Explore the Transient X-ray Sky with Einstein Probe

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Abstract

The Einstein Probe is a small mission of the Chinese Academy of Sciences dedicated to time-domain astrophysics to monitor the sky in the soft X-ray band. It will carry out systematic surveys and characterisation of high-energy transients at unprecedented sensitivity, spatial resolution, Grasp and monitoring cadence. Its wide-field imaging capability is achieved by using established technology of micro-pore lobster-eye X-ray focusing optics. Complementary to this feature is deep X-ray follow-up capability enabled by a narrow-field X-ray telescope with a larger effective area. It is also capable of real time triggering and downlink of transient alerts on the fly, in order to activate multi-wavelength follow-up observations by other astronomical facilities worldwide. Its scientific goals are concerned with discovering new or rare types of transients, particularly tidal disruption events, supernova shock breakouts, high-redshift gamma-ray bursts, and possible X-ray sources associated with gravitational wave events. The mission is approved and fully funded, aiming for launch by the end of 2022 with a nominal lifetime of 3 years.

Key words: X-ray: instruments — X-ray: time-domain astronomy — mission: Einstein Probe

1. Introduction

The X-ray sky is rich in transients and variables of various types. With diverse timescales from sub-seconds to years, a large variety of such dramatic objects have been discovered and extensively studied ever since the early days of X-ray astronomy, thanks to successive all-sky monitors in the X-ray (as well as γ-ray) waveband. In recent years the successful operations of *Swift* (Gehrels et al. 2004) and *MAXI* (Matsuoka et al. 2009) have greatly expanded our horizon in monitoring the X-ray sky and advanced our knowledge about the dynamic Universe (Gehrels & Cannizzo 2015; Mihara et al. 2017). New transients, particularly of previously unknown and scientifically important types, continue to be discovered. These include new Galactic black hole X-ray transients (candidates), relativistic outbursts on long timescales interpreted as arising from jets launched by massive black holes following tidal disruption events, gamma-ray bursts (GRBs) at high redshifts up to $z \sim 9$, supernova shock breakouts, etc. To characterise and understand these new phenomena, a large sample of events and detailed observations are needed.

With the advent of major wide-field sky-monitoring facilities across the entire electromagnetic spectrum, such as LSST and LOFAR/SKA, the turn of the decade will see a golden age of time-domain astronomy with flourishing discoveries, as generally anticipated. Even more excitingly, gravitational-wave (GW) astronomy will mature with the 2nd generation of GW detectors being able to detect a potentially large number of events. They call for synergy observations across the electromagnetic-wave spectrum to detect their potential electromagnetic counterparts. This is essential for identifying the associated objects/galaxies and to try to comprehend the nature of GW events.

In the X-ray regieme, the above driving science invokes the next generation of instruments with higher sensitivity and improved angular resolution (a few arc-minutes or better) than those currently available. These requirements are now readily enabled by novel X-ray focusing optics—the lobster-eye micro-pore optics, in which X-ray focusing imaging results in enormously enhanced gain in signal to noise, and thus high sensitivity, while a wide Field-of-View (FoV) can be maintained.

The Einstein Probe (EP) (Yuan et al. 2016b) is an approved and fully funded space astronomy mission of the Chinese Academy of Sciences (CAS), selected for implementation in the 2nd phase of its Space Science Programme. The mission is scheduled for launch by the end of 2022, with an operation lifetime of three years and five years as a goal. EP's wide-field capability is achieved by making use of the lobster-eye focusing technology, with an aim to monitor a large fraction of the sky at high sensitivity and cadence in the soft X-ray band.

2. Scientific objectives

Einstein Probe will carry out systematic wide-field sky monitoring surveys in the soft X-ray band with sensitivity one order of magnitude higher than those currently in orbit. The primary science objectives are:
(1) Discover and characterise cosmic X-ray transients, to reveal their properties and gain insight into their nature and underlying physics.
(2) Discover and characterise X-ray outbursts from normally quiescent black holes, for better understanding of the demography of black holes and their origin and evolution, as well as accretion physics.
(3) Search for X-ray sources associated with gravitational-wave events and precisely locate them.

The mission will address some of the key questions in astrophysics and cosmology, such as the prevalence of black holes in the Universe and how they formed and evolved, and how black holes accrete mass and launch jets; the astrophysical origins and underlying processes of gravitational wave events; details of the physics which operates in extreme conditions of strong gravity; when and where did the first stars form in the early Universe and how they re-ionise the Universe; the progenitors and processes of supernovae (Yuan et al. 2016a).

2.1. Systematic census of transients in the soft X-ray sky

EP will carry out systematic surveys to discover and characterise high-energy transients of various types over a wide range of timescales and at high cadence in the soft X-ray band. It will also perform immediate follow-up observations of newly discovered transients with its narrow-field X-ray telescope onboard, and will issue fast alerts to trigger follow-up observations by global multi-wavelength facilities. Most of the previous and current high-energy astrophysical monitors are operating in the medium and hard X-ray (even gamma-ray) bands, and the soft X-ray sky (from a fraction of 1 keV to several keV) has hardly been monitored extensively with both sufficient sensitivity and cadence. It is thus expected that EP will open up a new window in time-domain X-ray astronomy. This implies that the bulk of the targets and processes being monitored will probably change from the non-thermal, highly relativistic beaming regime (e.g. GRBs, blazars) to thermal, low-/non-beaming regime (e.g. accretion, shock), and thus new types of transients are expected to emerge. Above all, its increased sensitivity will enable unprecedented census of faint or distant high-energy transients beyond the horizons of the previous and contemporary X-ray monitors. As such, a large variety of X-ray transients are expected to be detected, even possibly previously unknown types.

Of particular interest, EP is expected to discover a large sample of black hole tidal disruption events, outnumbering the sparse and heterogeneous cases currently known, and may revolutionise the research of the field (see next subsection). Other important types of transients include GRBs at higher redshifts than the currently known sample (7 GRBs with z=6.2–9.4). These valued events, produced by violent death of stars in the early Universe, would carry unique information on early star-formation and metallicity evolution, and hopefully on the first generation of stars and the re-ionization in the dark early Universe, which are otherwise almost inaccessible from ground-based facilities (Yuan et al. 2016b). Shock breakout emission from supernovae is the prompt X-ray emission produced as the outward-propagating shocks generated by core-collapse breaks out of the stellar surface. X-ray observations can yield important clues to the properties of the progenitor stars. There are only a few candidate events known so far due to their elusiveness given the short burst durations ($\sim 10^3$ s) and moderate brightness. EP is also expected to detect more of such events. Other transient sources to detect and characterise in large numbers include X-ray flashes, low-luminosity GRBs, X-ray rich GRBs, GRB precursors, magnetars, stellar corona flares, classical novae, supergiant fast X-ray transients, and outbursts of active galactic nuclei and blazars, etc.

2.2. Tidal disruption events and quiescent black holes

Stars are tidally disrupted and accreted when their self-gravity cannot balance the strong tidal force as they approach massive black holes (MBHs) closely enough, producing a flare of electromagnetic radiation, preferably peaked in the UV and soft X-ray regime as predicted in theoretical models (Rees 1988). First discovered in the ROSAT survey (Komossa & Bade 1999), there are only a few dozen TDE candidates found so far, mostly in the declining phase via searches from multi-wavelength archives and surveys (Komossa 2015). As perhaps the most unique signature of the existence of MBHs in otherwise quiescent galactic nuclei, a systematic survey of TDEs provides a census of quiescent MBHs in the Universe, i.e. to constrain their occupation fractions in various types and masses of galaxies, which is essential for understanding the formation and evolution of massive black holes and of galaxies. Recent discoveries of a few jetted events by Swift and MAXI indicated that relativistic jets can be launched in at least some of the TDEs (Burrows et al. 2011). A distinctive X-ray lightcurve with large drops and recurrences was also seen in one case, which was interpreted as perhaps the most accessible signature of quiescent binary MBHs, via tidally disrupting a star (Liu et al. 2014).

With its soft X-ray bandpass and high sensitivity, EP is an ideal instrument to discover and study TDEs in a systematic way, and to catch them at the peaks of their X-ray flares out to at least a few hundred Mpc. The estimated detection rate of TDEs may range from several tens to hundreds per year, depending on the actual event rate per galaxy and the occupation fraction of MBHs. The resulting homogeneous sample of TDEs obtained by EP in several years' operation will provide useful constraints on the galactic occupation fraction of MBHs, by combining the incidence of TDEs for various type of galaxies, which can be determined from simulations. Some of the TDEs may be caught at the rising phase of the flares, making it possible to observe at multiple wavelengths over the entire cycle of TDEs from the onset of disruption till complete fading away.

Moreover, EP is expected to discover new stellar- and intermediate-mass black holes lurking in our Milky Way and in nearby galaxies, by detecting their X-ray outbursts due to some kind of instability of gas accretion. In this sense, EP is a black hole finder at almost all astrophysical mass scales.

2.3. Detecting electromagnetic sources of gravitational-wave events

Gravitational wave (GW) astronomy has come of dawn with the direct detections of the first GW event ever, GW150914 (Abbott et al. 2016) and subsequent a few others. Up on the completion of upgrade of Advanced LIGO, Advanced Virgo and other GW observatories, it is highly anticipated that, at the turn of the decade, GW events will be detected in large numbers. The detection of their electromagnetic (EM) counterparts is of great scientific significance in the sense that astrophysical observations in the EM domain will provide independent evidence for further establishing the model interpretation of the events solely based on the general theory of Relativity. Moreover, as the loci of GW sources can only be determined within regions from several hundreds to several tens of square degrees even for the upgraded global GW detector network, the detection of EM counterparts is essential for precisely locating the GW events and thus the identification of associated astrophysical objects. This will enable precisely measuring redshifts (thus the source distance and EM energy budget) and helping understanding the nature, origin and evolution of the progenitor systems. As a potentially even more far-reaching cosmological application, joint detections of GW and EM sources (redshifts) can be used to probe the geometry and expansion of the Universe, and to determine the cosmological parameters (Schutz 1986).

Although no EM counterparts have been reported for the several GW detections made so far[1], strong EM radiation associated with mergers of binary neutron stars or neutron star–black hole binary has been predicted

*1 Note added after publish: On Aug 17, 2017 a historical gravitational-wave event GW170817 resulting from a merger of two neutron stars was detected by ALIGO/AVIRGO and, remarkably, its electromagnetic-wave counterpart was also detected in multi-wavelength from gamma-ray to radio.

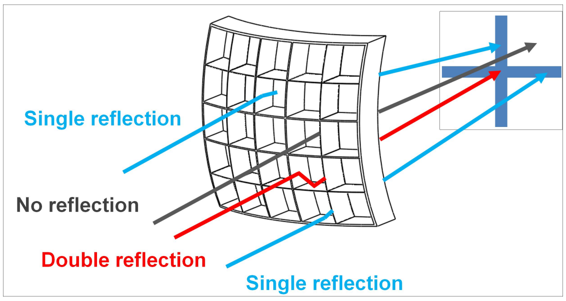

Fig. 1. Illustration of the light path of a point-like X-ray source through a lobster-eye optics

(Zhang 2013). With the combined high sensitivity, large field of view, manoeuvrability and rapid alert downlink, EP has great potential in detecting the EM counterparts of GW events by synergy with the next generation of GW detectors. This may be achieved either by directly detecting X-ray transient sources associated with GW events that happen to be within the large EP FoV, and/or by rapidly observing the sky region to cover the large loci area provided by the GW detectors as ToO observations. For the latter, fast uplink of GW alert data is essential.

3. Lobster-eye micro-pore optics

In general, X-ray focusing is realised by multiple grazing incidence reflections on surfaces almost parallel to the direction of incident X-rays. The conventionally and commonly adopted configuration is the Wolter-I optics, which reflects X-rays by a tubular, rotationally symmetric parabolic surface followed by a hyperbolic surface. The FoV of such optics is inherently small, typically less than one degree. Alternatively, the Lobster-eye Micro-Pore Optics (MPO) (Angel 1979), which mimics the imaging principle of the eyes of lobsters (Figure 1), can reach an unrestricted FoV. The lobster-eye optics is made of a thin spherical micro-channel plate with millions of square micro-pores, the axes of which all point radially to a common centre of curvature. Incoming light at a grazing incidence angle is reflected off the walls of the many tiny pores, and is brought onto a focal sphere with a radius of half the curvature of the optics. For any given direction of incoming light, a same large number of pores, whose reflection surfaces are configured orthogonal to each other, take part in the reflection. Such a configuration has no preferential optical axis, and can thus deliver an un-vignetted FoV as large as, in principle, the entire solid angle of 4π.

Such a focusing optics produces true imaging with a cruciform point spread function, which has a central peaking spot produced by two reflections from adjacent

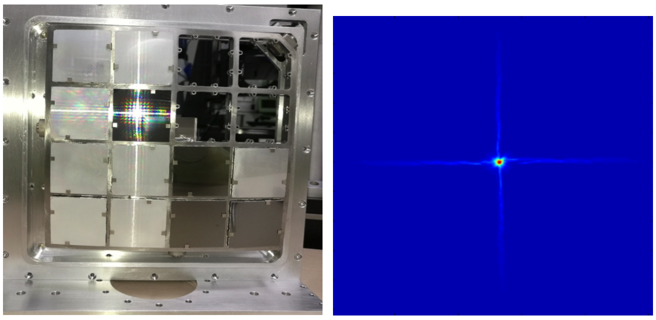

Fig. 2. A demonstration prototype of a lobster-eye MPO telescope assembly developed at X-ray Imaging Lab, NAOC (left-hand), and a true X-ray image formed on its focal plane for a point-like source (right-hand) showing the characteristic cruciform PSF of the lobster-eye optics

walls of the pores and cross-arms produced by single reflections. It can yield a large focusing gain of ∼2000, and a moderate resolution of FWHM the order of arcminutes delivered by the currently commercially available MPO pieces. In practice, the MPO Lobster-eye optics can achieve a FoV of thousands of square degrees with very light weight, which is unique for wide-field X-ray imaging. Figure 2 shows a demonstration prototype of a portion of the optics assembly of one WXT module (left panel), as well as an X-ray image obtained at the focal plane for a point-like X-ray source, i.e. PSF (right panel)

4. Mission concept

4.1. Instruments

EP carries two scientific instruments—an X-ray monitoring instrument Wide-field X-ray Telescope (WXT) with a large instantaneous FoV, and a narrow-field ($\sim 30'$) Follow-up X-ray Telescope (FXT). To achieve both wide FoV and X-ray focusing, the novel micro-pore optics in the lobster-eye configuration (see above) is adopted for WXT. WXT consists of 12 identical modules with a 375 mm focal length, each of which is composed of 6×6 mosaicking MPO plates, subtending $\sim$ 300 square degrees. Figure 3 (upper panel) shows the layout of one WXT module. An optical baffle is attached at the front end of the MPO assembly to shield optical stray light from the Sun, the Moon and the Earth. The 12 modules make a total vignetting-free FoV of WXT of $\sim$ 3600 square degrees (∼1.1 steradian), as illustrated in Figure 3 (lower panel).

WXT has a large-format focal plane of approximately 420 mm×420 mm. The baseline choice of the focal plane detectors is CMOS imaging sensors, developed at the Gpixel Inc. in China. The current design is to mosaic the focal plane detector of one WXT module by 2x2 CMOS

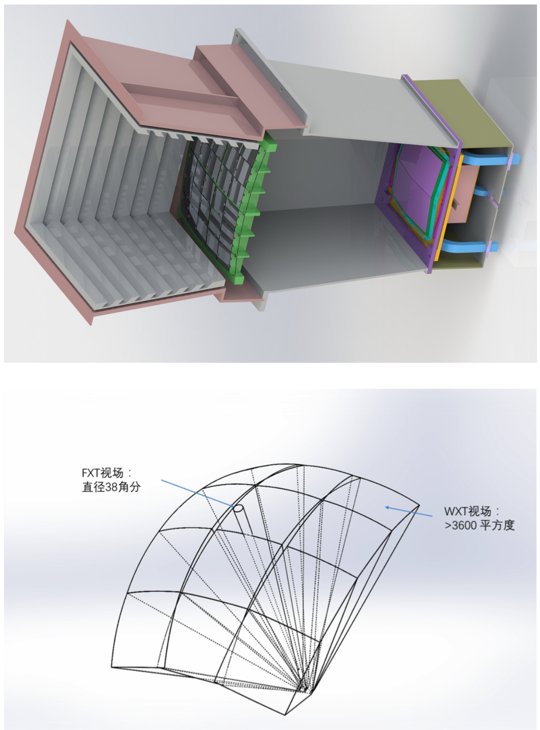

Fig. 3. Upper panel: Design of one module of the wide-field X-ray telescope. Lower panel: Illustration of the field of views of the WXT modules and the follow-up X-ray telescope

sensors. This new type of detectors, which are currently being under development, have 4 k×4 k pixels (of pixel size 15 micro) and 6 cm×6 cm in size. The CMOS detectors have some advantages over CCDs for their fast readout speed, as fast as several tens of frames per seconds. They can thus be operated at moderately low temperatures. One WXT module weights 17 kg including the MPO mirror assembly, detector and electronics unit, optical baffle, structure and thermal control.

The nominal detection bandpass of WXT is 0.5–4.0 keV. Figure 4 shows the effective area curves of WXT derived via realistic ray-tracing simulations taking into account the imperfectness of the MPO arrays (Zhao et al. 2014). The focal plane detector is a CMOS sensor coated with 200 nm-thick Aluminum. The peak effective area is ∼3 cm^2 at around ∼1 keV for almost any direction within the FoV except at the edge of the MPO plates. Thought the effective area for a given direction is not high, it has nearly the same value across the entire FoV, yielding a very large Grasp (effective area times FoV) of the order of $\sim 10^4$ cm^2 sq.deg., which is the largest among all focusing instruments in X-rays. Based on simulations of the X-ray background on the detector, including particle background and incident diffuse X-ray emission (both the cosmic X-ray background and Galac-

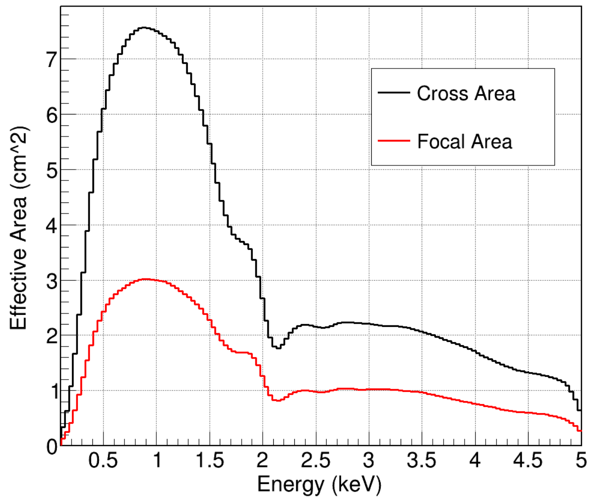

Fig. 4. Simulated effective area curves of WXT for the central focal spot and plus the cruciform arms. The MPO arrays are coated with Iridium, and have surface roughness of 0.55 nm and the tilts of pores following a Gaussian distribution with σ=0.85 arcmin. The focal plane detector is a CMOS sensor coated with 200 nm-thick Aluminum. For details of the simulations see Zhao et al. (2017)

tic diffuse emission), we estimate a theoretical detecting sensitivity for a point-like source[2] for WXT to be approximately a few times 10^{-11} ergs s^{-1} cm^{-2} (in the 0.5-4 keV band) at a 1000 second exposure[3], much more sensitive than previous and current wide-field X-ray monitors, including MAXI and Swift/BAT. The angular resolution is ∼5 arcmin (FWHM) for the central focal spot, limited by the manufacturing precision of the MPO plates for the current technology, and possibly by misalignment and distortion of the plates introduced in the process of assembling.

The EP FXT is composed of a focusing mirror assembly, which is of the conventional Wolter-I type with a focal length of 1.6 m and a CCD detector at the focal plane, cooled down to a temperature in the range of -70°– -100° C . Its covers an energy passband of 0.3–8 keV and has an effective area of $\geq$ 120 cm^2 at around 1 keV, much larger than that of WXT. The total weight of the FXT module is about 146 kg.

The specifications of WXT and FXT are summarised in Table 1. The combination of an array of wide-field lobster-eye modules to act as a soft X-ray transient monitor and a narrow-field telescope for deep follow-up observations gives unprecedented Grasp and sensitivity that will revolutionise X-ray time-domain astronomy.

*2 Assuming a power law spectrum with a photon index of -2 and a Galactic absorption column 3×10^{20} cm^{-2}.

*3 It should be noted, however, that these values are based on the simulations and may be considered to be nominal; the true sensitivity may be somewhat lower considering possible degradation of the performance of the actual MPO plates used, as well as the actual environment of charged particles in orbit.

Table 1. Specifications of WXT and FXT

Parameters	WXT	FXT
Number of modules	12	1
Field-of-view	3600 sq.deg.	38' (diameter)
Spatial resolu. fwhm	5'	<2'
Bandpass (keV)	0.5–4.0	0.3–8.0
E resolution (eV) @1 keV	170	170
Effective area @1 keV (cm^2)	∼3	≥120

4.2. Mission Profile

One possible configuration of the EP payload is shown in Figure 5. The payload has a weight of 340 kg and power of 430 W, and whole satellite has a wight of ∼1050 kg and power of ∼825 W on average. The satellite platform is to be provided by MicroSat, CAS.

The satellite will be in a circular orbit at an altitude of 550-600 km and a period of ∼97 minutes, and an inclination angle of ∼29°. The survey strategy of EP will be composed of a series of pointings to mosaic the night sky in the directions avoiding the Sun, with an avoidance angle to the edge of the WXT FoV always greater than 90 degrees, as illustrated in Figure 6. During its 97-minute orbit of the satellite, three fields will be observed with WXT on the night-side of the sky, each with a 15–20 min exposure. Over three successive orbits almost the entire night sky will be covered, with sampling cadences for a given sky region ranging from 5 to 25 times per day. Monitoring the night sky also makes it possible to perform follow-up observations of detected transients by ground-based optical/IR telescopes. The set of pointing directions is shifted by about 1 degree per day to compensate the daily movement of the Sun on the sky. In this way, the entire sky will be covered within half-a-year's operation of the mission.

There are three basic observing modes for EP: the monitoring survey mode using WXT, the following observation mode using mainly FXT (while WXT continues to be in data acquisition mode), as well as the ToO observation mode of both WXT and FXT upon requests from the ground segment via the command data uplink route.

During observations of WXT, onboard computers will search for transients from X-ray photon events collected in real time over a range of timescales. Once a transient source is detected, classified, and triggered by the data

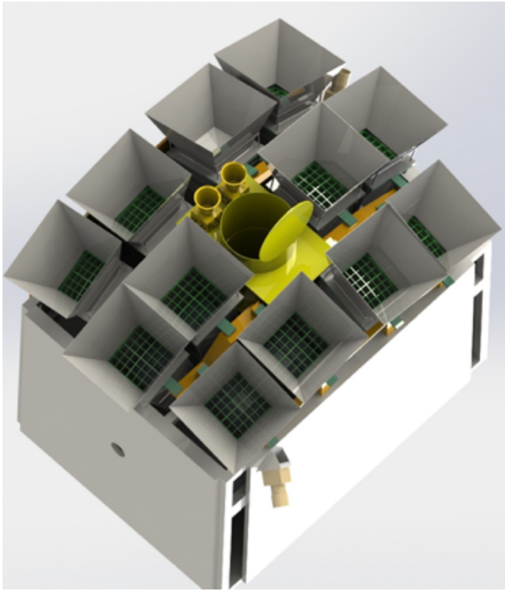

Fig. 5. A possible configuration of the EP payload, with twelve WXT modules and one FXT module (at the centre) (credit: MicroSAT, CAS).

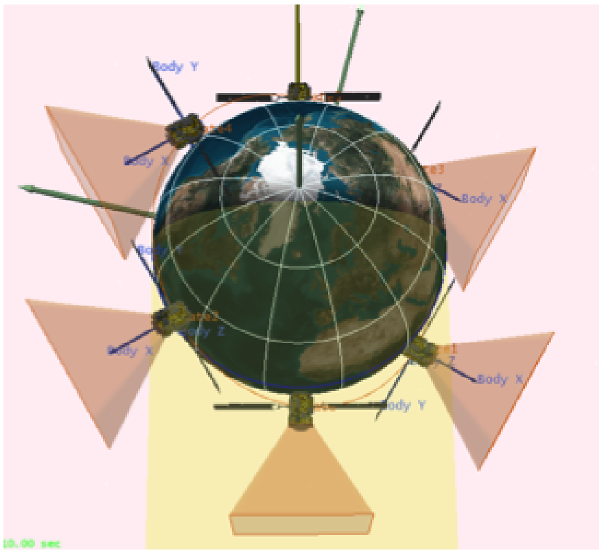

Fig. 6. Illustration of the field-of-view and staring observations in one orbit (credit: MicroSAT, CAS).

processing and alerting system onboard, the satellite will slew (with a slewing speed of 15 degrees per minute) to a new position to enable pointed follow-up observations with FXT by targeting the new source within its FoV. Meanwhile, WXT continues to monitor the new sky region centering the position of the transient. It is essential to transmit alerts quickly to the ground segment, preferably within a few minutes or so. One of the designs is to make use of the short text message capability of the Chinese satellite navigation system *Beidou*, which covers the Asia-Pacific region currently and will be extended to complete the global coverage by 2020. One interesting feature of the *Beidou* system is its quick uplink capability, which will enable fast ToO observations, as required by follow-up observations of urgent multi-waveband and multi-messenger transient sources such as GW events. A second design is to make use of the French VHF ground station system, which is being built for the joint Chinese-French GRB mission SVOM, via international collaboration with CNES currently being under discussion. The normal telemetry data will be transmitted to the ground segment via the X-band using the ground tracking stations of CAS at Sanya, Kashi and Miyun in China.

The EP payload is designed and built jointly by a consortium of CAS's institutions, mainly National Astronomical Observatories, Institute of High Energy Physics, Shanghai institute of Technical Physics, and Shanghai Micro-Satellite Engineering Center, etc. The Space Science Programme of CAS is managed by the National Space Science Centre (NSSC).

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