by a Ti-block (blue). An additional graded shield (magenta) suppresses fluorescent X-rays generated in the housing and leading to an enhanced background.

eROSITA Camera

Since more than 17 years, our semiconductor laboratory manufactures radiation sensitive detectors for space applications. Outstanding achievements are the pn-CCD-camera onboard XMM-Newton and the sensors operating on the Mars-rovers Spirit and Opportunity.

The pn-CCD camera onboard XMM-Newton (Pfeffermann et al. 2003) works without reduction of its performance since more than six years. During the recent years we have further improved the concept (Meidinger et al. 2006):

- The CCD has been extended by a frame store area which allows the fast shift from the image area in order to reduce so called out-of-time events, photons which are recorded during charge-transfer.

- The pixel size has been reduced to 75µm which fits best to the resolution of the eROSITA telescope.
- The use of 6inch silicon wafers with 450µm thickness gives higher quantum efficiency at higher energies.
- The low energy response and energy resolution could be improved by a modification of the wafer-processing. At the same time, the operating temperature can be now as high as -60°C (XMM-Newton: -90°C). However, we conservatively aim for a temperature of -80° because we do not yet have an experience with radiation damages in a low earth orbit (SAA!).

Each of the seven mirror modules has its own camera in its focus, each equipped with a CCD-Module and a processing electronics. The eROSITA-CCD has 384 × 384 pixels or an image area of 28.8mm × 28.8mm, respectively, for a field of view of 1.03° diameter. The 384 channels are read out in parallel by three modified CAMEX-ASICs (Figure 8). The nominal integration time for eROSITA will be 50msec. The integrated image can be shifted into the frame store area by less than 100µsec before it is read out within about 5msec. CCD together with the two CAMEX and the (passive) front-end electronics are integrated on a ceramic printed circuit board (= CCD-module) and is connected to the "outer world" by a flexlead. A flight-batch of more than 70 CCDs has been already fabricated. The CCDs are tested and parameters have been studied in detail in our semiconductor lab. The CCD-module is already designed, fabricated, tested, and qualified (thermal vacuum, vibration). A prototype of the eROSITA camera is already installed in the PANTER X-ray test facility as a new "working horse".

The design of the camera housing follows particular thermal constraints in order to reduce parasitic thermal loads (Figure 9). While the active load (primarily CAMEX) is 0.67W, the total heat load is of the order of 2W per camera. A temperature control maintains the stability of the CCD-temperature within ± 0.5K. The CCD is shielded against particle radiation by a massive copper plate on both sides. Fluorescence X-ray radiation generated by cosmic particles is minimized by a graded shield consisting of aluminium and boron carbide. For calibration purposes, each camera housing contains a radioactive Fe^{55} source and an aluminium target providing two spectral lines at 5.9keV (Mn $K\alpha$) and 1.5keV (Al $K\alpha$). The mechanism for moving the calibration source into and out of the field of view is adopted from an earlier rocket flight experiment. The design of the housing has been finished, and we are now preparing the engineering model.

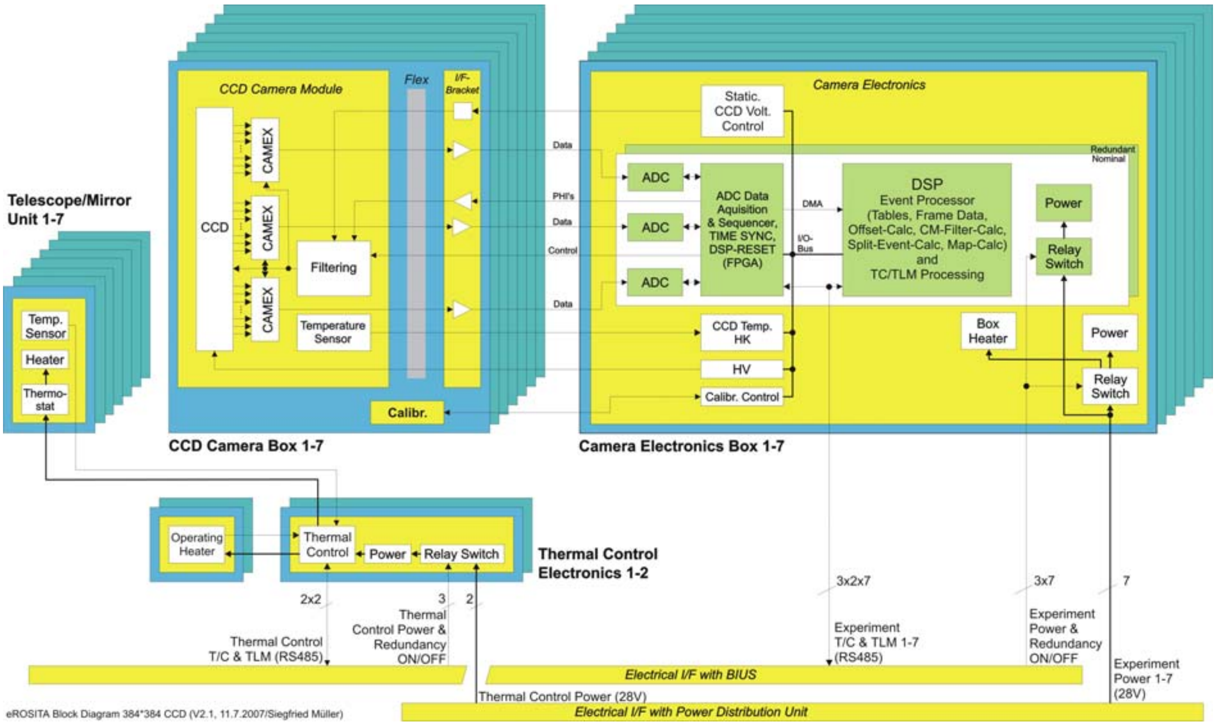


Figure 10: Scheme of the Camera Electronics. Each camera has its own (but identical) electronics. The critical part of the electronics (ADC, FPGA, DSP) is (cold) redundant. An 8th electronics box is for thermal control of the instrument.

The experiment electronics, separated in seven electronics boxes has the following tasks:

- A "sequencer" consisting of a FPGA logic provides the correct timing signals for CCD, CAMEX and the two ADC.
- Two 14-bit ADC for each CCD-module digitize the CAMEX output signal.
- The main event processing is performed by a DSP. This comprises the subtraction of an offset-map, the correction of common modes, the application of pixel-wise thresholds using a previously stored noise map, and the delivery of event data frames to the controller. The DSP acts also as control unit, which collects telemetry information (both, events and housekeeping), executes commands, and forms the interface to the S/C.
- The critical components of the electronics (ADC, FPGA, DSP) are on one single circuit board; this is (cold) redundant.

Since the radiation load in low inclination, low earth orbit is rather low, we plan to use components which are qualified according to MIL883 as far as possible (not rad. hard).

The complete electronics exists and works already as breadboard model for TRoPIC (Third Roentgen PANTER Imaging Camera) in our long beam test facility.

The average data rate is determined by the brightness of the extragalactic sky background. We assume to detect between 30 and 40 photons per second (all modules). Since most of the detected photons produce charges in more than one pixel (split-events), and each event is coded using 30 bits, we will have ~ 3.6kbit/s. With some overhead and together with HK data, the data rate will be below 10kbits/s. A bright source (e.g. Cyg X-2) will increase this number to 100kbits/s, for a short time.

Commanding of the eROSITA cameras is simple because only a few operational modes are implemented:

- Standby: camera completely switched off, survival heaters are controlled by S/C.
- Checkout, Test: Electronics switched on, CCD still off.
- Normal: camera is completely switched on and working; this includes also calibration.

Thermal Control

Two radiators facing to opposites sides will be used for cooling the CCD-Modules down to -80°C ± 0.5°. They are connected to “cold storage” by variable conductance heatpipes which to switch between the two radiators. The cold storage uses the melting enthalpy of a liquid which freezes at -81°C in order to bridge short (~ 20 minues) phases where none of the radiators is capable to provide sufficient cooling powar, particularly in spring and fall.

Additionally heaters on the mirrors will keep their temperature at 20°C ± 2°. Survival heaters in the Focal Plane Assembly guarantee a minimum survival temperature. Both thermal systems will be controlled by a Thermal Control Electronics which forms the 8th electronics box of eROSITA.

Telescope Structure

The optical bench connects the mirror system and the baffles on one side with the focal plane instrumentation on the other side. Additionally it forms the mechanical interface to the S/C bus. It has to meet the tough requirements concerning cleanliness, particularly dust. For this reason the telescope contains a front cover which is closed during ground operations and liftoff. The stiffness of the structure requires particular emphasis because the weight of the telescope is dominated by the mirror system which is far above the S/C structure. The dimensions of the telescope structure will be of the order of 1.3 m diameter x 2.6 m height. The total weight of eROSITA is specified to 660 km maximum. The design shall ensure a first eigenfrequency higher than 40 Hz and aim at a mass of less than 100 kg. Several alternative design concepts are currently studied in parallel, both aluminium and CFRP structures are included in the investigation. The design of the telescope structure is currently studied by several studies running in parallel. Part of the telescope structure is the front door, which serves as contamination shield during ground operation and liftoff. In orbit, it will be opened only once and serves then as sunshield in order to prevent direct sunlight entering the baffles.

Sensitivity Calculation

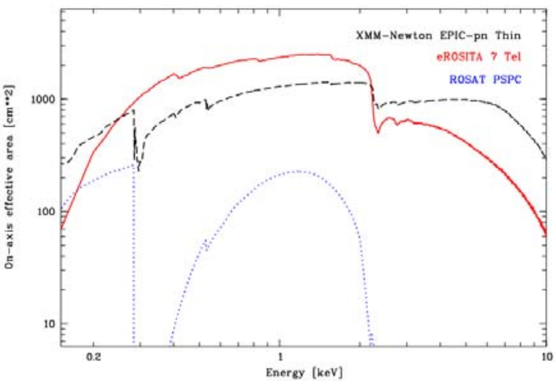


Figure 11: On-axis effective area of eROSITA (red

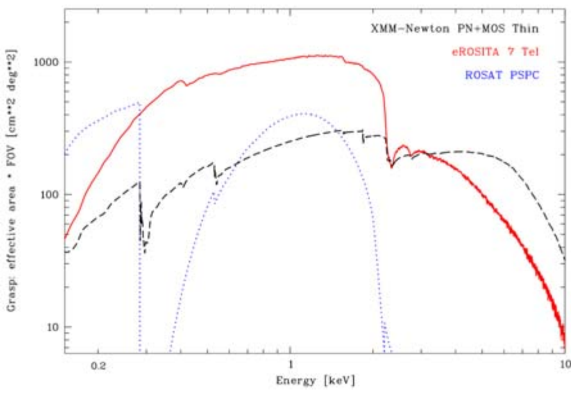


Figure 12: Grasp of eROSITA (red) in comparison

line) in comparison with one XMM-Newton telescope (black) and the ROSAT-PSPC (blue).

with one XMM-Newton telescope (black) and the ROSAT-PSPC (blue).

Figure 11 shows the expected on-axis effective area of all seven eROSITA telescopes in comparison with XMM-Newton and ROSAT, Figure 12 the grasp, i.e. the product of effective area and solid angle of the field of view. The effective area of eROSITA is about twice that of one XMM-Newton telescope in the energy band below 2keV, whereas it is three times less at higher energies. This is a consequence of the small f-ratio (focal length vs. aperture) of the eROSITA mirrors. An advantage of the short focal length is the low instrumental background (per solid angle) and a larger field of view. Since the effective area is split into seven telescopes, also pile-up is less than with a single telescope having comparable area. The eROSITA angular resolution (averaged over the field of view) is better than that of ROSAT due to the smaller field of view and the better spatial resolution of the frame store pn-CCD than that of the ROSAT-PSPC. Furthermore, we will scan for four years (ROSAT 1/2 year). Therefore the eROSITA sensitivity during this all-sky survey will be approximately 30 times ROSAT. When extrapolating from the ROSAT results, we expect to detect 3.2 million AGN and 86,000 clusters of galaxies in the extragalactic sky (see Table 2).

Table 2: Sensitivity calculation for all-sky survey

collecting area (7 Tel., 1.5 keV)	2,471 cm^2
field of view (single telescope)	41 arcmin x 41 arcmin
mean vignetting	0.70
spatial resolution (detector)	0.075 mm
angular resolution telescope	< 25 arcsec
solid angle all-sky survey	41,253 deg^2
survey duration	4 years
observing efficiency	0.9
mean exposure time per FoV	1342 s

BKGR countrate, total	16.35 counts/s
BKGR countrate, particles	<0.15 count/s
sensitivity 0.5-2 keV AGN	$9 \cdot 10^{-15}$ erg cm^{-2} s^{-1}
2-10 keV AGN	$1.5 \cdot 10^{-13}$ erg cm^{-2} s^{-1}
0.5-2 keV Clusters	$4 \cdot 10^{-14}$ erg cm^{-2} s^{-1}
detected sources:	
0,5-2 keV AGN (10 cts)	3,200,000
2-10 keV AGN (10 cts)	180,000
0,5-2 keV Clusters (50 cts)	86,000

7 OBSERVING STRATEGY

The scientific goals required originally a variety of mission phases and observing modes, respectively:

- All-sky survey, i.e. a continuous scan with one revolution per orbit
- Extragalactic survey (survey with variable scan speed)
- Deep Survey
- Pointed observations

In order to keep S/C operations as simple as possible, we will combine the three surveys into a single one with a rotation axis which is tilted with respect to the Sun: a simple geometry having this rotation axis facing towards the Sun (ROSAT, ABRIXAS) would lead to an overlap of all great circles at the ecliptic poles. Tilting the rotation axis towards the galactic plane would automatically give the extragalactic sky a higher exposure with a rather deep exposure closer to the galactic poles (Figure 13 and Figure 14). A tilt of <30° away from the Sun seems to be compatible with other constraints, e.g. the minimum Sun angle. A precession of the rotation axis will distribute smoothly the exposure time over a region of 200 deg^2 around the survey poles.

- **This combines the three survey in one (scanning!) all-sky survey.**

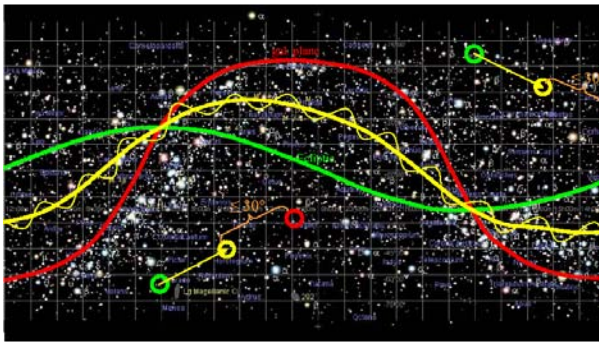


Figure 13: Galactic equator and poles (red line and circles, respectively) and ecliptic equator and poles (green), and the scan geometry (yellow).

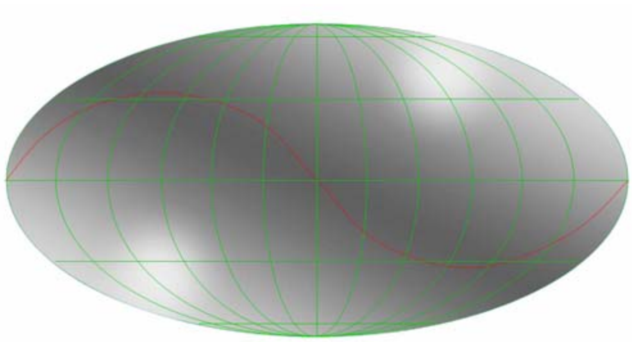


Figure 14: Exposure map for the scan geometry described in Figure 13. The red line represents the galactic plane. The deepest exposure corresponds to the areas where all great circles overlap.

8 LAUNCH VEHICLE

Soyuz

- A Soyuz launch vehicle is proposed for the delivery of SRG project. The total mass incl. FREGAT is 8100 kg, for Baikonur, 51.5° inclination. FREGAT will be used also to reach a 30° orbit.

FREGAT payload assist module

For the final insertion of SRG S/C into the operational orbit "Fregat Payload Assist Module" (Figure 15) will be used in case of Baikonur or Kourou (as option). Three stages of the Soyuz launch vehicle put Fregat upper stage with spacecraft onto a low (200 km height) parking circular orbit. In case if Baikonur is chosen as launch site to put the S/C onto 600 km orbit, then minimum achievable inclination taking into account required payload mass is 30 degrees. This change in inclination requires approximately 130 kg fuel per 1°. Only Kourou launch site is possible for near equatorial 600 km height operational orbit, taking into account a minimum acceptable mass of payload on target orbit. Very big excessive mass is left (5215 kg including Fregat) which can be used for launching an additional payload (for example 800 kg onto geostationary orbit).

Height (m)	1.5
Diameter (m)	3.35
Dry mass (kg)	970
Total mass with propellant (kg)	6635

Figure 15: FREGAT Payload Assist Module (PAM), with its basic parameters

Final S/C orbital parameters.

- height 580-600 km
- inclination <30° for Baikonur
- orbit period 96 min
- maximal shadow duration 27 min for Baikonur
- S/C total mass 2180 kg

Platform

A medium class platform Navigator (Lavochkin Association, Russia – under development) will be used for the project.

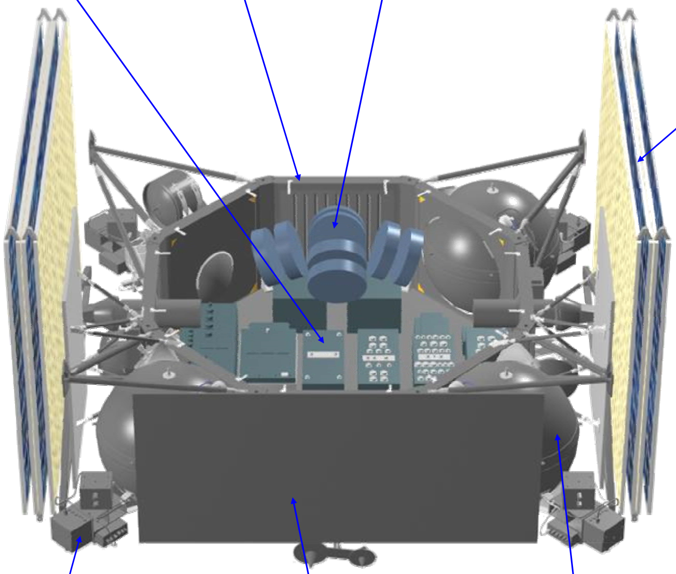


Figure 16: Schematic view of Navigator

Life in orbit	5 years
Mass total	2150 kg
Mass payload	1250 kg
Power payload	600 W
Pointing mode	
Accuracy	15″
Stabilization	5″
Stabilization rate	1″/s
Scanning mode	
Pointing accuracy of axis of rotation	1′
Max slew rate	20°/min

Figure 17: Main characteristics of the platform needed for SRG

9 GROUND SEGMENT

- S/C Flight Control Center in Moscow (RSC Energia, Korolev or Lavochkin Association, Khimki, Russia);
- Ground Station is tbd.

10 CONCEPT JUSTIFICATION

Mirrors

The main scientific goal, which drives the design, is the X-ray detection of 100,000 clusters of galaxies. This requires a combination of telescope grasp, angular resolution and mission duration. The angular resolution of 25 arsec which is needed to distinguish (extended) clusters from (pointlike) AGN can be achieved only by means of Wolter-I telescopes. Starting with the already existing ABRIXAS design, we had to extend the mirrors by adding outer shells. This gives us a factor of 7 more collecting power at energies around 1-2 keV, exactly the range where clusters are best found. At higher energies we will stay with the ABRIXAS performance. This concept allows use of the already existing mirror hardware (mandrels). Some parameters, e.g. focal length, are fixed.

Camera

After XMM-Newton, the development of detectors went on in our semiconductor lab. Now we can use a technology which fits better to the need of eROSITA (pixelsize, framestore, readout speed, low energy response etc.). On ABRIXAS the seven telescopes shared 1 pnCCD camera (6cm×6cm). The new CCDs have a size which matches the FoV of a single telescope. eROSITA will contain 7 individual but identical cameras instead of only one. This provides a high degree of redundancy but gives us also more flexibility in the co-alignment of the 7 telescopes. We have decided to align them in parallel in view of the pointed observations in the later phase of the mission.

Spacecraft

SRG seems to be an excellent opportunity for putting eROSITA into space. A free flyer gives much less constraints on operation, cooling of the CCDs etc. than the previously studied ISS-version. Among the payload, eROSITA puts the most stringent constraints and requirements onto the spacecraft and its operation. All of these have been understood and accepted by our Russian partners.