Status of x-ray imaging and spectroscopy mission (XRISM)

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ABSTRACT

The X-Ray Imaging and Spectroscopy Mission (XRISM) is the successor to the 2016 *Hitomi* mission that ended prematurely. Like *Hitomi*, the primary science goals are to examine astrophysical problems with precise high-resolution X-ray spectroscopy. XRISM promises to discover new horizons in X-ray astronomy. XRISM carries a 6 x 6 pixelized X-ray micro-calorimeter on the focal plane of an X-ray mirror assembly and a co-aligned X-ray CCD camera that covers the same energy band over a large field of view. XRISM utilizes *Hitomi* heritage, but all designs were reviewed. The attitude and orbit control system were improved in hardware and software. The number of star sensors were increased from two to three to improve coverage and robustness in onboard attitude determination and to obtain a wider field of view sun sensor. The fault detection, isolation, and reconfiguration (FDIR) system was carefully examined and reconfigured. Together with a planned increase of ground support stations, the survivability of the spacecraft is significantly improved.

Keywords: X-ray, X-ray Astronomy, microcalorimeter, CCD

1. INTRODUCTION

After the generation of baryons in the Big Bang Universe, hot plasmas traced the flows of energy and matter, and played a crucial role in the formation of every celestial structure in the universe. *Hitomi*[1] (formerly ASTRO-H), demonstrated the potential of high-resolution X-ray spectroscopy with imaging. By observing hot plasma emission, *Hitomi* succeeded in precisely measuring the kinetic energy or physical state of cosmic hot plasmas.[2–8]

Initial results from *Hitomi* showed the potential for transformative science. For example, measurement of energy shifts or line broadening enables precise determination of velocity and dynamic pressure in cosmic plasmas. The X-ray microcalorimeter can constrain the Doppler broadening in the iron-K emission line to an accuracy of $\sim$ 50 km s^{-1}. *Hitomi* revealed the velocity of plasmas in clusters of galaxies and various X-ray objects.[2,3,8–11] The high energy resolution with high throughput leads to unprecedented high sensitivity to the spectral features. The comparison of emission line measurements of the elements, including rare metals, with theoretical calculation, reveals the state of chemical evolution in the source.[4,12–14] A mechanism for X-ray emission, reflecting the physical condition in the source, can also be examined by performing diagnostics in the fine structure of lines.[6,7] Furthermore, the state-of-the-art microcalorimeter is the ideal tool for observing charge exchange, resonance, and Compton scattering in cosmic plasmas.[5]

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XRISM was proposed as the *Hitomi* recovery mission and initially called the X-ray Astronomy Recovery Mission. It carries identical soft X-ray telescopes as those onboard *Hitomi*. The scientific objectives of XRISM are similar to those of *Hitomi*. XRISM shall provide a multi-faceted tool for revealing material circulation and energy transfer in cosmic plasmas, and elucidating cosmic structures and evolution.

The four science objectives for XRISM to explore are as follow:

1. Structure formation of the universe and evolution of clusters of galaxies;
   Galaxies and clusters of galaxies are formed in dark matter halos and evolve into the large scale systems through collisions and mergers. The enormous gravitational energy is released into thermal energy through the kinetic motion of the hot plasma in the systems. XRISM measures the plasma velocities to reveal the processes and the hidden energy flow channels in the structure formation.

2. Circulation history of baryonic matters in the universe;
   Supernovae remnants inject thermal and kinetic energy, heavy elements, and high energy cosmic rays into the interstellar and intergalactic space. Thus these objects play an essential role in constructing variety in the universe. The explosions dissipate energy and elements through the gradually thermalized optically thin plasma. Therefore the plasma diagnosis with the high-resolution X-ray spectroscopy is ideal for revealing dissipation and circulation of baryonic matter in the universe.

3. Transport and circulation of energy in the universe;
   The co-evolution of galaxies and their central supermassive black hole is one of the most central modern astronomy themes. Although the concept of "co-evolution" is widely accepted, the mass feeding mechanisms onto the supermassive black hole from the host galaxy is still a missing piece of the puzzle. XRISM with the capability to measure the iron-K emission line energy in the accuracy of ≤ 200 km s^{-1} resolves velocity fields in the accreting matter, leading to understanding the mass feeding structure surrounding the supermassive black hole. Furthermore, outflows, including jets and disk winds, from black holes or other compact objects, are also important for understanding energy transportation and energy circulation in the universe. XRISM measures the hot plasma flows in the spectral absorption features.

4. Promote new science endeavors with unprecedented high-resolution X-ray spectroscopy.
   The high-resolution spectroscopy extracts information on the physical state of plasmas that we could not obtain so far. For example, the plasma diagnosis of the fine spectral features enabled by XRISM, provides understanding of the plasma ionization history. The high-resolution spectroscopy can probe gravitational redshifts in relativistic objects. These new observable properties will expand new areas of astrophysics.

XRISM will fulfill these scientific objectives with the high-resolution X-ray spectroscopy with imaging by observing the fine structure in the X-ray spectra and the spatial distribution of cosmic plasmas.[15]

2. SPACECRAFT

2.1 The orbit and operations

Figure 1 shows the schematic view of the spacecraft. XRISM will be launched into a circular orbit with an altitude of 575 ± 15 km and inclination of 31 degrees by a JAXA H-IIA rocket. The satellite operation is conducted at the Sagamihara Satellite Operation Center of ISAS/JAXA, utilizing the ground station at the Uchinoura Space Center (USC), Japan. The spacecraft on the near-earth orbit circulates the earth for 96 minutes and contacts the ground station, USC, on 5 out of the 15 orbits a day. *Hitomi*, having employed only USC, inevitably had ten successive remote orbits. For ~ 15 hours, *Hitomi* did not have ground support. XRISM will employ the JAXA global network (GN) stations and the NASA near-earth network (NEN) stations in addition to the nominal operation station USC. The additional GN and NEN stations covering the remaining ten orbits that will be used to monitor the spacecraft essential status. The monitoring is carried out with the Automatic Telemetry Monitor Software (ATMOS) developed for the telemetry data in JAXA standard format from the Center for Science-satellite Operation and Data Archive (C-SOCDA) of ISAS/JAXA. According to users rules, the ATMOS monitors and evaluates each telemetry data and warns the operation staff to detect any anomaly. The additional

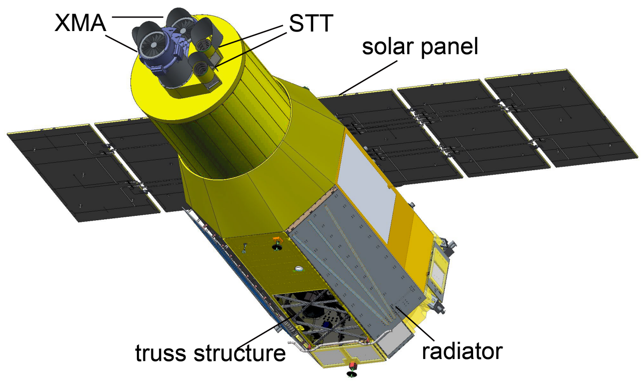

Figure 1. Shematic view of XRISM

Table 1. Key parameters of spacecraft

Launch site	Tanegashima Space Center, Japan
Launch vehicle	JAXA H-IIA rocket
Orbit type	Approximate circular orbit
Altitude	575 ± 15 km
Orbit inclination	31 degree
Dimension	7.9 m $\times$ 9.2 m $\times$ 3.1 m
Mass	2.3 tons
Design Life	≥ 3 years

network stations with ATMOS support reduces the ground support response time down to ≤ 96 minutes or two orbits in the worst case, and improves on spacecraft survivability even in unexpected emergencies.

Science operations will be similar to those of *Suzaku*. The basic pattern is to point to an object during the planned exposure time and then slew to the next target. Referring to specific target objects observed with *Suzaku*, whose orbital elements are similar to those of XRISM, each typical observation of XRISM is expected to require from one to a few days. Therefore each observation command plan will be uploaded during the daily contacts of the USC station. The XRISM Mission Operation Team of JAXA is in charge of the satellite operation by commanding and data downlink. Collaborating with the Mission Operation Team, the XRISM Science Operations Team (SOT), consisting of dedicated duty scientists, is in charge of observation planning, science data processing, distribution, archiving, and user support. The XRISM SOT consists of members from the three agencies; XRISM Science Operation Centre in JAXA, XRISM Science Data Center in NASA, and members from the European Space Astronomy Centre of ESA. The detailed description of the science operations is shown in two separate papers.[16,17]

The current plan is to use the first three months for commissioning and check-out, and to start the Performance Verification phase. During this phase, the data rights belong to the XRISM Science Team with a limited number of XRISM Guest Scientists, which will be invited by the three space agencies. Guest observing time will commence ~ 9 months after the launch. The three agencies will call for proposals for guest observations from the worldwide astronomical community. The nominal observation phase is defined to last for three years after the launch.

2.2 Configuration of the spacecraft

To recover the mission promptly, efficiently, and reliably, the *Hitomi* basic design was adopted for XRISM, but with the removal of the hard X-ray mirrors and imagers mounted on the extendable optical bench, and the soft gamma-ray detectors mounted outside the spacecraft. As shown in Figure 1, XRISM is equipped with two sets of co-aligned X-ray Mirror Assemblies (XMAs), and two sets of star sensors (Star Trackers: STT) to

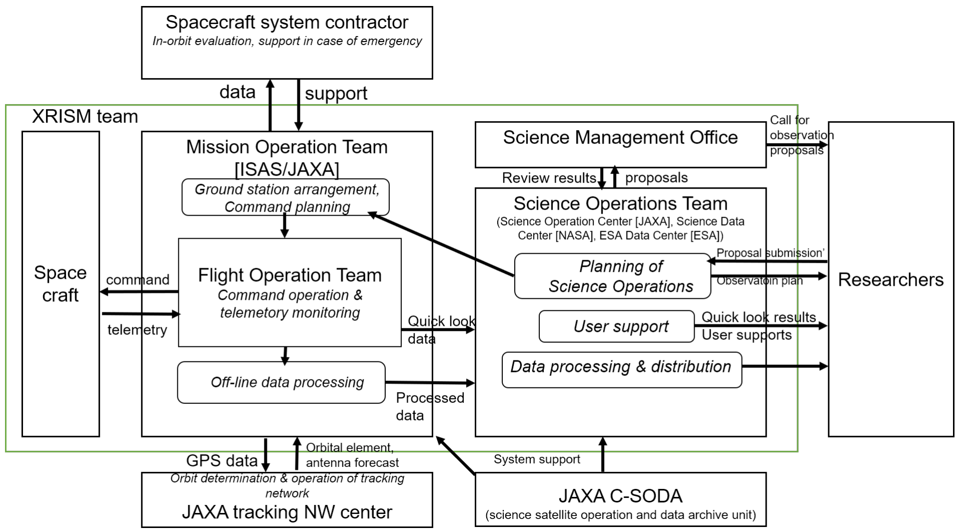

Figure 2. Organizations for the science opearations.

the right of the XMAs. Behind the central XMA, we see part of the sunshade from the third STT. The side panels, equipped with electronics inside, shape an octagonal pillar. The two sets of science instrument detectors sit on the spacecraft base plate and are surrounded by the side panels. On the side panel opposite the black solar panel arrays, is a truss structure between two grey thermal radiators. The dewar containing the X-ray microcalorimeter is installed beyond the structure, facing anti-solar direction and performing effective radiation cooling through the dewar surface and its radiators connected heat pipes. The CCD camera of Xtend is placed inside the spacecraft and connected with its radiator via two heat pipes.

Figure 3 shows the function block diagram of XRISM. The bus system mainly consists of the power supply subsystem, the communication and data handling subsystem, and the attitude orbit control subsystem. The above right portion of the figure shows electronics for science instruments. As the primary design policy, we require the spacecraft bus system to be designed to be one-fail-operative. According to the policy, almost all the bus electronics components configure redundant systems, as indicated with overlapped rectangles. The exceptions are only the electronics for the Global Positioning System Receiver (GPSR) and the X-band transponder. They are single systems, but functionally redundant with the on-ground time assignment / orbit determination systems or S-band communication.

3. ATTITUDE CONTROL SYSTEM

XRISM is a three-axis stabilization satellite pointing at a celestial object with telescopes and fixed solar panels facing the sun. Therefore, the attitude and orbit control system (AOCS) is crucial for both the mission and spacecraft survival. The AOCS is composed of attitude sensors, data processors, and actuators.

The attitude sensors consist of four independent components: digital sun sensors (DSSs), geomagnetic attitude sensors, inertial reference units, and the STTs. The solar panels are fixed to the spacecraft and restrict attitude operation to keep the normal against the sun inclination angle within 30 degrees on orbit. The DSS measures the sun-angle against the solar panels to maintain the power generation. The linear measurement range is a ± 64 squared degree region. The area is much broader than that of *Hitomi*, to cover the sun inclination angles with enough margin. The pointing accuracy is assured by the attitude determination using the star sensors (STTs) installed on the top plate with the XMAs. Figure 4 shows the STTs fields-of-view and avoidance angles for interfering light from Earth albedo. The view centers are offset from the normal of the top panel by 12 degrees, and the position angles of STTs are separated by 120 degrees. With this configuration, the STTs cover a broad field of view, avoiding the earth occultation to realize a long time coverage for the attitude determination with

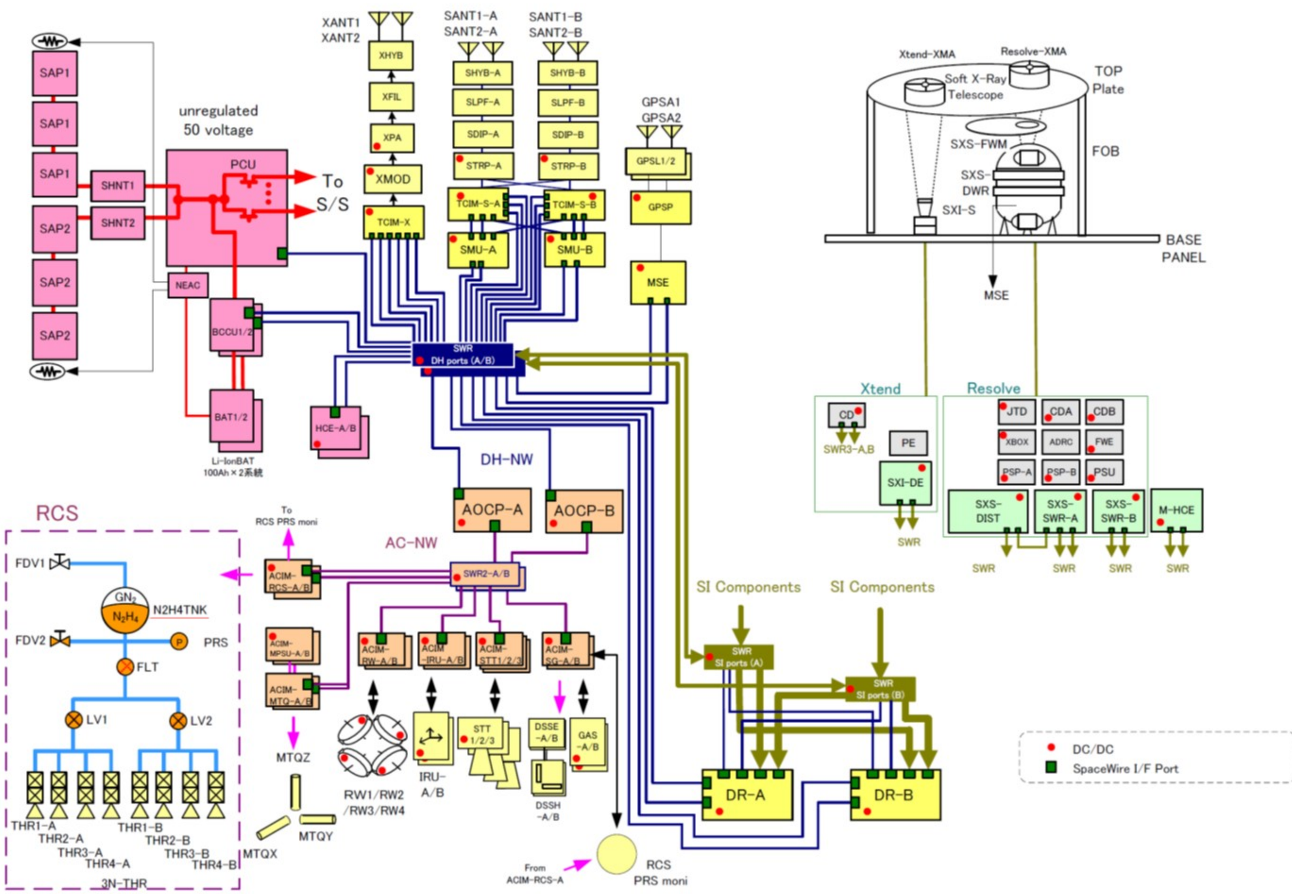

Figure 3. Function block diagram of XRISM

STTs. Also, simultaneous measurement with two or three STTs increases attitudes determination accuracy down to ≤ 20 arcsecond through the on-ground attitude determination process.

The actuators are reaction wheels and thrusters (reaction control systems). The former is the primary actuator to stabilize or point the telescopes to the target, while the latter points the satellite at the first sun acquisition after the satellite separation and at emergency safe hold operation. The magnetic torquers dissipate angular momentum accumulated in reaction wheels.

In addition to the regular attitude control operation and debris avoidance maneuver, one of the most crucial functions of the data processor on the attitude control system is the Fault Detection Isolation and Reconfiguration (FDIR) system. The FDIR system consists of four layers, as summarized in Table 2. Each component employs reliable parts (level 4) error detection and correction system in the data transfer lines (level 3). Also, the RMAP/ SpaceWire network protocols assure the communication between components (level 2). The Attitude and orbit Control Flight Software (ACFS), installed in the data processor, watches both the hardware and inter-component consistency by comparing the sensor output values. Once hardware error or inter-component inconsistency is detected, the ACFS switches the whole system to the redundant side (level 1). The lower level hardware/system detects a definite abnormality in each component quickly and automatically switches to the redundant system. On the contrary, at the higher level, the ACFS detects inter-component inconsistency to isolate and reconfigure the AOCS. By separating each level of fault detection and reconfiguration function, the system avoids congestion and a chain of abnormality faults.

The AOCS FDIR process is triggered in cases as follows.

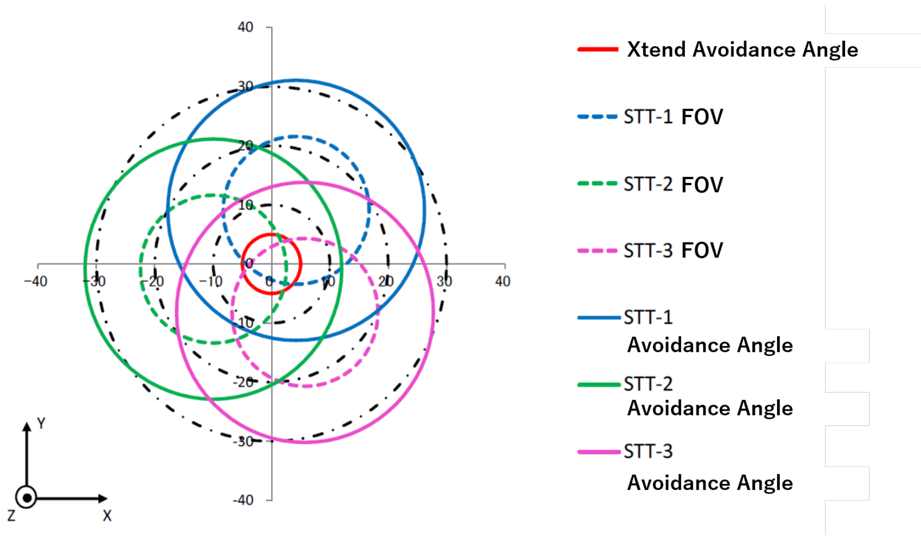

Figure 4. The fields-of-view and avoidance angles for interfering light of the three STTs and the avoidance angle of Xtend.

Table 2. FDIR levels in the attitude control system

1	subsystem	Fault detection by watching hardware status, and reconfiguration by ACFS.
		Both component self-check and inter-component consistency checks are equipped.
2	network	Detection of communication error in the SpaceWire packet or RMAP protocol.
3	computer	Memory error detection by EDAC, watchdog timer for auto reconfiguration, or reset.
4	hardware	Employing radiation hard, high-reliability parts. Redundant configuration.

1. attitude control command:
   Every command is verified on-ground before the launch. The command plan of each daily operation is checked before being uploaded to the satellite. The onboard AOCS software ACFS calculates the "expected solar angle" for each programmed target attitude independently. If the calculated value exceeds 30 degrees, the ACFS onboard rejects the uploaded command to avoid solar angle violations as a fail-safe. Other critical parameters stored in ACFS, including the alignment matrix of sensors, or thruster vector matrix, are also checked onboard and will be rejected by ACFS in case the values are inconsistent mathematically.

2. attitude control behavior:
   Onboard, the ACFS watches each axis angular velocity and discrepancy from the target attitude after the slew. Once one of the values exceeds the predefined threshold, ACFS triggers the FDIR process.

3. verification of attitude control result:
   The ACFS monitors consistency between the ACFS calculated values and the values measured by the sensors, such as solar angles or calculated quaternion values and those derived by STT components. Once the discrepancy exceeds a threshold, the ACFS triggers the FDIR process (level 4).

The initial stage of FDIR is a fault-tolerant or fail-operational modes. In these levels, the spacecraft continues pointing operation by resetting or switching to the redundant system. However, if the fault is not corrected in the initial stage, the attitude control mode is changed to safehold mode in which pointing operation to free-spinning around the +Y axis (the normal of solar panel), and control the angular moment to direct the +Y axis to the sun. Momentum wheels control the safehold at first. If this fails, the attitude control actuator is switched to the thrusters. However, the AOCS cut the thruster at the last stage when it detects high angular velocity to avoid spacecraft breakup. After the cut-off, there is no active actuator controlled by onboard AOCS. The spacecraft shall be saved by commanding from the ground support stations.

4. DEVELOPMENT STATUS OF SCIENCE INSTRUMENTS

XRISM carries two science instruments: the *Resolve* Soft X-ray Spectrometer and the *Xtend* Soft X-ray Imager, as mentioned in Section 2. Two identical XMAs mounted on the spacecraft top plate are conically approximated Wolter I optics consisting of 203 nested shells, following the basic design for the *Hitomi* Soft X-ray Telescopes (SXTs). Although the SXTs are calibrated in ISAS/JAXA after fabricated in Goddard Space Flight Center of NASA, for XRISM, both construction and on-ground calibration of XMAs are conducted in the GSFC. Improvement in the point spread function applied for the XMA is described in [18] The two have been fabricated and under calibration. Recent status is reported in [19].

Resolve is equipped with an X-ray microcalorimeter array that delivers better than 7 eV energy resolution at helium superfluid temperature.[20] The basic design of the X-ray microcalorimeter and the cooling system follows that of the SXS onboard *Hitomi*, though newly developed mechanisms are adopted in the gate valve (GV) and vibration interference isolators (VIS). We installed an eddy current dumper in the GV opening mechanism. The GV protects the sensor in the vacuum dewar from the atmosphere and shall be opened in orbit. The eddy current dumper controls the opening speed and reduces the shock to the thermal shield films in front of the sensor. On the other hand, the VIS is installed between the mechanical cooler compressor and the dewar and restricts the vibration noise from propagating to the sensor. The isolation mechanism is redesigned for the spacecraft mechanical environment of XRISM at the launch and spacecraft separation. Detail description is shown in [21]. The status of development and the on-ground calibration are reported in [22, 23].

Xtend X-ray CCD camera delivers a broad field of view with a moderate energy resolution.[24,25] Performance requirements derived per the mission requirements are summarized in Table 3 as described in [15]. The basic design of the CCD camera is identical to that of the *Hitomi* SXI, and some improvements are adopted on the CCD chip and the scheme for preventing light leakage. The development and on-ground calibration status are reported in [26–29].

Table 3. Key parameters and performance requirement of the payload

Parameter	Resolve	Xtend
X-ray mirrors	conically approximated Wolter I optics (203 nested shells)	
Focal length	5.6 m	
Angular resolution	$\leq$ 1.7 arcmin (HPD)	
Detector technology	X-ray micro-calorimeter	X-ray CCD
Effective area	≥ 210 cm^2 @ 6 keV, ≥ 160 cm^2 @ 1 keV	≥ 270 cm^2 @ 6 keV
Field of View	$\geq 2.9 \times 2.9$ arcmin^2.	$\geq 30 \times 30$ arcmin^2
Energy range	0.3 – 12 keV	0.4 – 13 keV
Absolute energy scale	≤ 2 eV	—
Energy resolution	≤ 7 eV FWHM @ 6 keV	≤ 250 eV @ 6 keV (EOL)
Non X-ray background	$\leq 2 \times 10^{-3}$ c/s/keV/array	$\leq 1 \times 10^{-6}$ c/s/keV/arcmin^2/cm^2 (in 5 – 10 keV)
Time tagging accuracy	≤ 1 ms	—

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