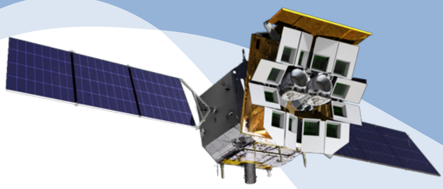
爱因斯坦探针
einstein probe



THE EINSTEIN PROBE MISSION

TECHNICAL HANDBOOK

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Table of Contents

List of Figures

List of Tables

1 Scope of the Document

1.1 The Einstein Probe Technical Handbook

The Einstein Probe (EP) Technical Handbook is written to offer EP users the technical information of the EP satellite.

1.2 Mission Overview

The Einstein Probe is a mission managed and fully funded by the Chinese Academy of Sciences (CAS) within its Strategic Priority Research Programme of Space Science (2nd phase). The mission concept was proposed by the National Astronomical Observatories, CAS (NAOC), in conjunction with the CAS Institute of High-Energy Physics (IHEP), in 2013 in response to a call of CAS for small- and medium-sized mission concepts for an 'Advanced Study' phase of candidate missions. Since 2011, the X-ray Imaging Lab of the Space Science Division, NAOC has set out the research and development of X-ray focusing technology based on lobster-eye micro-pore optics (MPO), including the simulation and design, testing and assembly of lobster-eye optics and telescopes, as well as the X-ray detector technology. In 2013, EP was selected for the 'Advanced Study' program. Funded by CAS, it was carried out from Jan 2014 to May 2016 to develop and demonstrate the key technologies adopted and to study the science case. In 2013, a science working group was set up to develop the science case of the mission, which is mainly composed of a large group of active scientists working in the field of high-energy astrophysics and time-domain, multi-messenger astrophysics in China.

At a further down-selection in 2015, EP advanced to become one of the candidate missions of priority. In May 2016, a prototype of lobster-eye mirror assembly was built and tested at NAOC, and its performance was demonstrated to meet the designed goal. During the time between Nov 2016 and Dec 2017, the project was under final reviews to assess its scientific goals, technology readiness, and programmatic and budget feasibility. The approval of the mission was officially endorsed by CAS in Dec 2017, whilst the engineering implementation phase for the EP hardware started in advance in Sep 2017.

EP's primary goals are to discover high-energy transients and monitor variable objects in the X-ray band. To achieve this, EP employs a very large instantaneous field-of-view (3600 square degrees), along with moderate spatial (point spread function or Point Spread Function (PSF) ~5 arcmin FWHM) and energy (FWHM ~ 150eV @ 1.5keV) resolution. Its wide-field imaging capability is achieved by using established technology of novel lobster-eye optics, thereby offering unprecedentedly high sensitivity and large Grasp, which would supersede previous and existing X-ray all-sky monitors. To complement this powerful capability to discover and monitor sources over a wide area, EP also carries a conventional X-ray focusing telescope with a larger effective area to perform follow-up characterization and precise localization of newly-discovered transients. Public transient alerts will be issued rapidly to trigger multi-wavelength follow-up observations from the world-wide community. The mission is aimed for launch by the end of 2023 with a nominal lifetime of 3 years (5 years as a goal).

The primary science objectives are:

1) Discover and characterize cosmic X-ray transients and monitor the X-ray variability of known celestial objects;
2) Discover and characterize X-ray outbursts from otherwise normally dormant black holes; and
3) Search for X-ray sources associated with gravitational-wave events and precisely locate them.

These populations of cosmic high-energy transients will be characterized over wide time-scales and at relatively high cadences, providing new insights into a diverse set of systems, including dormant black holes, neutron stars, supernova shock breakouts, active galactic nuclei, X-ray binaries, gamma-ray bursts, stellar coronal activity, and electromagnetic-wave sources and gravitational-wave events. Meanwhile, EP will also monitor the variability of various types of X-ray sources in large samples all over the sky. In light of the multi-messenger and multi-wavelength all-sky monitoring capability highly anticipated in the next decade, EP will produce a legacy data set in the X-ray band that are key to characterizing and understanding the nature of cosmic transients and variables, by working in synergy with the sky surveys by other facilities.

1.3 Payloads Overview

EP will carry two instruments: a Wide-field X-ray Telescope (WXT) with a large, mostly unvignetted field-of-view of 3600 square degrees (~1.1 sr), and a narrow-field (38') Follow-up X-ray Telescope (FXT).

1) The WXT consists of 12 identical modules that are based on the novel lobster-eye MPO to achieve both wide field-of-view and X-ray focusing. The focal plane detectors are made of back-illuminated CMOS imaging sensors with fast readout capability. The nominal detection bandpass of WXT is 0.5–4.0 keV.
2) The FXT consists of 2 nearly identical Wolter-I type X-ray focusing telescopes (focal length 1.6m) equipped with CCD cameras, each having an effective area of ~300 cm^2 at 1.25 keV and a bandpass of 0.3–10 keV.

EP has the capability of onboard data processing and transient search, and fast downlink for alert information. Some of the specifications and performance are summarized in the table below.

Table 1-1: The specifications and performance of EP

Parameters	WXT	FXT
No. of modules	12	2
Field of view	3600 sq. deg.	38’
Energy band	0.5–4 keV	0.3–10 keV
Effective area (@1.25keV)	2–3 cm^2	~ 300 cm^2 (one unit)
Angular resolution	~ 5′ (FWHM)	30” (HPD)
Energy resolution (@1keV)	170 eV	<170 eV

The EP WXT has a large Grasp (the product of effective area and FoV) of ~10^4 cm^2 sq. deg. at 1 keV, about one order of magnitude larger than the existing missions with focusing X-ray instruments. The PSF central spot of ~5 arcmin, improving significantly upon those of the wide-field X-ray monitors currently in orbit (order of degrees), enables good source localization at a 90% uncertainty of ~1 arcminute. The detection flux limit of WXT is estimated to be a few times 10^{-11} erg s^{-1} cm^{-2} (~1 mCrab) for a 1000-second exposure (for a source with a typical X-ray power-law spectrum of photon index -2 and a moderate absorption column density of 3×10^{20} cm^{-2}, at 5-sigma). This value is obtained by simulations using the instrument performance characterized by the on-ground calibration, and is confirmed by real data from observations made with the WXT-pathfinder LEIA (Lobster Eye Imager for Astronomy) currently in orbit.

With a total effective area of about 600 cm^2 for the 2 units, a good angular resolution of < 30” (HPD) and quick response, FXT is expected to be one of the most powerful X-ray telescopes dedicated to follow-up observations.

1.4 Mission Profile:

The satellite weighs ∼1450 kg and operates at an average power of ∼1217 W. The satellite platform is developed by the Innovation Academy of Micro-Satellite of CAS (IAMC, or MicroSat). The satellite will be in a circular orbit of 600 km altitude, with a period of ∼97 minutes and an inclination angle of 29°. The satellite will be launched by a CZ2-C rocket from the Xichang satellite launch center by the end of 2023, with a nominal lifetime of 3 years (5 years as a goal).

In the regular survey mode, during one circle of 97 minutes’ orbiting, three fields are to be observed on the night-side of the sky, each with a ~20 min pointing. Over three successive circles, the entire night sky will be largely sampled, with cadences ranging from several to more than 10 revisits per day, depending on the sky location. The entire sky will be covered within half a year of the operation.

The daily regular data rate is estimated to be ~60 Gbit. The regular telemetry data will be transmitted to the ground segment via the X-band using the Sanya ground station in China. During the orbiting where the satellite is inaccessible from the Sanya station, X-band data telemetry will be provided by one of the following stations made available via collaboration with ESA, ESOC Kurou, KSAT Singapore and KSAT Western Australia.
Once a transient source is detected and an alert is produced onboard, the satellite will slew to a new position to enable pointed follow-up observations with the FXT within ~4 minutes. Meanwhile, the alert information of the newly discovered transient will be downlinked rapidly within minutes to the ground segment via the Chinese Beidou navigation system and the French VHF (Very High Frequency) network being developed for the SVOM mission. The alert information will be made public once received and validated at the EP Science Center, in order to trigger multi-wavelength follow-up observations from the world-wide community. Target of Opportunity observations (ToO) can be performed on request, with a time latency of typically several hours. A significantly reduced latency as low as ~10 minutes may also be achieved for time-critical ToO requests targeting significant events (such as gravitational-wave events).

1.5 Mission Management

EP is a mission managed and funded by CAS within its Strategic Priority Research Program of Space Science, with international collaboration. The overall mission management agency is CAS's National Space Science Center (NSSC). The Innovation Academy of Micro-Satellite of CAS develops the spacecraft and implements the management at the satellite level including the scientific payloads. The WXT instrument is developed jointly by the Shanghai Institute of Technical Physics (SITP) and National Astronomical Observatories of CAS (NAOC), with the MPO microchannel plates provided by NNVT in China. The FXT instrument is developed by the Institute of High-Energy Physics (IHEP) of CAS, with its mirror assemblies provided by ESA and MPE, and the mirror design and PN-CCD camera modules provided by MPE. The ground segment includes the Mission Operation Center (MOC) based at NSSC for operation of the mission and the legacy archives, and the EP Science Center (EPSC) based at NAOC and IHEP for science operation concerning the development of the data processing pipeline for both WXT and FXT, scientific observing plan, the generation of scientific data products, and also the instrument calibration as well as in-orbit maintenance and operations.

1.6 International Collaboration

The Einstein Probe is a CAS-led mission with international participation from the pre-launch phase. The EP consortium, aside from CAS, include the following agencies: The European Space Agency (ESA), via the provision of one set of the FXT mirror assembly and electron diverter, support of telemetry by ground stations, and independent test and calibration of part of the WXT mirror assemblies, MPO devices and CMOS sensors); the Max-Planck-Institute for Extraterrestrial Physics (MPE) in Germany, via the provision of pn-CCDs detector modules, the other FXT mirror assembly, and support to the delivery of both the mirror assemblies; the French Space Agency (CNES), via the provision of the VHF network and quick telemetry of alert data.

The EP science team (EPST) is a joint team composed of scientists appointed by CAS, ESA, MPE and CNES, respectively, with the relative numbers in proportion to their respective contribution to the EP project. EPST is composed of several Science Topical Panels of different research topics, which are managed by a Science Management Committee (SMC).

2 Mission Profile

EP is an X-ray astronomical satellite, which is equipped with two kinds of payloads. The characteristic payload is WXT, which adopts lobster-eye MPO to achieve both X-ray focusing and a large field-of-view (FoV). With 12 identical WXT modules, EP can achieve an instantaneous FoV of ~3600 deg^2 in 0.5–4 keV. The positioning accuracy is ~1 arcmin. The other type of payload is FXT, which is the classic Wolter-I type X-ray telescope. The main energy band of FXT is 0.5–10 keV, and the FoV is ~1 deg^2. The two FXT modules together can achieve an on-axis effective area of ~600 cm^2 at 1.25 keV. The positioning accuracy is 8.6 arcsec. Therefore, WXT is mainly used for the discovery of X-ray transients and extremely variable sources, while FXT is mainly used for high-precision follow-up observations to provide much better measurements on source positions and other X-ray properties.

The EP satellite platform has strong maneuverability and online data reduction capabilities. WXT can detect transients onboard and transmit the transient alerts to the ground through Beidou and VHF network. The satellite can also automatically turn to the newly found transient to perform follow-up observations with FXT. Meanwhile, urgent target-of-opportunity (ToO) commands can be uploaded to the satellite through Beidou channel, enabling EP's ToO observation to be quickly triggered from the ground within tens of minutes the fastest.

Below we provide more detailed descriptions about the scientific observing modes and operation constraints of the EP satellite.

2.1 Observing Modes

The main scientific observation modes of EP include: the survey mode, the autonomous follow-up mode, the ToO mode and the calibration mode. It must be noted that EP does not have a scan mode. All observations of EP are carried out as pointed observations. Besides, all telescope modules are fixed on the satellite platform, thus the fields of view of WXT and FXT move together as the satellite slews from one direction to another. In extremely rare and special circumstances, EP satellite may enter the safe mode.

Survey mode:

The survey mode is the most basic observing mode of EP, which mainly takes advantage of the large FoV of WXT to search for new transients and variable sources. The survey model consists of a series of pointed observations. In order to improve the observing efficiency of WXT, normal survey observations will be carried out as 2 to 3 pointed observations per orbital cycle (see Fig.1), with each observation lasting about 20 to 30 minutes. Then the whole night-sky may be covered within 3 to 5 cycles, and the sampling frequency of each point on the night-sky maybe 3 to 5 times per day. In this way, after operating in-orbit for about half a year, a full sky coverage can be achieved by WXT.

In the meantime, however, FXT is also observing normally in the survey mode; and the pointing of WXT does not need to follow a strict strategy (the uniformity of WXT sky coverage is not the most important factor). Therefore, the all-sky survey of EP is in fact driven by the FXT survey-mode target observation (FSTO). These FXT observing programs are proposed by users through observation proposals, and after being evaluated and approved by the time allocation committee (TAC), the selected targets will be included in the planning of survey observations in the following observing year. In the survey mode, EP can also use FXT to conduct deep exposures of specific sources for multiple orbital cycles. The duration of such a long-pointed observation is mainly determined by the scientific requirements and value.

It should be noted that the survey mode is the lowest-priority observation mode of the EP satellite. During the survey mode, if WXT detects a new transient which exceeds the onboard triggering threshold, the satellite will terminate the current survey-mode observation and enter the autonomous follow-up mode (see the next chapter). In addition, ToO observations uploaded from the ground can also interrupt survey-mode observations anytime.

WXT transient information generated onboard will be quickly downlinked to the ground through Beidou and VHF networks and publicly released to the community, thereby guiding follow-up observations of other facilities. The complete dataset of survey-mode observations will be transmitted to the ground timely for more detailed data analysis when the X-band data transmission channel is available.

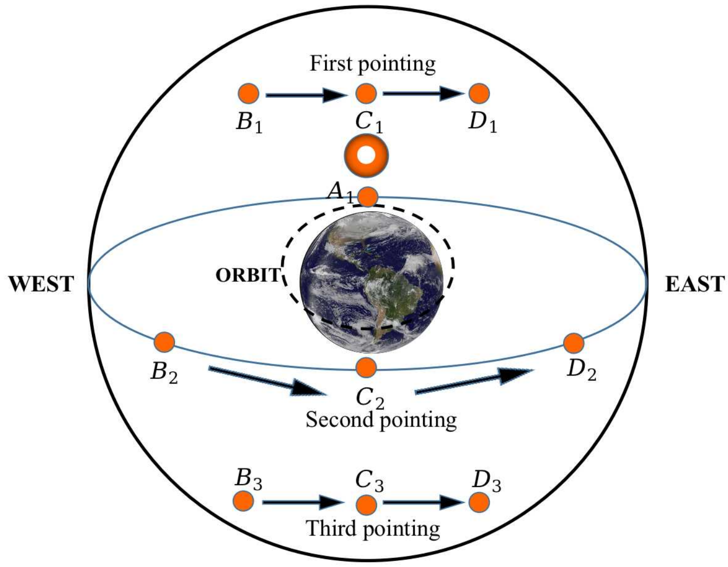


Figure 2-1: Directions of WXT pointing in three successive cycles of orbiting in the normal survey mode. In such a way most of the night sky can be covered in three cycles. With the motion of the Sun on the sky, the whole sky can be covered by WXT in roughly half a year.

Autonomous follow-up mode:

The autonomous follow-up mode is another important observation mode of EP. When WXT discovers a new transient, and the parameters of the transient exceed the onboard triggering threshold, EP will automatically enter its follow-up mode. Firstly, EP will automatically terminate the current survey-mode observation (or other observations of low priorities, see the next chapter), and then automatically slew to the position of the new transient determined by WXT, and then carry out deep follow-up observation with FXT.

Depending on the transient properties, autonomous follow-up mode is divided into two levels on the satellite (Level-1 and Level-2), with Level-1 having a higher priority and defaulting to 5-cycle observation. Level-2 has a lower priority and defaults to 3-cycle observation. A Level-2 observation can be interrupted by a Level-1 observation, but observations of the same level cannot interrupt each other. In addition, exceptional ToO observations (see the next chapter) can interrupt autonomous follow-up observations (both Level-1 and Level-2). Note that the WXT onboard triggering threshold is adjustable, and the catalog stored onboard for known sources that need to be skipped in onboard triggering can also be updated in real-time.

It should be noted that in the autonomous follow-up mode, WXT also keeps observing and detecting possible new transients. Regardless of whether EP performs autonomous follow-up observation of the newly discovered transient, the alert information of the transient will still be quickly transmitted to the ground through Beidou and VHF, and promptly released to the public.

During the autonomous follow-up mode, FXT will also perform rapid onboard data reduction, and the preliminary quick-look data will be transmitted to the ground through the VHF network (including more accurate information such as the source coordinates, flux and hardness ratio), which will better guide the follow-up observations of other facilities.

Once an autonomous follow-up observation is finished, the complete dataset will be transmitted to the ground timely for more detailed data analysis when the X-band data transmission channel is available.

Target-of-Opportunity mode:
The Target-of-Opportunity (ToO) mode will also be a commonly used observation mode of EP. ToO programs need to be proposed by users and uploaded to the EP satellite from the ground through EPSC and then MOC. ToO observations can be divided into two categories, namely the normal ToO and the exceptional ToO, based on their different levels of onboard priority. The complete onboard priority hierarchy of different observation modes is as follows:

Survey Observation < Normal ToO Observation < Level-2 Follow-up Observation < Level-1 Follow-up Observation < Exceptional ToO Observation

High-priority observations can interrupt low-priority observations. ToO observations of the same priority level can also interrupt each other, but autonomous follow-up observations of the same level cannot interrupt each other.

In addition, ToO observations can be divided into regular and urgent ones, depending on the urgency requirement. Urgent ToOs will be uploaded as soon as possible through Beidou or S-band TT&C channel (normally within hours), while regular ToOs will be scheduled on the following day or later. All ToO proposals must first be evaluated at EPSC for approval before they can be scheduled. Note that due to limited resources, only proposals of special scientific importance and urgency can be uploaded as urgent ToO programs, while most programs will be handled as regular ToOs. In addition, EP has a special ToO-Multi-Messenger (ToO-MM) mode for multi-messenger alerts (such as gravitational wave events and neutrino events), which also falls into exceptional ToO modes, and has the highest onboard priority along with other exceptional ToOs. Either exceptional ToOs or ToO-MMs can only be triggered by the mission's Principal Investigator or his representatives.

During a ToO observation, WXT also keeps observing and detecting possible new transients. Regardless of whether or not EP performs an autonomous follow-up observation on the newly discovered transient, the alert information of the transient will still be quickly transmitted to the ground through Beidou and VHF, and promptly released to the public. If a new transient exceeds the WXT onboard triggering threshold, and meanwhile the satellite is executing a normal ToO, then the ToO will be interrupted by the autonomous follow-up observation triggered for the new transient.

Once a ToO observation is finished, the complete dataset will be transmitted to the ground timely for more detailed data analysis when the X-band data transmission channel is available.

Calibration mode:
EP satellite will carry out a series of calibration observations for both WXT and FXT, such as flux, positioning and spectral calibration. Calibration observations often have higher priority than normal scientific observations. Calibration observations can either be replanned observations for regular in-orbit calibration, or ToO observations for temporary in-orbit calibration. They will be proposed by the WXT and FXT instrumentation team within EPSC.

2.2 Orbital Information

A Long March 2C rocket will be used as the launcher for the EP satellite. A direct injection strategy is adopted to directly send the satellite to its operating orbit. The satellite will be in a circular orbit of 550–600km, with a period of ~97 minutes and an inclination angle of 29°.

2.3 The South Atlantic Anomaly

During orbital operation, EP will pass the South Atlantic Anomaly (SAA) region regularly. Neither WXT nor FXT will be turned off during the SAA passage. The irradiation of high-energy particles in SAA can greatly enhance the background flux level, invalidating the observational data. This will cause further loss of good time interval (GTI). The length of SAA time interval varies every orbital cycle. However, the duration of SAA passage, averaging a few minutes per cycle, can be predicted. Since the boundary of SAA is known, the observing time during the SAA passage will be excluded from the GTI automatically by the WXT and FXT data reduction pipeline.

2.4 Slewing and Pointing Constraints

The EP satellite platform has strong maneuvering capabilities. Once EP finishes an observation, it will slew to the next pointing direction, and then stabilize its attitude to start a new observation. The time required for this process, if measured in seconds, is roughly equal to the required maneuvering angle plus 50. For example, if one observation ends and the satellite needs to slew 10 degrees to the next source, the required maneuvering time in between is approximately 60 seconds.

Since both WXT and FXT must avoid solar irradiation, the EP satellite adopts an anti-solar pointing strategy. Figure 2-2 shows the defined satellite coordinates and axes. The attitude constraints of EP in-orbit include:

1) In survey, follow-up, and normal ToO modes, the angle between the positive X-axis and the solar vector must be larger than 94.5 degrees. For exceptional ToOs (such as ToO-MM), this constraining angle can be relaxed to 65 degrees.
2) The angle between the positive Y-axis and the solar vector must be larger than 85 degrees.
3) The angle between the negative Y-axis and the solar vector must also be larger than 85 degrees.
4) The angle between the negative Z-axis and the solar vector must be greater than 90 degrees.
5) For normal observations, the angle between the FXT optical axis and the lunar vector should be larger than 10 degrees.

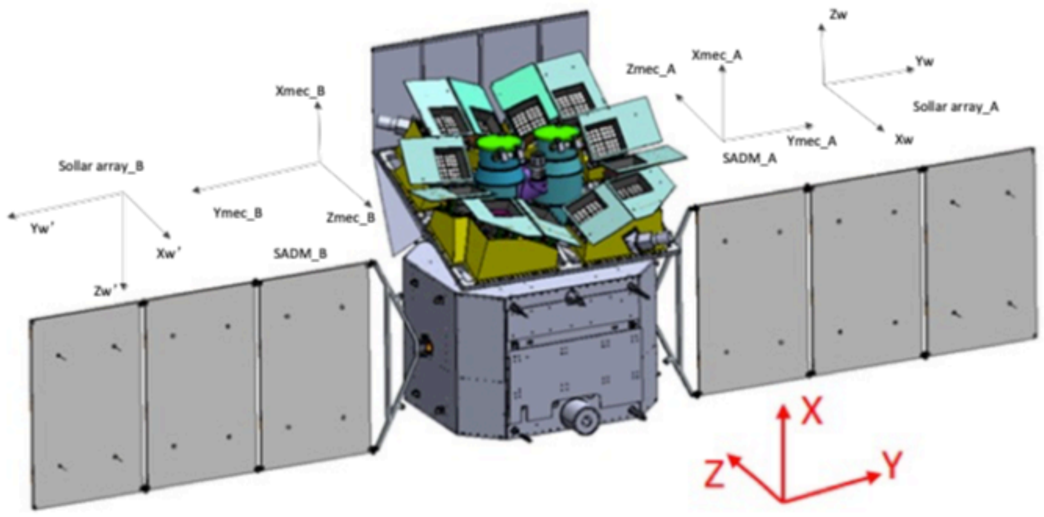


Figure 2-2: the definition of satellite coordinates and axes.

3 Wide-field X-ray Telescope

3.1 Design of WXT

To achieve both a wide FoV and X-ray focusing, WXT employs the lobster-eye micro-pore optics. There are twelve almost identical WXT modules, each of ~300 deg^2 FoV. The shape of the overall FoV is shown in Figure 3-1 (right panel), which makes ~3,600 deg^2 (~1.1 steradians) in total and is mostly vignetting-free. WXT will be the first wide-field X-ray focusing telescope utilizing the lobster-eye MPO optics on a large scale.

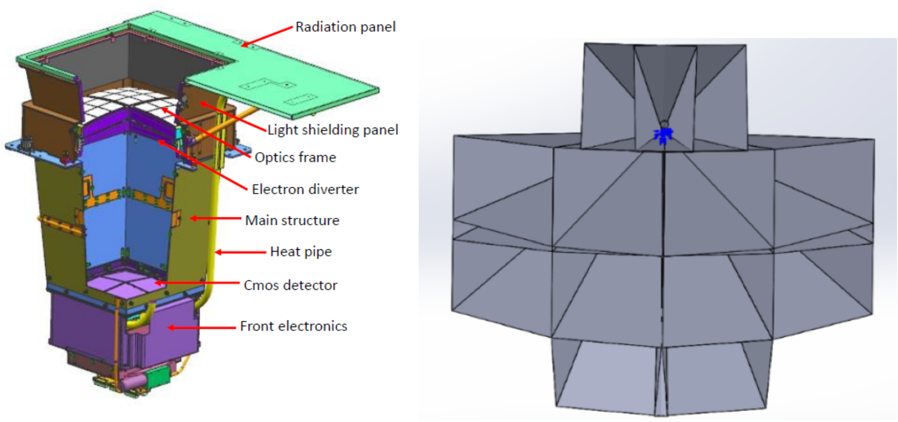


Figure 3-1: The structure of one WXT module (left). Configuration of the WXT FoV is mosaicked by twelve identical modules. The two upper modules have partially overlapping FoVs, which cover the FoV of the FXT (right).

The left panel of Figure 3-1 shows the design layout of the WXT module, whose main components include an MPO mirror assembly, a focal plane detector array, and an electronics unit with thermal control and mechanical structure. The mirror assembly is the X-ray focusing unit. An optical baffle (light shielding panel) is attached to the front end of the mirror assembly to shield stray light from the Sun, Moon, and Earth. A radiation panel is attached to the optical baffle at the top. The focal plane detector unit and its front-end electronics are located at the bottom of the WXT module. The mechanical support structure is designed to connect the mirror assembly with the detector unit; it is used to shield effectively some of the charged particles in orbit. The main specifications of WXT are listed in

Table 3-1.

Table 3-1: Main specifications of WXT

WXT parameters	Value
Energy range	0.5–4 keV
Optics	Micro-Pore Optics
Detector	CMOS
Energy resolution	170 eV @1.0 keV
Effective area	2–3 cm^2 @1 keV
Field of view	3600 square degree
Detector elements	4096 pixel x 4096 pixel
Pixel Scale	15 μm (8.2 arcsec)
PSF	5 arcmin (FWHM)
Positional error (90% C.L.)	2 arcmin
Sensitivity (1000 s)	0.8 mCrab, 2.6×10^{-11} ergs s^{-1} cm^{-2}

The mirror assembly of each module comprises 36 MPO optics mounted on a supporting alloy frame. Each optic measures 42.5×42.5 mm^2 in area, and 2.5 mm in thickness, with a focal length of 378 mm. The pores measure 40 *μ*m×40 *μ*m each, and are coated with Iridium to increase reflectivity. There are 432 optics in total for the twelve modules. An electron diverter is mounted below the optic frame of each module, which will be used to deflect and prevent low-energy electrons in orbit from reaching the detectors.

WXT has a large-format focal plane (sphere) of approximately 420 mm×420 mm in total. The focal detector array is composed of four back-illuminated CMOS sensors, each of 6 cm×6 cm in size. A layer of 200 nm aluminum is coated on the surface to block optical light.

The frame rate used is 20 Hz and the corresponding dead-time is less than 0.05 %. The readout noise is lower than 5 electrons at 20 Hz. The front electronics will read the full-frame image and extract X-ray events as the signals are above a threshold. All the recorded events are sent to the instrument electronics box for package, and then to the satellite and the onboard trigger module for further processing. The CMOS detectors will be operated at a temperature of -30±2 ℃, which will be achieved by a thermoelectric cooler. A heat pipe is used to transfer the heat from the electronics to the main structure of the WXT module.

The electronics control box is used to provide power supply to WXT, to package the X-ray events data, and to offer thermal control, onboard data processing and necessary alert triggering. The front electronics software is designed to be refactorable in-orbit.

3.2 Performance of WXT

The performance of WXT has been studied extensively via realistic ray-tracing simulations based on the designed WXT model by taking into account the imperfectness of the MPO optics (Zhao et al. 2014, 2017). Some parameters were also measured by ground calibration and compared with the simulation results.

The derived energy-dependent effective areas of WXT are shown in Figure 3-2.

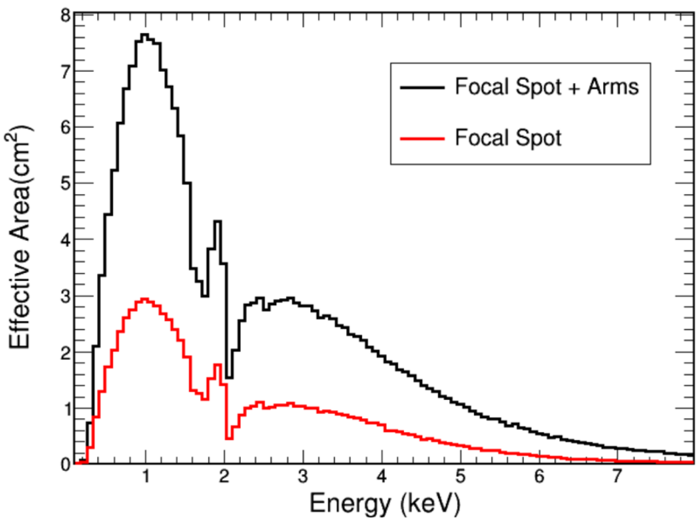


Figure 3-2: Simulated effective area curves of WXT for the central focal spot (red) plus the cruciform arms (black). The pores are coated with Iridium, which produces the absorption edge seen at ~2 keV. The response of the detectors, coated with a 200 nm-thick Aluminum layer, is incorporated.

The effective area for the central spot peaks around ~3 cm^2 at 1 keV. When all the photons focused onto both the central spot and the two cross-arms are collected, the effective area increases to ~7.6 cm^2 at 1 keV. The areas drop towards both the higher and lower energies, mainly due to the decreasing X-ray reflectivity with increasing energy, the stronger absorption at lower energies, and the energy dependence of the detector quantum efficiency. The effective area curves define basically the detecting bandpass of WXT. The nominal band is from 0.5 to 4.0 keV, beyond which the effective area drops rapidly. In fact, the effective area also varies across the FoV of the WXT module. This is caused mainly by effects such as the shadowing of the supporting frame and being close to the edges of the FoV.

Although the effective area for most directions is only in the order of several cm^2, its variations are small across almost the entire FoV. This leads to an enormous grasp – effective area times FoV, which peaks around 10^4 cm^2 deg^2 at 1 keV. As shown in Figure 3-3, WXT has the largest grasp in soft X-rays among the X-ray focusing telescopes built so far.

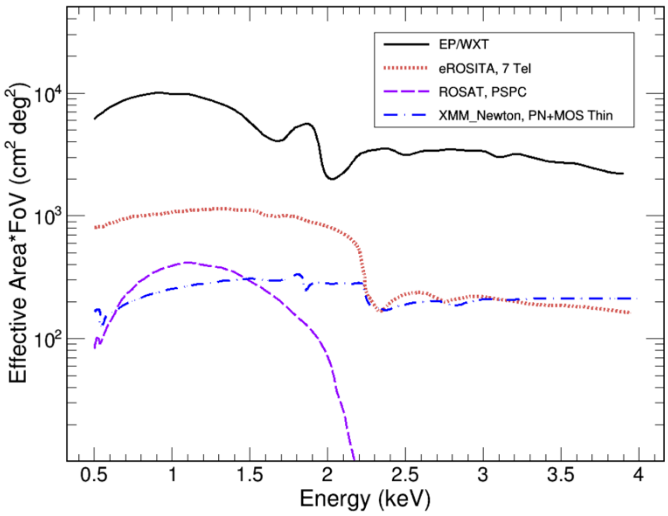


Figure 3-3: Representative grasp (effective area times FoV) of WXT as a function of photon energy (black). As a comparison, the grasp parameters of several X-ray focusing telescopes are overplotted (update based on the results in Zhao et al. 2014).

Each of the MPO optics was tested in X-rays, and the majority have an angular resolution of ~5 arcmin (FWHM) or better. Two qualification models of the WXT module have been tested and calibrated with X-ray beams. Good agreements on both the PSF and effective area were found between the measurements and simulations. In most of the directions across the 300 deg^2 FoV of the WXT module, the angular resolution was found to be ≤ 5

arcmin (FWHM, central spot) on average, and the effective area in the range of 2–3 cm^2. Figure 3-4 displays an X-ray image produced by one of the WXT mirror assemblies, which was obtained at MPE/Panter by using a parallel beam of a Cu-Lα line source of 930 eV.

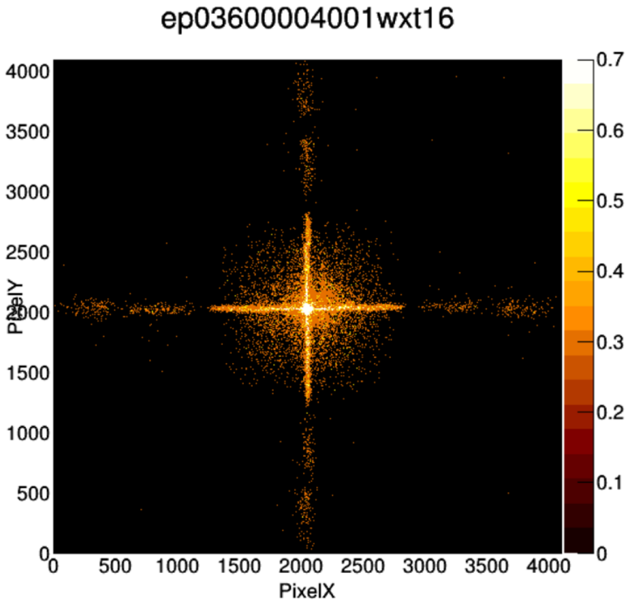


Figure 3-4: True X-ray image produced by one mirror assembly qualification model of the WXT module developed at NAOC (measured at MPE/Panter by using a parallel beam of a Cu-Lα line source of 930 eV). The PSF is symmetric, with an angular resolution ~5 arcmin in FWHM for the central spot. (Courtesy ESA/MPE)

The EP satellite will be subject to a complex space environment full of cosmic rays including photons and various types of energetic charged particles. Simulations of the WXT background (Zhao et al. 2018) were carried out by using the toolkit of Geant4 (Agostinelli et al. 2003), as well as XRTG4 (Buis et al. 2009) to simulate the grazing incidence of X-rays. The X-ray background is composed of the cosmic X-ray background (CXB) and the diffuse soft X-rays within the Galaxy, dominating below 1 keV. Different from the X-ray background whose contribution is mainly determined by the optics of WXT, the background produced by energetic charged particles depends strongly on the thickness of the depletion-layer of the detector. As a result, in the 0.5–4 keV band, a background level of about 0.3 counts s^{-1} cm^{-2} is predicted for the WXT detectors. Among them, the diffuse X-ray background contributes about 0.2 counts s^{-1} cm^{-2} and dominates the soft X-ray band below 2 keV (Zhao et al. 2018).

The detection sensitivity of WXT is determined by a number of factors, mainly the effective area and PSF of the entire imaging system, the background count rate, the energy bandpass, and the source spectral shape. By using the values derived from the simulations discussed above as well as the PSF measured from the ground calibration of the qualification models, the detection sensitivity was evaluated from simulations. For a point-like source, the medium values of the limiting flux in the 0.5–4 keV band are approximately 8.9×10^{-10} ergs s^{-1} cm^{-2} (27.6 mCrab) for an exposure of 10 seconds, 1.2×10^{-10} ergs s^{-1} cm^{-2} (3.9 mCrab) for 100 s, and 0.26×10^{-10} ergs s^{-1} cm^{-2} (0.8 mCrab) for 1,000 s (assuming a power law spectrum with a photon index -2 and a Galactic absorption column 3×10^{20} cm^{-2}). It is clear that EP WXT is much more sensitive compared to the previous and current wide-field X-ray monitors by one order of magnitude or more. However, these values should be considered as nominal, as the true sensitivity depends on the in-orbit performance of the instrument and strongly on the background level determined by the actual environment of charged particles.

Because of the fast frame rate of the CMOS detectors, the pileup fraction is predicted to be lower than 1% for a source as bright as 10 Crab.

3.3 WXT In-orbit Operation

One system requirement of the mission is real-time detection of transients on the fly and quick response for both onboard and ground-based follow-ups. To this end, an onboard data processing and triggering system (ODPTS) was designed. While data acquisition is ongoing during a WXT observation, the onboard computer will search for transients in real time by processing the acquired WXT data. The search is performed over each CMOS chip and over a range of timescales. It has been demonstrated that the data processing for all the 48 CMOS detectors can be achieved within 10 seconds using the real hardware. A source detection sensitivity of ~1 mCrab for a typical 1,000 s exposure of one survey pointing can be achieved. The source location accuracy is about 2 arcmin, as demonstrated by both simulations and ground experimental tests.

The candidates are further compared against a source catalogue to find any transients. Whenever a new transient is picked up, the ODPTS will trigger a FXT observation. Meanwhile, an alert message will be downlinked to ground in time. Transient alerts will be made public upon receipt and subject to manual screening in real time, to trigger follow-up observations from the worldwide community.

Upon detection of a transient source, its alert information will be downlinked to the ground segment with a latency of about 10 minutes or so. The alert data includes the coordinates, flux, spectral hardness ratio, and possibly a simple light curve of the source.

To do this, the Beidou (the Chinese satellite navigation system) system will be utilized by taking advantage of its short text message capability and global coverage. To enhance the alert capability to transmit more of the quick-look data of transients, the VHF network system of the CNES (France), which is built for the Chinese-French SVOM mission, will be used via collaboration.

3.4 WXT Data & Software

3.4.1 WXT data analysis software

The WXT data analysis software (WXTDAS) is developed under the HEASARC framework. It will be incorporated into the FTOOLS software. It uses WXT Level 1 data as input and calls the CALDB of WXT to generate Level 2 & 3 data.

3.4.2 WXT data structure

WXT data conforms to the HEASARC standards. There are three levels of data that are archived.

Level 1: Raw Data
Level 1 data are telemetry (also known as Level 0) data that have been converted to FITS format files. No data processing is done in the conversion from telemetry format to FITS format (e.g. uncalibrated event lists).

Level 2: Reduced Data
Level 2 data have been calibrated and have had some data processing done on it (e.g. calibrated event lists).

Level 3: High-Level Data Products
Level 3 data are source level products. They are science data that can be used by the community (e.g. source catalogs, spectra, and light curves).

EPSC will automatically generate data of Levels 1 to 3 when the telemetry data is available. Most scientists should start their analysis using the Level 2 & 3 products.

The Level 1 data of WXT are organized according to Observation ID, which is an 11-digit number, to identify the observation. The structure of files under the directory of an Observation ID is shown in Table 3-2.

The WXTDAS will process the data of each CMOS separately and generate Level 2 & 3 data indicated in Table 3-3.

Table 3-2: The content of Level 1 data

Root	1st Subdirectory	2nd Subdirectory	File name	Description
[ObsID]	auxil	——	ep[obsID].orb	orbit file
			ep[obsID].att	attitude file
			ep[obsID].mkf	make filter file
	wxt	event	ep[obsID]wxt[number][pp]_uf.evt	event file

[ObsID]	an 11 digits number to identify the observation
[Number]	the number of CMOS, from 1 to 48
[Pp]	satellite status: po — pointing settled sl — during a slew
[Level]	level of event file： Level 1: uf — unfiltered event file Level 2: cl — cleaned event file

Table 3-3: The content of Level 2 & 3 data.

ep[obsID]wxt[number][pp]_cl.evt	event file

ep[obsID]wxt[number].mkf	make filter file
ep[obsID]wxt[number].img	image
ep[obsID]wxt[number].exp	exposure map
ep[obsID]wxt[number].expcorr	corrected exposure map
ep[obsID]wxt[number].cat	source catalog
ep[obsID]wxt[number]arm.reg	arm region file
ep[obsID]wxt[number]s[sourceID].lc	source light curve
ep[obsID]wxt[number]s[sourceID]bk.lc	background light curve
ep[obsID]wxt[number]s[sourceID].pha	source spectrum
ep[obsID]wxt[number]s[sourceID]bk.pha	background spectrum
ep[obsID]wxt[number]s[sourceID].arf	ancillary response file
ep[obsID]wxt[number].rmf	response matrix

3.4.1 WXT calibration database

The WXT calibration database (WXTCALDB) includes the pre-launch results obtained from the analysis of the ground calibration data and also those derived from calibration observations taken in flight during the lifetime of the mission. The results are stored in the OGIP CALDB structure as FITS file following the OGIP standard.

The WXT calibration files are produced by the WXT Calibration team and delivered to the EPSC which maintains the WXTCALDB. The WXTCALDB is delivered by EPSC to the archive database each time an update is performed.

3.5 WXT Online Simulator

The WXT online simulator (https:///ep.bao.ac.cn/ep/simulator), provided by the EPSC, is an online tool to simulate WXT data.

4 Follow-up X-ray Telescope

Einstein Probe's Follow-up X-ray telescope (FXT) is designed to perform prompt follow-up observations of trigged sources from WXT and observe other interested targets during the all-sky survey at the rest time. Table 4-1 summarizes the FXT parameters.

Table 4-1: FXT parameters

FXT parameters	Value
Energy range	0.3–10 keV
Mirror	Wolter-I
Detector	pn-CCD
Effective area	≥ 600 cm^2@1.25 keV (on-axis)
Field of view	1°×1°
Detector elements	384×384
Pixel Scale	75 μm×75 μm
PSF	≤30" (HEW)
Sensitivity	10 μCrab, 2.4×10^{-13} erg cm^{-2} s^{-1}

4.1 FXT Technical Description

FXT is a Wolter-I telescope operating in the 0.5–10 keV energy range. Its field of view (60 arcmin in diameter) is narrow, and its source localization error varies within the range of 5–15 arcsec (90% c.l.), depending on the source strength. The FXT is responsible for the quick follow-up observations (within 5 minutes) triggered by sources discovered by WXT (above a pre-set threshold), and will also observe other interested targets during the all-sky survey at the rest time.

The design of FXT is shown in Figure 4-1. The FXT detector is made of two pnCCD modules (the image size 28.8mm × 28.8mm, from MPE). The two pnCCD modules are cooled (-110~-80℃) by two helium pulse tube refrigerators, respectively. The mirror module comprises of 54 nested gold coated nickel shells of Wolter-I type, to be fabricated by Media Lario in Italy. The half energy width (HEW) is about 30 arcsec (on axis) at energy of 1 keV. The temperature of the mirror module is controlled by several heaters and thermal filters. The X-ray baffle at the entrance of the mirror can protect against the X-ray stray-light from single reflections in the Wolter-I type mirror.

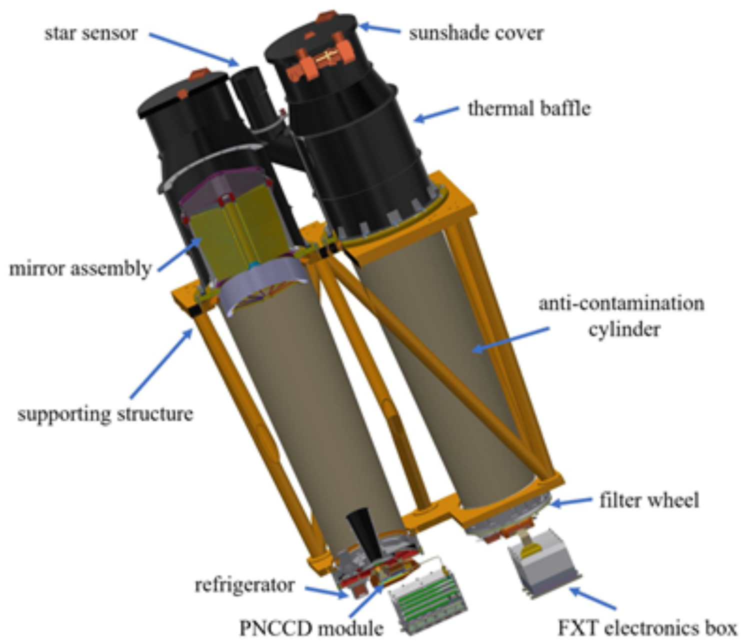


Figure 4-1: The design of FXT

The electronic box under the detector performs clock generation, data acquisition, voltage supply and mode switch for FXT.

The scientific observation modes of the FXT camera include the Full-Frame Mode (FF), the Partial-Window Mode (PW), and the Timing Mode (TM). FF is the normal mode. The advantage of TM is its good time resolution, and its operation to read out the events continuously without position information. PW is a special mode, in which only a small imaging area is active so as to achieve good time resolution. These three operation modes of FXT could be chosen through sending orders from the ground.

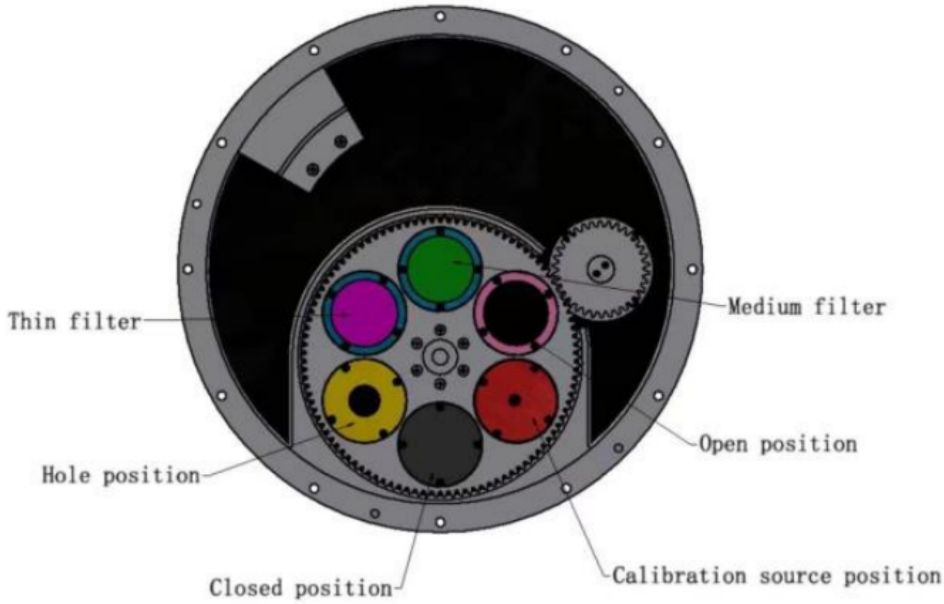


Figure 4-2: The filter wheel of FXT

In front of the pnCCD module, there is a filter wheel with 6 options. Besides the open position, FXT has two kinds of filters mounted on the filter wheel: medium filter and thin filter (Figure 4-2). The hole position, calibration source position and closed position could be applied in some special scenarios.

4.1.1 FXT point spread function

The Point Spread Function (PSF) of EP-FXT varies with the energy and the off-axis angle. In the central region, the PSF is generally circular, but it becomes butterfly-shaped in the outer regions. In the ground calibration experiment, the multi-target X-ray sources are used to measure the PSF shape at various energy points and different off-axis angles, as shown in the figure below.

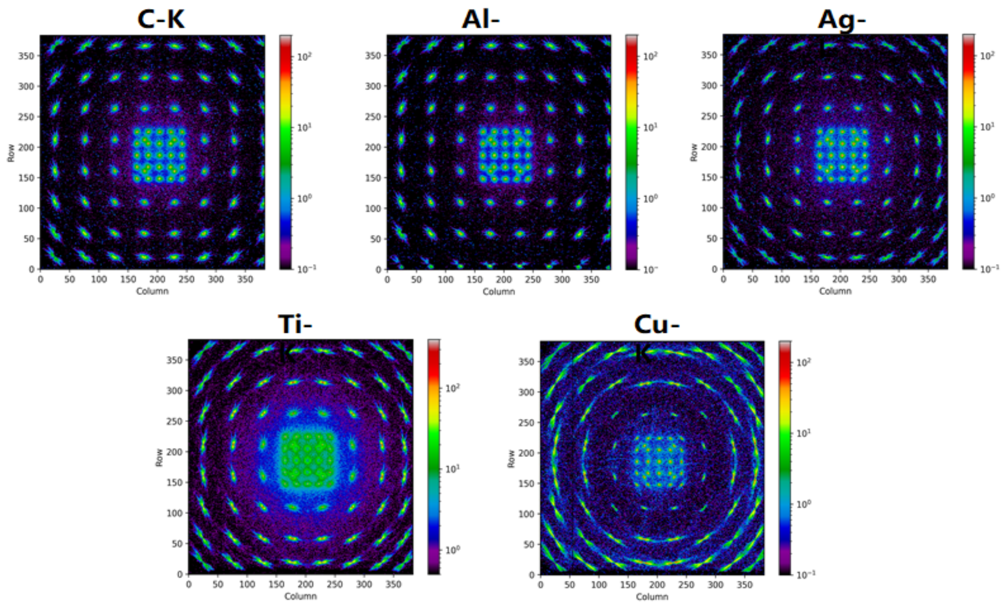


Figure 4-3: The PSF shape for FXTA at 5 energies.

4.1.2 FXT angular resolution & positioning accuracy

The on-axis angular resolution of FXT is shown as in the figure below.

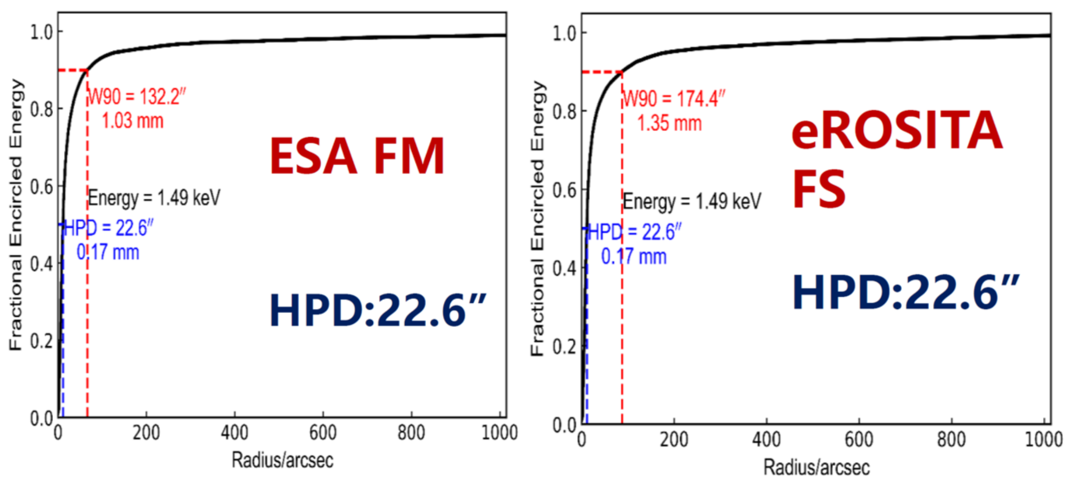


Figure 4-4: The Fractional Encircled Energy profile of FXTA (left) and FXTB (right).

Based on the PSF obtained from the ground calibration, the accumulated integrals are used to determine the Half Power Diameter (HPD) and the 90% Power Width (W90), which are 22.6” and 132.2” for FXTA, and 22.6” and 174.4” for FXTB, respectively.

The positioning accuracy of FXT depends on the characteristics of its PSF. Considering the systematic uncertainty, the positioning accuracy of FXT is approximately 8.6” (90% c.l.).

4.1.3 FXT energy resolution

The spectral resolution of FXT, as a function of energy, is obtained from on-ground calibration. The figure below shows that the energy resolutions of FXTA and FXTB are ~90 eV and 95 eV at 1.25 keV, respectively.

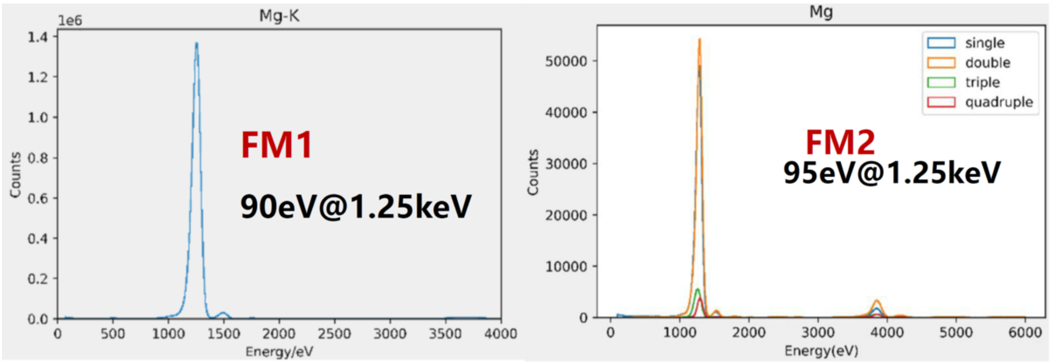


Figure 4-5: FXT energy resolution at 1.25 keV.

Due to the CTI (Charge Transfer Inefficiency) in the transmission and reading out of the photoelectrons in pnCCD, the energy resolution varies with the Row. The following figure presents the energy resolution at different energies for 384 rows of FXT. The energy resolution of Al-K line at 1.49 keV is approximately between 90–100 eV. It is obvious that the energy resolution deteriorates with the distance from the readout terminal.

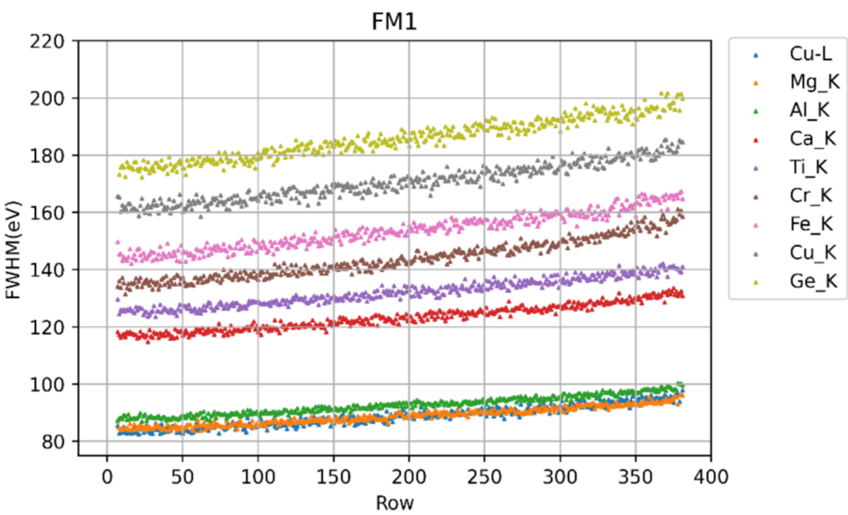


Figure 4-6: The energy resolution at different energies for 384 rows in pnCCD.

4.1.4 FXT quantum efficiencies

Currently, the quantum efficiencies (QE) of FXT pnCCDs are generated by Geant4 simulation. The simulated QE is shown in the following figure, where the green line is for the total efficiency and the red line for the QE of the full energy-peak. The total efficiency is used to determine the arf of FXT.

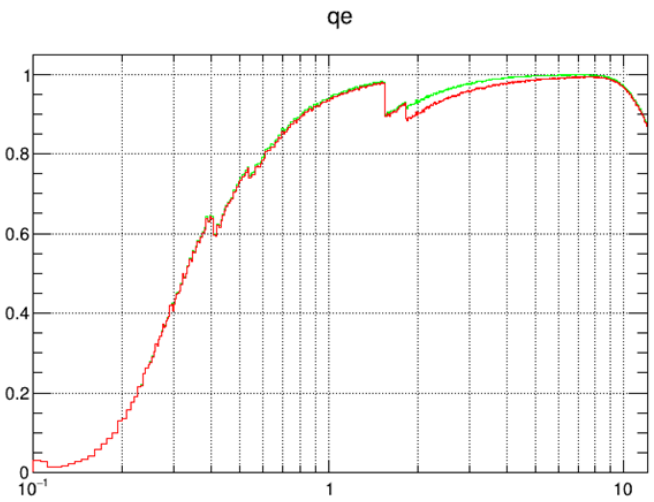


Figure 4-7: The simulated QE of FXT pn-CCD

4.1.5 FXT background

Zhang et al. (*Astroparticle Physics* 137 (2022) 102668) has given an estimation of the in-orbit background of EP/FXT, which is shown in the following figure.

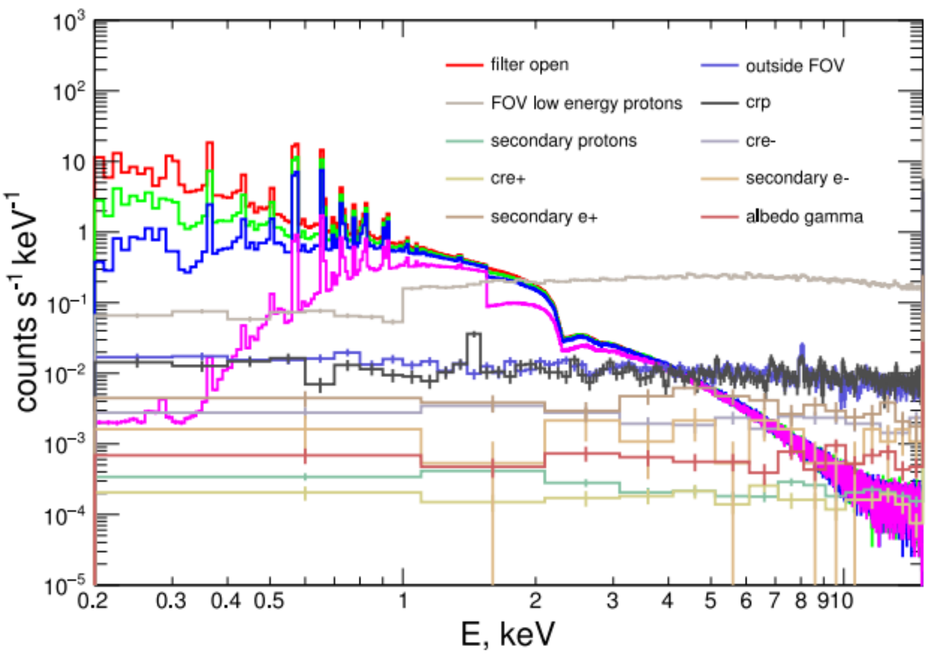


Figure 4-8: The background spectra caused by various space components on the imaging area of the FPD of FXT

The red (green, blue and magenta) line denotes the FOV background of cosmic photons corresponding to the open (thin, medium and thick) filter position on the filter wheel. The "FOV low energy protons" represents the background induced by the low energy protons near the geomagnetic equator through the funneling effect of the mirrors. For the instrumental background components, the "outside FOV" shows that induced by cosmic photons, "crp" by primary cosmic ray protons, "secondary protons" by secondary cosmic ray protons, "cre-" by primary cosmic ray electrons, "cre+" by primary cosmic ray positrons, "secondary e-" by secondary cosmic ray electrons, "secondary e+" by secondary cosmic positrons and "albedo gamma" by albedo gamma rays.

The instrumental background is ~ 3.1×10^{-2} counts s^{-1} keV^{-1} in the imaging area of the focal plane detector (FPD) at 0.5–10 keV, which is mainly induced by cosmic ray protons and cosmic photon background. This corresponds to a level of 3.7×10^{-3} counts s^{-1} keV^{-1} cm^{-2} after normalization to the FPD area. The instrumental background of FXT is lower than that of one eRosita module by seven times. The FoV background, which is induced by the cosmic photons reflected by the optical mirror, dominates below 2 keV.

4.1.6 FXT sensitivity

In the following figure, we present the estimated FXT sensitivity as a function of exposure time (Zhang et al., *Astroparticle Physics* 137 (2022) 102668).

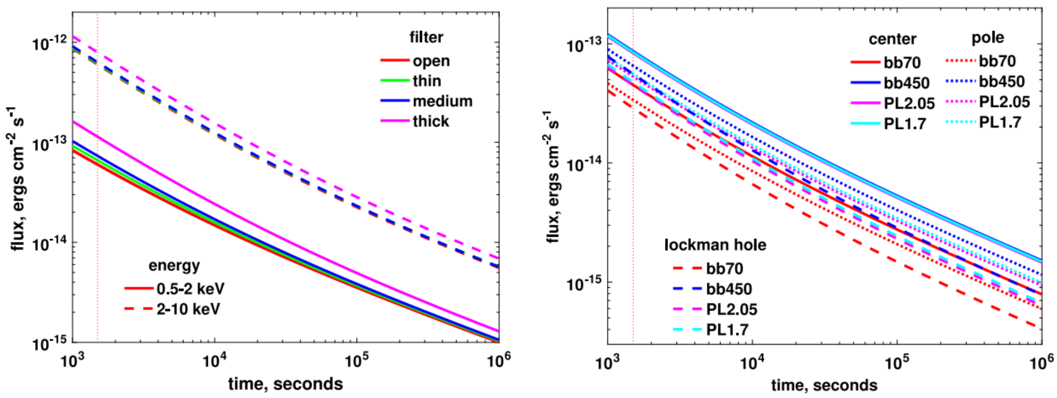


Figure 4-9: The estimated sensitivity of one EP/FXT module.

The vertical dotted line marks a typical exposure time of 1500 seconds. *Left*: Sensitivity is computed for an assumed Crab spectrum, i.e. an absorbed power-law spectrum with an index of 2.05 and a column density nH = 2×10^{21} cm^{-2}. *Right*: The sensitivity of FXT for different pointing directions and source spectral shapes at 0.5–2 keV when the filter wheel is set to open position. Solid lines correspond to the Galactic center pointing direction with a column density nH ~ 10^{22} cm^{-2}, dotted lines Galactic pole with nH ~ 10^{20} cm^{-2}, and dashed lines the Lockman Hole with nH ~ 5×10^{19} cm^{-2}. Red lines indicate the black body spectrum with a temperature of 70 eV, blue lines the black body spectrum with a temperature of 450 eV, magenta lines the power-law spectrum with an index of 2.05 and cyan lines the power-law spectrum with an index of 1.7.

The sensitivity of FXT is calculated based on the simulated background level within the focal spot (a 30″-radius circle), which could theoretically achieve several μcrab (in the order of 10^{-14} erg cm^{-2} s^{-1}) in 0.5–2 keV and several tens of μcrab (in the order of 10^{-13} erg cm^{-2} s^{-1}) in 2–10 keV for a pointed observation with an exposure of 25 min. This sensitivity becomes worse by a factor of $\sim$2 if an additional 10% systematic uncertainty of the background subtraction is included.

4.1.7 FXT time resolution

The three science modes of FXT have different time resolutions, 50 ms for the full-frame mode, 2 ms for the partial-window mode, and 44 μs for the timing mode.

4.1.8 FXT photon pile-up & optical loading

In X-ray astronomy, pile-up refers to a phenomenon where two or more X-ray photons arrive at the same pixel or trigger two or more adjacent pixels of a detector within a single readout frame and are recorded as a single event with an energy that is the sum of the energies of the individual photons. This can cause distortion in the recorded spectrum and lead to incorrect measurements of the source properties. Pile-up is more likely to occur at high count rates. Various techniques, such as using a smaller window around the source or adjusting the readout time, can be used to mitigate the effects of pile-up. For the different read-out modes and different filter positions, the simulated pile-up fraction is shown in the following figure.

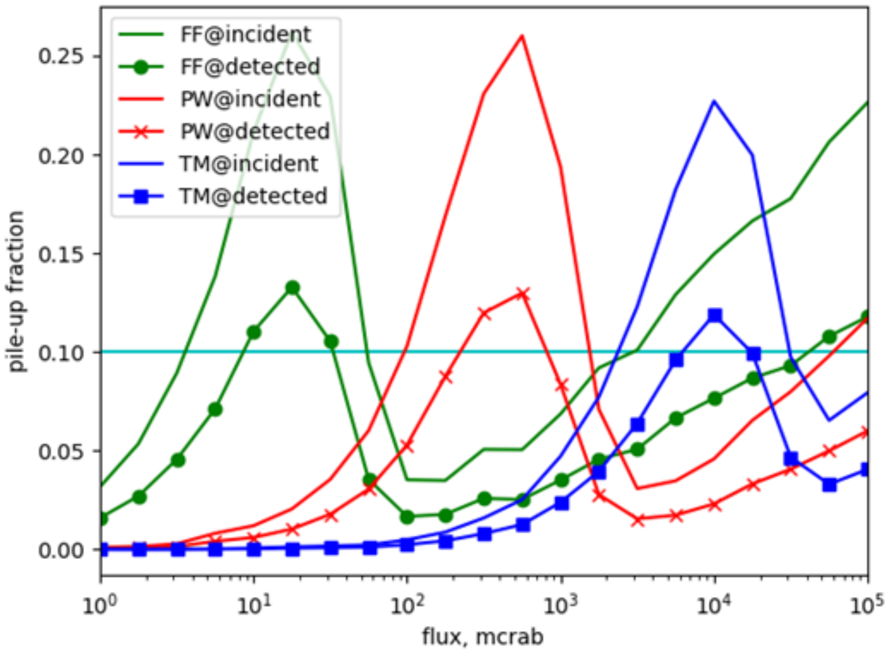


Figure 4-10: The pile-up fraction of valid events, calculated from theoretical simulation.

The solid line represents the results obtained from the perspective of incident photons, while the dotted line represents the results obtained from the perspective of detected events.

Optical loading refers to the amount of star lights that enters the telescope's optical system and is recorded by the detector. Given the experience of XMM-Newton EPIC/PN, there are few optical loading effects from bright stars for the medium filter setup, which is composed of 80 nm Aluminum and 160 nm PI. Considering that the default/recommended filter position of FXT is thin (80 nm Al + 200 nm PI) and that there is an extra layer of 90-nm Aluminum on top of the pnCCD, we conclude that the bright stars won't cause noticeable optical loading effects on the X-ray observation of FXT.

Therefore, FF is recommended for the sources < 5 mCrab, PW for <200 mCrab, and TM for <2 Crab. On-line tools are provided to estimate the effects of pile-up and optical-loading. Please refer to the Section of "FXT On-line Tools" for more details.

4.1.9 FXT out-of-time events

For the imaging modes (FF and PW), the photons are not only registered during the integration time but also during the readout time of pnCCD. These events during the readout time are called out-of-time events (OoT events).

The pnCCD channel is converted to the Pulse Invariant (PI) mode based on its position, due to the gain and CTI. However, the OoT event is assigned a wrong position in image, and leads to a wrong PI correction which will broaden the spectral features.

In the data reduction, a common technique to eliminate the OoT events is the exclusion method. Normally, the fraction of OoT events is about 0.23% for FF and 3.345% for PW. We generate the simulated OoT events from the original events (constructed and calibrated). The images and spectra extracted from this OoT events should be subtracted from those produced from the original events to clean the effects of OoT.

4.1.10 FXT event grade selection

Typically, for the pnCCD, the charge cloud produced by an X-ray photon is probably not localized into one pixel and it can be spread out over several pixels. We use grade algorithm of FXT to identify if the charge in the pixel is due to the main X-ray event or its diffusion, and then reconstruct the event.

The grade of FXT is defined as the figure below. Among them, the grades from 1 to 12 are recommended for general usage of FXT.

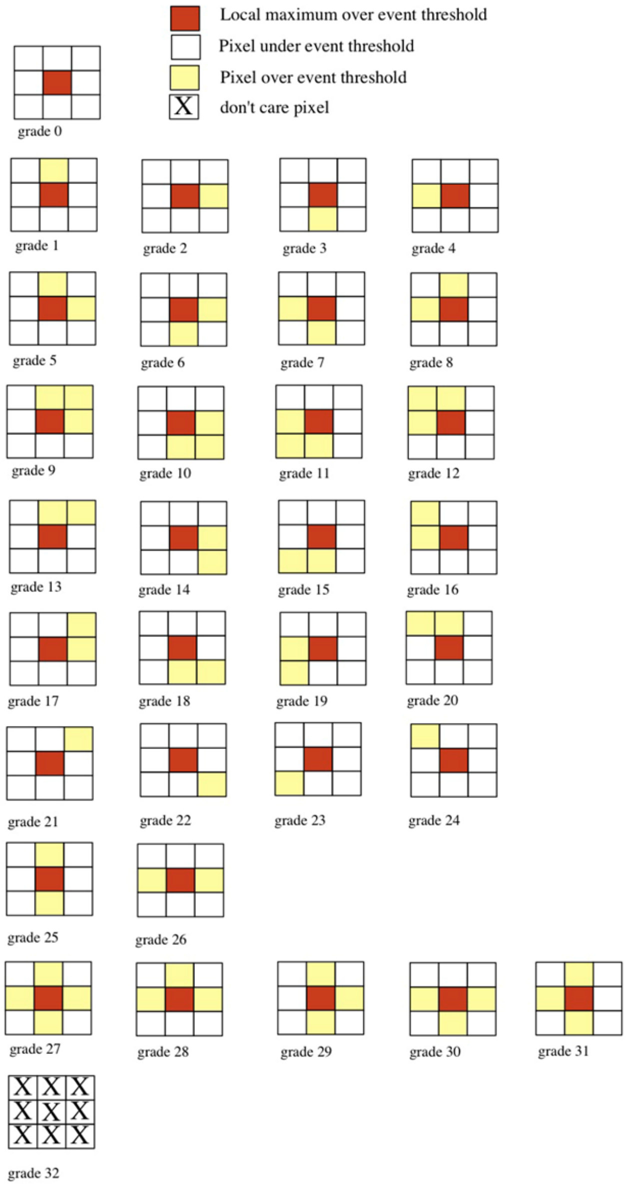


Figure 4-11: The grade definition of FXT (from the data reduction of Swift/XRT).

4.2 FXT Observation Modes

4.2.1 FXT readout modes

FXT is mainly operated in three scientific observation modes:

1) full-frame mode (FF)
2) partial-window mode (PW)
3) timing mode (TM)

In Table 4-2 below, we summarize the properties of various FXT modes.

Table 4-2: The properties of FXT modes.

Science mode	Time resolution	Out of Time [%]	Max. count rate diffuse [s^{-1}] ([mcrab])	Max. count rate (flux) point sources [s^{-1}] ([mcrab])
full-frame mode	50 ms	0.23%	/	5 mCrab
partial-window mode	2 ms	3.345%	/	200 mCrab
timing mode	44 μs	/	/	2 Crab

4.2.2 FXT filters and effective area

The effective area of the FXT module consists of the contribution from effective area of the mirror assembly, the transmission of the filters, and the detector QE of pnCCD.

For the filters, there are six positions on the filter wheel of FXT, which is illustrated in the following figure.

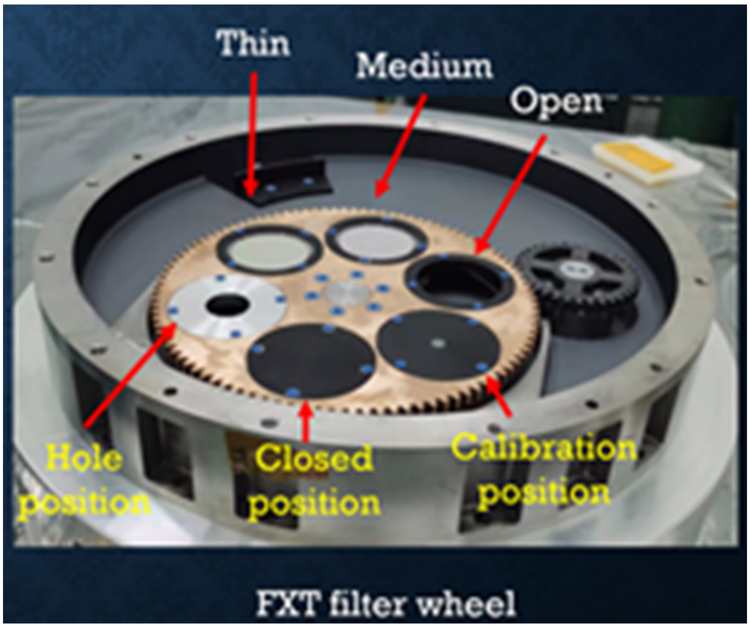


Figure 4-12: The filter wheel of FXT

The calibration position is equipped with an internal ^{55}Fe source. The composition of the thin, medium and closed filters is shown as below. And the hole filter is the same as the thin filter except that it opens a smaller window to suppress the stray lights of the off-axis sources.

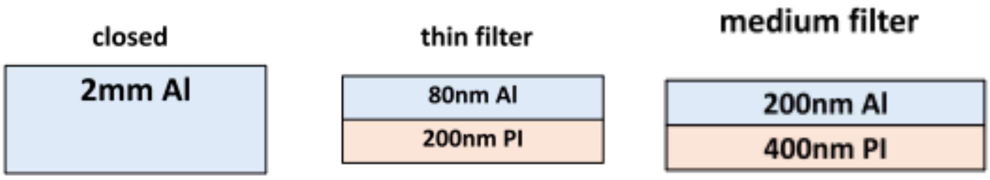
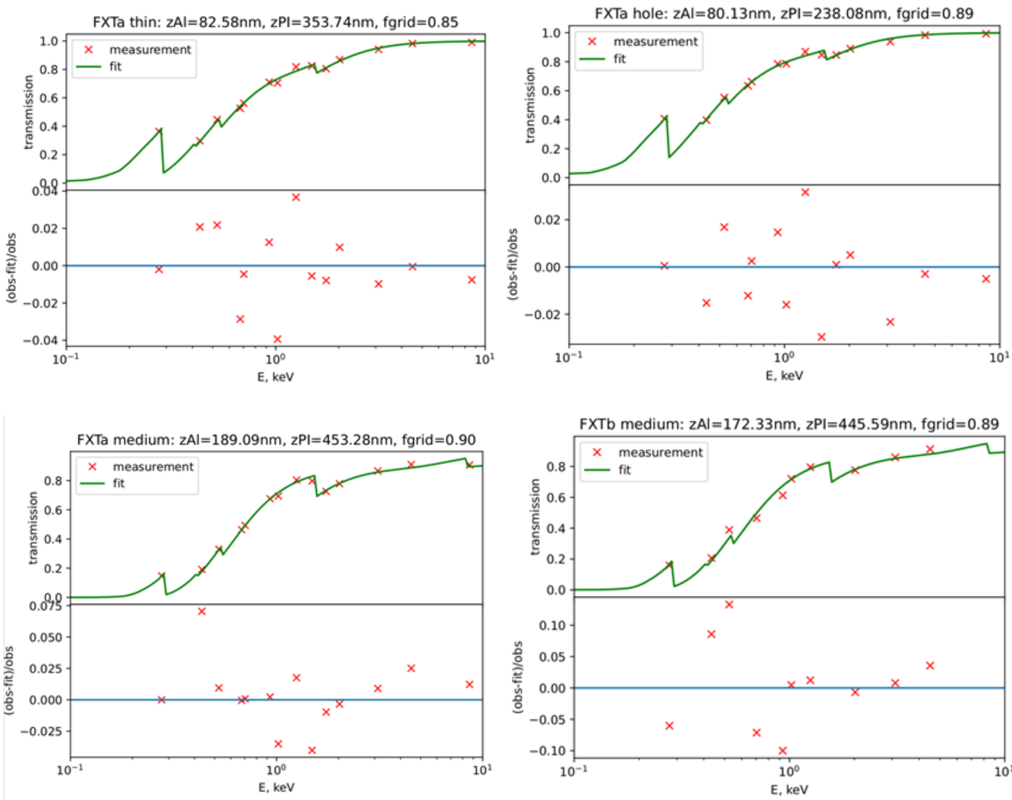


Figure 4-13: The designed geometries of FXT filters

Fitting to the measured transmission data gives the transmission curve like this:



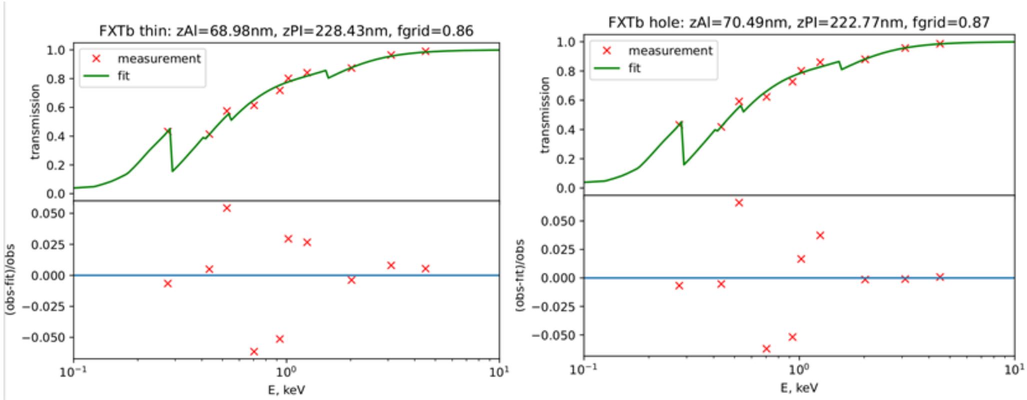


Figure 4-14: The transmission curve of FXT filters

For the effective area of the mirror assemblies of FXTA and FXTB, the fitting results are shown in the figure 4-15.

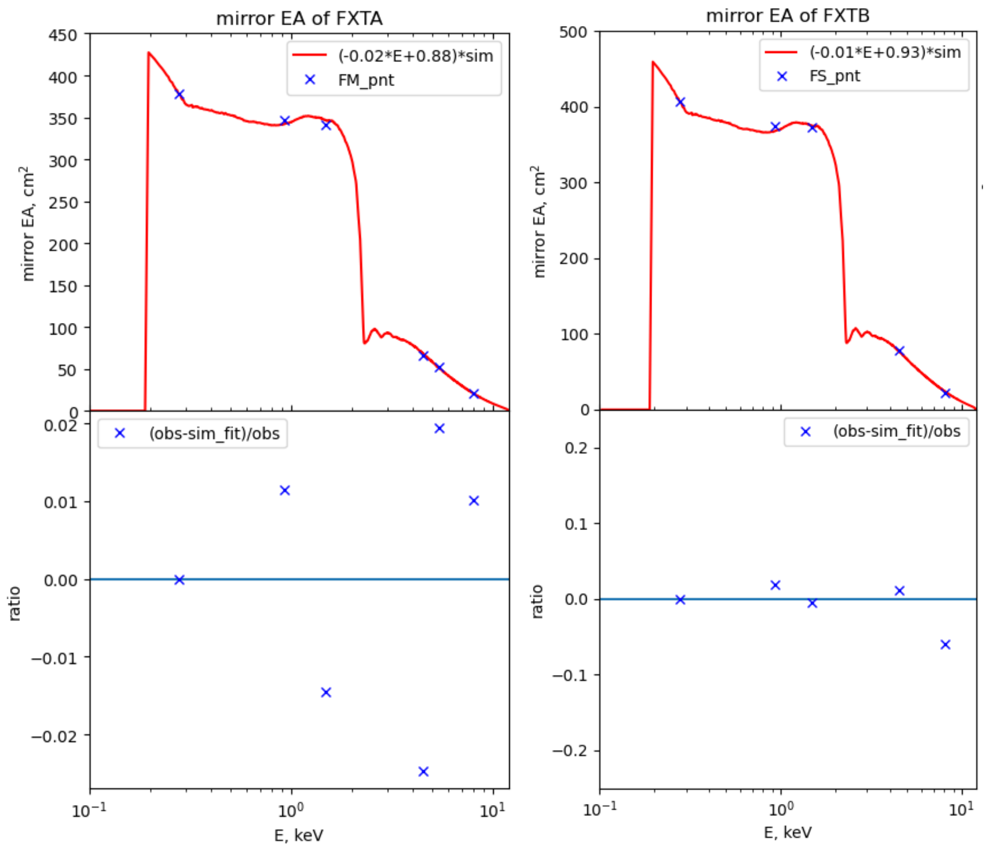


Figure 4-15: The effective area of the mirror assembly

Based on the above fitting results and the QE given in Section 4.1.4, the effective areas of the FXTA and FXTB modules are given in the figure 4-16.

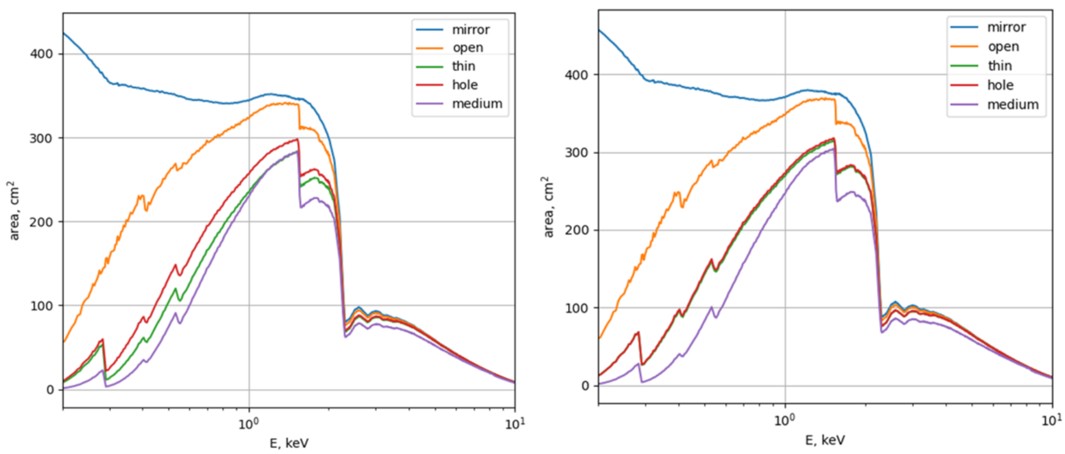


Figure 4-16: The effective areas of FXTA (left) and FXTB (right)

4.3 FXT In-orbit Operation

FXT in-orbit software has three operation modes:

1) Normal mode
2) Auto mode
3) ToO-MM mode

The Normal mode is designed to work in the sky survey observation, the ToO observation and the following-up observation, which can be set by the ground commands. It searches for the sources in the center region of pnCCD (61 pixels × 61 pixels, ~10" × 10"). The key data containing the positions of the brightest 3 sources will be downloaded through Beidou. Then, the spectrum, image and light curve of these sources will be downloaded through VHF, every five minutes.

The auto mode is similar to the normal mode, except that it can automatically switch to the appropriate imaging mode according to the properties of the source detected. FXTA and FXTB are set to the Partial-window (PW) mode by default. Under the auto mode, if no source is found, FXTA will be changed to FF automatically; if the source is too bright, FXTA will be changed to TM. However, please note that this switch can only be automatically performed for once.

The ToO-MM mode is designed to search for the electro-magnetic counterparts of multi-messenger sources in the whole field of view (384 pixels × 384 pixels, ~61" × 61"). In this mode, the key data with the positions of the brightest 3 sources will be downloaded through Beidou, and the ToO-MM data including the binary image and the source positions (up to

50) will be downloaded through VHF.

4.4 FXT Data & Software

4.4.1 FXT Data structure

For science user, the data analysis starts from the FXT data products, which are organized by the Observation ID and shown as followed:

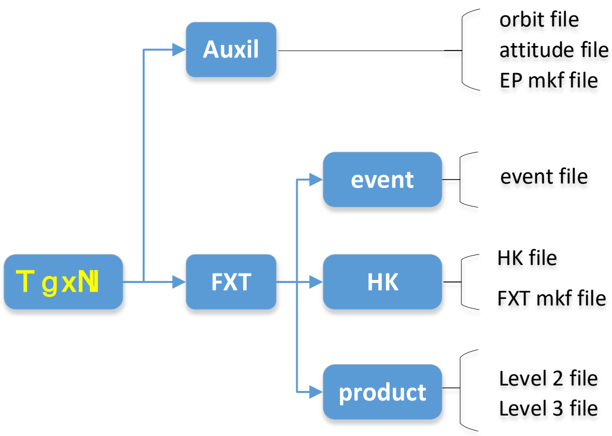


Figure 4-17: The FXT data structure

The 'Auxil' directory stores attitude, orbit, and make-filter file (MKF) data of EP. The 'FXT' directory includes the 'events' and 'HK' directories. The 'event' contains the event files in the science modes and 'HK' stores the MKF and housekeeping data of FXT.

4.4.2 FXT Data reduction software

The Follow-up X-ray Telescope Data Analysis software (FXTDAS) is to achieve the FXT data analysis processing and extract the scientific products, e.g. energy spectra, images, and light curves.

The FXTDAS performs data processing from the calibration, the screening, to the extraction of the collected science data, with several tools to help users finish the data analysis of FXT. The figure below shows the data reduction for the science observation modes FF, PM and TM.

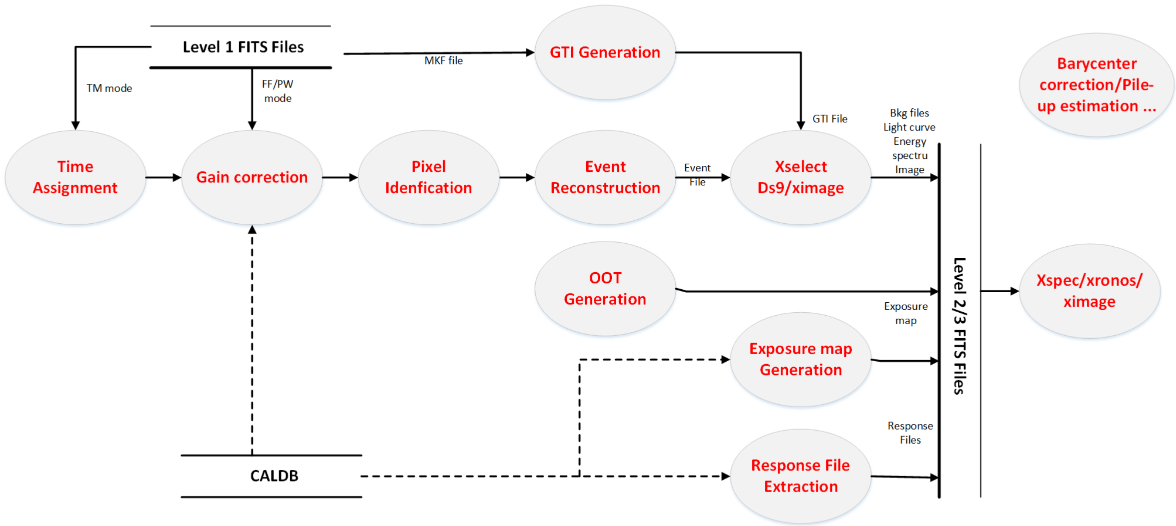


Figure 4-18: The FXT data reduction process

To perform data analysis of FXT, we have developed a set of data analysis software, with different modules to conduct tasks including fxttimecor, fxtpical, fxtgtigen, fxtbadpix, fxthotpix, fxtgrade, fxtootest, fxtexpogen, fxtarfgen, and fxtrmfgen.

1) **fxttimecor (Time Assignment):** This task corrects the time of the event for TM mode based on the Y values stored in the data.
2) **fxtpical (Gain and CTI correction):** This task uses the gain and CTI files in the CALDB and calls on engineering and scientific data that affect this relationship, such as temperature data and the detector coordinate position of events. It then converts the PHA to energy and energy to PI for the input level 1 data products.
3) **fxtgtigen (GTI Generation):** This task mainly generates the GTI files.
4) **fxtbadpix (pixel identification):** This task identifies the bad pixels in pnCCD based on the bad pixel calibration file in FXT-CALDB, and flags the corresponding events.
5) **fxthotpix (pixel identification):** This task searches for the hot or flickering pixels by comparing the counts in each pixel to the mean background counts.
6) **fxtgrade (event reconstruction):** This task assigns the grades and calculates the PI values for the FF, PW and TM modes.
7) **fxtootest (OoT generation):** This task generates the simulated OoT events from the constructed and calibrated events.
8) **fxtexpogen (exposure map generation):** To generate an exposure map, considering the effective exposure duration, bad pixels, and the impact of vignetting.
9) **fxtarfgen (arf generation):** This task calculates and generates the Ancillary Response Files (ARF) corresponding to the input spectrum, taking into account the effects of PSF and vignetting.

10) **fxtrmfgen (rmf generation):** This task extracts the Response Matrix Files (RMF) corresponding to the input spectrum from the FXT-CALDB. The RMF files in the database store both the central region RMF and the averaged RMF.

4.4.3 FXT calibration database

The FXT Calibration Database (CALDB) is an essential resource for researchers working with EP-FXT data. The CALDB contains a comprehensive collection of calibration files necessary for accurate data reduction and analysis. These files provide detailed information about the properties and performance of the EP-FXT detectors, mirrors, and other instrument components. The CALDB is organized into a well-defined directory structure, making it easy for users to locate and access the calibration files required for their specific analysis tasks.

Some of the key calibration files included in the EP-FXT CALDB are:

1) **Ancillary Response Files (ARF):** These files contain information about the effective area of the detectors and mirrors as a function of energy.
2) **Response Matrix Files (RMF):** These files characterize the energy response of the EP-FXT detectors, accounting for energy dispersion and detector resolution.
3) **Point Spread Function (PSF):** These files describe the spatial distribution of X-ray photons as they are focused by the EP-FXT mirrors.
4) **Energy Encircled Fraction (EEF):** These files provide information on the fraction of energy contained within a given radius for a point source.
5) **Telescope Definition (TELDEF) files:** These files describe the geometry and alignment of the EP-FXT detectors and mirrors.
6) **Vignetting files:** These files contain information on the reduction of the telescope's effective area due to off-axis angles.
7) **Filter Transmission (FTRANS) files:** These files describe the transmission properties of the filters used in EP-FXT.
8) **Quantum Efficiency (QE) files:** These files provide information on the detectors' sensitivity to incoming photons as a function of energy.
9) **Gain and Charge Transfer Inefficiency (CTI) files:** These files contain information about the gain calibration and charge transfer inefficiency of the EP-FXT detectors.
10) **Mirror effective area (EFF) files:** These files provide data on the reflectivity and

efficiency of the EP-FXT mirrors as a function of energy.

11) **Background files:** These files contain information on the instrumental and astrophysical background components relevant to the EP-FXT observations.

The EP-FXT CALDB plays a crucial role in ensuring that researchers can obtain the most accurate and reliable results from their analysis of EP-FXT data. By providing up-to-date calibration information, the CALDB enables scientists to fully exploit the exceptional capabilities of EP's FXT and contribute to the advancement of our knowledge of the high-energy universe.

The calibration database is stored under the $CALDB environment, with all contents stored in the data/EP/fxt/ directory, divided into the index, bcf, and cpf directories. The index directory stores the calibration index files, the bcf directory contains basic calibration files, and the cpf directory holds calibration product files.

Table 4-1: The directory structure of FXT-CALDB

TELESCOP	**INSTRUME**	**INDEX/CCLS**	**CCNM**
$CALDB/data/EP/	fxt/	index/	(index files)
		bcf/	badpix/, teldef/, effarea/, ftrans/, qe/, gain/, background_model
		cpf/	psf/, arf/, rmf/, vignetting/, bkg/, eef/

4.5 FXT On-line Tools

4.5.1 FXT online simulator

The FXT online simulator (http://epfxt.ihep.ac.cn/simulation), provided by the EPSC, is an online tool to simulate the observation of one FXT module.

4.5.2 FXT pile-up/optical-loading checker

We also provide an on-line evaluation (http://epfxt.ihep.ac.cn/simulation) to estimate the effects of pile-up and optical loading.

Click the button ‘Filter and Window Mode Evaluation’ on the left in this page, input the source information of interest, select the stellar type of the bright star if suitable and input its visible magnitude, input the observation setup, and click 'calculation'. You will obtain a report of the pile-up fraction and the optical-loading counts if selected.

5 Mission Operation

5.1 Beidou & VHF Channels

Upon the detection of a transient source, its alert information will be downlinked to the ground segment with a latency of about 10 minutes or so. The alert data includes the coordinates, flux, spectral hardness ratio, and possibly a simple light curve of the source. To do this, the Beidou-9 system will be utilized, taking advantage of its short text message capability and global coverage. To enhance the alert capability to transmit more of the quick-look data of transients, the VHF network system of the CNES (France), which is built for the Chinese-French SVOM mission, will be used via collaboration. The quick-look data will be helpful for the assessment and diagnostics of the transients. For time-critical ToO observations, the Beidou system will be used to send uplink commands with short latencies, which will enable time-critical ToO observations such as a search for electromagnetic-wave sources of gravitational-wave events. A sketch of EP data and information flows and ground segment is shown in Figure 5-1.

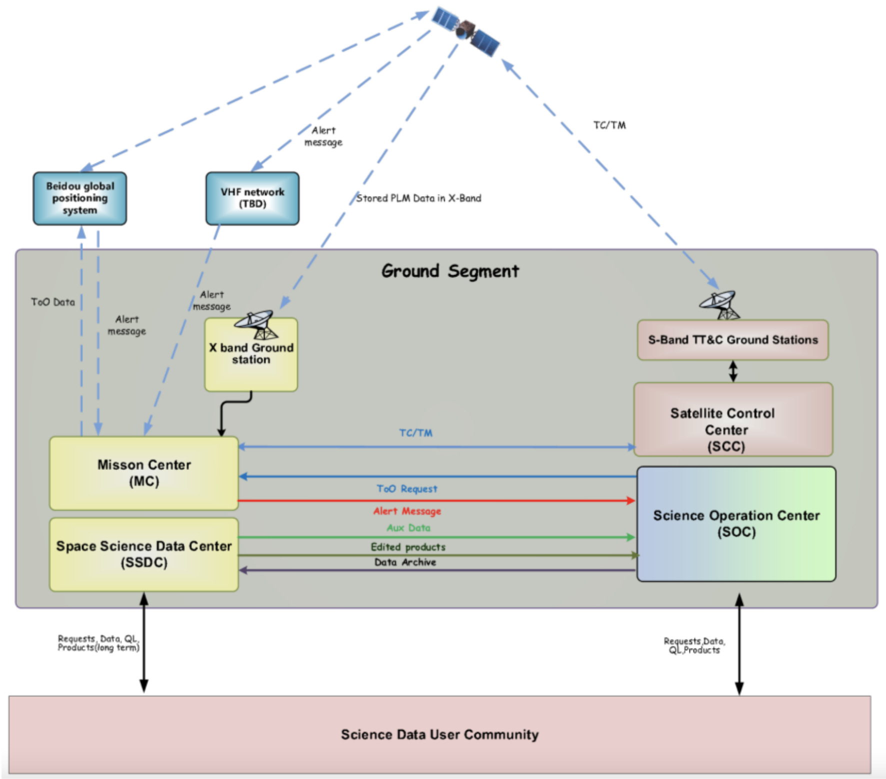


Figure 5-1: Sketch of EP data and information flows and the ground segment

5.2 Ground Stations

The scientific payloads and platform are expected to generate science and housekeeping data of about 134 Gbits per day. The regular telemetry data will be transmitted to the ground segment via the X-band. Several different ground stations are responsible for the X-band downlinking, demodulating, descrambling, decoding, and data recording of EP data, as well as their transmission to the mission centre (MC). During satellite passages inside China, the Sanya station at Hainan will be used; whereas for other passages beyond the reach of Sanya the data downlink will be provided by other ground stations made available via the ESA contribution. The majority of the data generated by the satellite will be transmitted to the MC and Science Operation Centre (SOC) within a few hours.

The supporting capabilities of the Sanya station for the EP satellite data reception:

1) The daily average maximum reception time: 55 minutes.
2) The daily average maximum reception interval: 14.1 hours
3) The passes per day: 6.6

5.3 Mission Center

The Mission Center (MC) is responsible for integrated operation and management of the EP mission. The MC will be developed and operated by the NSSC of CAS.

5.3.1 Overall mission coordination and payload operations

The EPSC will submit ToO observation plans, calibration plans and payload parameter adjustment requirements to the MC. MC is responsible for processing and approving these plans and requirements to generate TC plans and pointing plans, and subsequently send the TC and pointing to the Satellite Control Center (SCC) for uplinking. The SCC generates the final pointing TC plans, and uplinks all the TC plans on available passes before execution.

For routine observations and normal ToO observations, the observation plan should be scheduled in less than 60 minutes, and the mission planning and command generation should be completed in less than 60 minutes. Whereas for high-priority ToO requests, the planning and command generation should be completed in less than 10 minutes (TBC). For time-critical ToO observations, the Beidou system will be used to send uplink commands with short latencies.

5.3.2 Data downlinking and monitoring

MC is responsible for retrieving telemetry data from the SCC, X-band raw data from X-Band stations, and alert message from the Beidou system and VHF network. MC will process these data in real time to monitor payload status and to check for off-nominal situations, and then send the raw data to SSDC for science data production.

5.3.3 Other services

MC also provides other services, including target visibility checker to compute the visibility window of a given target throughout a year, and several technical supports for both routing operations as well as emergency situations.

5.4 EP Science Center

The EP Science Centre (EPSC) is led by the Key Laboratory of Space Astronomy and Technology at NAOC of CAS, in collaboration with IHEP of CAS. The main purposes of EPSC are to support payload operation, to optimize observation efficiency, and to maximum scientific output. The EPSC consists of five subsystems: the EP Science Operation Center (EPSOC); the EP Data Center (DC); two Instruments Centres (ICs); and the EP Science Support Centre (SSC). Figure 5-2 illustrates the structure of the EPSC.

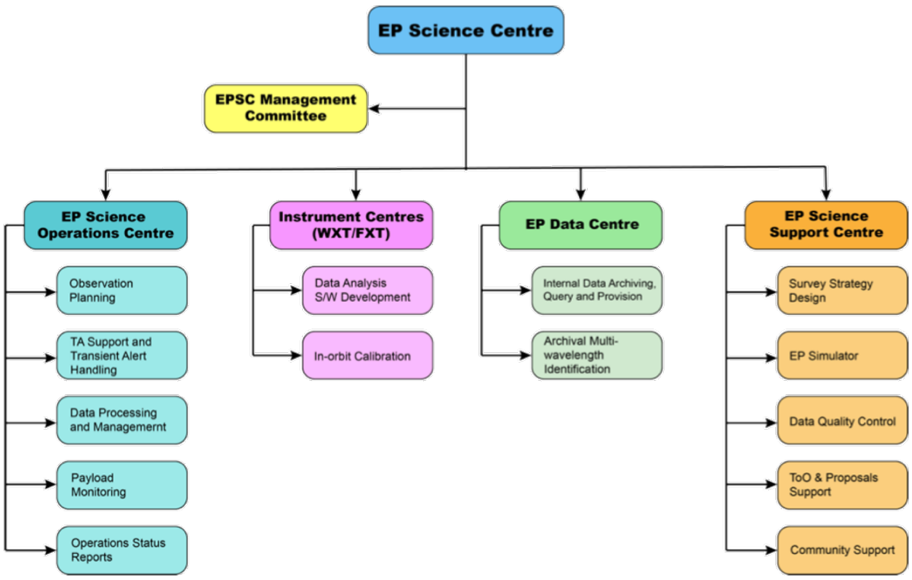


Figure 5-2: The structure of the EPSC

The EP Science Operation Centre is responsible for:

1) **Monitoring payload status:** the EPSOC will monitor instrument operations, performances, and safety. Any instrument anomaly status should be sent to the respective IC immediately.
2) **Planning observation:** EP provides three basic observation modes: the monitoring survey mode, the following-up observation mode, as well as the ToO observation mode. The EPSOC is responsible for preparing short-term and long-term observation plans for the survey mode. For the following-up observation mode, it decides when to resume to survey mode from following-up observations. For the ToO observation mode, the EPSOC will generate the observation plan rapidly. All the observation plans will be transmitted to the EPMC.
3) **Distributing Alert data:** with higher sensitivity and soft X-ray bandpass, the WXT is

estimated to generate several triggers per day. To quickly distribute these alerts, an alert distribution system is developed to broadcast an alert report which is automatically processed by the DTSS.

4) **Reporting on scientific operation:** the EPSOC will generate short- and long-term science operation reports.

The EP Data Center will:

5) **Maintain IT and communication network:** which is responsible for communication within EPSC and with external groups.
6) **Receive external data**: it will handle level 0, housekeeping data received from EP SSDC as well as alert data received from the downlink system or MC.
7) **Develop proposal management tool**: this tool will be used to manage proposals as well as user accounts. In addition to normal proposals, it allows user to submit ToO observation proposal quickly. The proposals will then be assessed by the SOC committee.
8) **Analyze alert data**: an alert database is created for storage, tracking and visualization of the alert data. The format of alert message will also be defined.
9) **Support Transient Advocate (TA)**: each of the triggered transients will be assigned a unique Transient Advocate (TA) who provides scientific guidance and immediate response to the alert. An interactive transient analysis system is developed to support the TAs. It can analyze transient observation data quickly, circulate GCN/Atel report easily, and update following-up observation of the transient.

The two ICs, namely the WXT and FXT instrument centres, will be hosted at the respective leading institute. They are responsible for:

10) **Providing data analysis software**: the data from EP will be processed quickly by the corresponding data analysis software developed at each instrument centre. The WXT adopt the MPO technology, which is a new type of X-ray focusing optic; however, the basic steps in data analysis are similar from more conventional X-ray telescope.
11) **Pipe-line processing of all EP data**: the data is automatically processed by the pipe-line as soon as it reaches each instrument centre, producing high level data products (including X-ray spectra, calibrated event files, and light curves). The data products will be in FITS format, which will be compatible with most of the current X-ray analysis software. They will be sent to SSDC for long-term archiving (at least 30 years).
12) **Providing quality control of data products**: all data products are subject to quality control before delivery to the SSDC. A system will be developed for the verification

and validation of EP high level data products.

13) **Archiving data**: the high-level data products, original observation data, housekeeping data, software source code and binary files, and documents are stored and managed locally at each IC. Internal users can access these data through dedicated EP data portal.
14) **Providing instrument support**: the ICs are also responsible for supporting instrument calibration, providing simulation tools, handling instrument anomaly and monitoring instrument performance.

The EP SSC is responsible for:

15) **Supporting observation strategy planning**: EP will survey a significant fraction of the sky every day. A well-defined survey strategy is therefore essential for the mission. The survey strategy is planned by a science committee, and can be changed based on the instrument performance to maximize the scientific outcomes. The SSC supports the science committee by providing information on instrument performance and performing scientific simulations. Announcement of opportunity will be made by USS. USS will also support a dedicate coordination group to evaluate the ToO proposals and transient follow-up observations.
16) **Coordinating follow-up observations**: multi-wavelength/messenger observation is crucial to reveal the nature of transients. A multi-wavelength/messenger database, which is compiled using data from other missions, will be created by the USS. Transients detected by WXT will be cross-matched with this database. The USS is responsible for planning multi-wavelength follow-up observations and coordinating joint observations with other missions.
17) **Developing EP simulator**: a simulator is essential for SOC to optimize the ToO/follow-up observations and for user to prepare observation proposals. The simulator will integrate the instruments response files (the effective area, the response matrix, and the point spread functions). For a given model, it will simulate observed event list, as well as high level data products (spectrum and light curve).
18) **Providing science support for users**: the USS is the sole point to contact with external users. It supports the users by maintaining an EP website, distributing the software and documents, providing a helpdesk, and organizing software training workshops.
19) **Supporting public outreach:** by organizing public lectures, preparing images and videos.

6 Abbreviations and Acronyms

This appendix contains a list of the abbreviations and acronyms used in EP Technical Handbook.

EP	Einstein Probe
CAS	Chinese Academy of Sciences
NAOC	National Astronomical Observatories, CAS
IHEP	Institute of High Energy Physics
MPO	micro-pore optics
WXT	Wide-field X-ray Telescope
FXT	Following-up X-ray Telescope
LEIA	Lobster Eye Imager for Astronomy
IAMC	Innovation Academy of Micro-Satellite of CAS
ToO	Target of Opportunity
NSSC	National Space Science Center
SITP	Shanghai Institute of Technical Physics
MOC	Mission Operation Center
EPSC	EP Science Center
ESA	European Space Agency
MPE	Max-Planck-Institute for Extraterrestrial Physics
CNES	French Space Agency
EPST	EP science team
ToO-MM	ToO-Multi-Messenger
FSTO	FXT survey-mode target observation
SMC	Science Management Committee
SAA	South Atlantic Anomaly
GTI	Good Time Interval
CALDB	Calibration Database
FPD	Focal plane Detector
OoT	Out-of-time
PI	Pulse Invariant
FF	Full-frame Mode
PW	Partial-window Mode

TM	Timing Mode
ARF	Ancillary Response Files
RMF	Response Matrix Files
PSF	Point Spread Function
EEF	Energy Encircled Fraction
TELDEF	Telescope Definition
VHF	Very High Frequency
MC	Mission Centre
SCC	Satellite Control Center
SOC	Science Operation Center
SSC	Science Support Centre