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NinjaSat: Initial Operation Results of the First Japanese 6U CubeSat for Bright X-ray Sources

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ABSTRACT

We report the initial operation results of the first Japanese 6U CubeSat X-ray observatory NinjaSat, which was launched into a sun-synchronous orbit at an altitude of 530 km on November 11, 2023, by the SpaceX Transporter-9 mission. NinjaSat is designed to observe bright X-ray sources in the sky, such as black holes and neutron stars, which are often difficult to observe with modern large X-ray satellites due to instrument limitations. After the payload verification, NinjaSat observed the Crab Nebula on February 9 and correctly detected the 33.8 ms pulsation from the neutron star. With this observation, NinjaSat met the minimum success criteria. NinjaSat observed 10 X-ray sources by June 20 and successfully demonstrated that many X-ray sources can be observed even with a CubeSat, which is limited in terms of resources available for science payloads. Specifically, NinjaSat conducted the follow-up observation of a newly discovered X-ray transient SRGA J144459.2−604207 two days after its discovery, detecting multiple type I X-ray bursts. NinjaSat also observed type II X-ray bursts from a rapid burster MXB 1730−335. To the best of our knowledge, these are the first observations of X-ray bursts with a CubeSat, enabled by the large effective area of NinjaSat. NinjaSat continues observations to achieve full success and extra success.

INTRODUCTION

In recent years, CubeSats have increasingly been employed in scientific missions. In X-ray astronomy, observations of celestial sources must be performed in space to avoid attenuation of X-ray photons by the atmosphere. The usefulness of CubeSat, with its low cost and short development time, is therefore beginning to be widely recognized, and more and more CubeSat missions are being planned. CubeSat X-ray observatories have already achieved notable successes. For instance, HaloSat[1,2] conducted a near-all-sky survey of oxygen line emission to map the spatial distribution of hot gas in the halo of the Milky Way. PolarLight[3] is an X-ray polarimeter onboard CubeSat to observe bright X-ray compact objects such as black holes and neutron stars.

NinjaSat[4,5] is the first Japanese 6U CubeSat observatory designed to observe bright X-ray sources in the sky. NinjaSat was launched into a sun-synchronous orbit at an altitude of 530 km on November 11, 2023, by the SpaceX Transporter-9 mission. NinjaSat is equipped with two sets of non-imaging gas X-ray detectors (Gas Multiplier Counters; GMCs[6]) for observing 2–50 keV X-rays and Radiation Belt Monitors (RBMs)[7] to ensure the safe operation of GMCs. Ninjasat performs long-term monitoring for bright X-ray sources such as black holes and neutron stars. Modern, highly sensitive large satellites optimized for observing fainter sources often encounter challenges when observing very bright sources due to limitations in their maximum counting rate and data handling capacity. In contrast, NinjaSat, with its relatively modest effective area, can observe even Scorpius X-1, the brightest source in the sky. Using the operational flexibility of NinjaSat, we will conduct multi-wavelength observations with optical or radio telescopes. Furthermore, prompt follow-up observations of X-ray transients discovered with all-sky telescopes are also conducted. The NinjaSat project established three tiers of success criteria:

- Minimum Success: To conduct a pointing observation of an X-ray source and to detect X-ray emissions from the source.
- Full Success: To observe at least two distinct X-ray sources and publish a minimum of two peer-reviewed scientific papers.
- Extra Success: To achieve one of the following two. 1) To conduct simultaneous multi-wavelength observations with other observatories and discover something new. 2) To determine the rotation period of an accreting neutron star and contribute to the discovery of continuous gravitational waves.

This paper presents a brief overview of NinjaSat and its initial operation results.

SPACECRAFT AND PAYLOADS

spacecraft

NinjaSat is a 6U-size (10×20×30 cm^3) CubeSat X-ray observatory. We have outsourced the development and operation of the satellite bus to Kongsberg NanoAvionics, a Lithuanian satellite manufacturer. The science payloads were developed by the RIKEN team and assembled into the satellite in Lithuania in March 2023. This collaboration enables scientists to concentrate on the scientific objectives and the development and operation of the science payloads necessary to achieve them.

Figure 1 shows the schematic illustration of NinjaSat, which is based on the NanoAvionics M6P satellite bus and customized to accommodate our scientific payloads. Approximately 2U of the 6U volume is occupied by two GMCs and two RBMs. The star tracker's foresight is aligned with those of detectors. The Attitude Determination and Control System (ADCS), which includes a star tracker, six sun sensors, four reaction wheels, and a three-axis magnetic torque, provides a pointing accuracy of less than 0.1 degrees. The key information on NinjaSat is summarized in the table 1.

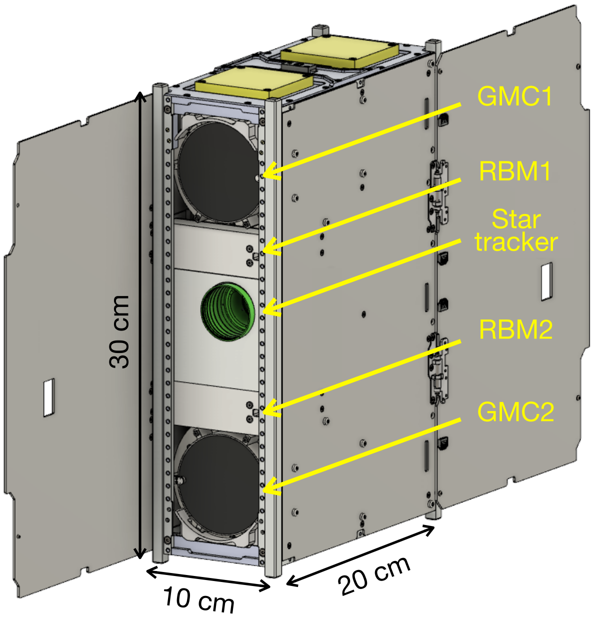

Figure 1: The NinjaSat observatory viewed from the side without solar panels

Science payloads

NinjaSat has two sets of GMC and RBM, the former serving as the primary science payload for observing X-rays from celestial sources. GMC is a 1U non-imaging gas X-ray detector sensitive to 2–50 keV X-rays, as shown in figure 2a. In CubeSat missions, power budgets and space constraints make it difficult to install cooling systems. Therefore, employing gas detectors is advantageous because they do not require temperature control and can expand the sensitive volume more easily compared to other types of detectors, such as semiconductor detectors.

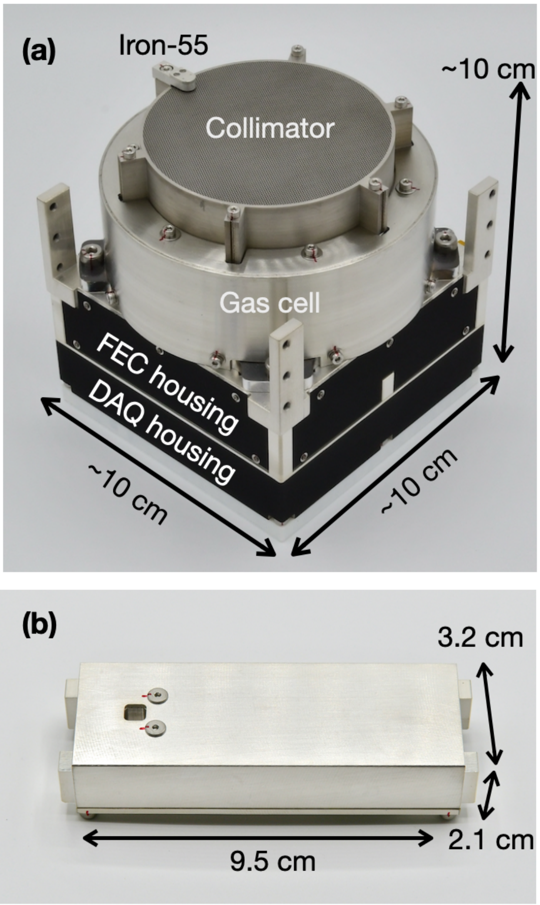

Figure 2: Photographs of the NinjaSat payloads.

GMC consists of a gas cell equipped with a space-proven Gas electron multiplier (GEM),[8,9] a high voltage supply and analog signal processing board (front-end card; FEC), a digital signal processing board (data acquisition board), an X-ray collimator with a field of view of 2.1°, and iron-55 calibration source. GMC is designed to fit into a compact 1U-size (10 cm cubic) space, suitable for utilization on a CubeSat. The most significant feature of the GMC is its large effective area of 32 cm^2 at 6 keV, which is more than one order of magnitude larger than the X-ray detectors onboard previously launched CubeSat, leading to NinjaSat's capability to observe over 100 objects with X-ray fluxes of several 10^{-10} erg cm^{-2} s^{-1} for about 1-day observation.

To ensure the safe operation of the GMC, Ninjasat is also equipped with RBMs, as shown in figure 2b, that continuously measure the charged particle flux in orbit. High voltages of up to 2 kV are applied to the GMCs. In high-radiation regions such as the auroral zones and South Atlantic Anomaly (SAA), scheduled commands should ramp down the high voltage to prevent breakdowns of GMCs due to discharge. The role of the RMB is to detect unexpected increases in radiation, such as during solar flares; alerts are sent to GMCs, which then automatically ramp down the high voltage. More detailed aspects of spacecraft, GMC, and RBM are described in Tamagawa et al.(2023),[4] Takeda et al.(2023),[6] and Kato et al.(2023),[7] respectively.

Table 1: Key information about NinjaSat

Item	Value or Note
Size	6U CubeSat (NanoAvionics M6P)
Power consumption	16.4 W
Weight	8.14 kg
Orbit	Sun Synchronous Orbit
Altitude	519 km (Semi-major axis altitude)
Communication	S-band & UHF
Ground station	Svalbard (primary) & Awaruwa (backup)
Downlink	60 MB day^{-1} (minimum)
Launch date	2023 November 11 10:49 (PST)
Launcher	SpaceX Falcon 9
Launch mission	Transporter 9
science payloads	Two Gas Multiplier Counters (GMCs)
	Two Radiation Belt Monitors (RBMs)

OPERATION

The operation of NinjaSat can be broadly categorized into satellite bus operations and payload operations. NanoAvionics handles satellite bus operations such as attitude control and communication with ground stations, while the RIKEN team is responsible for payload operations, including selection of celestial targets, determination of observation schedules, and creation of operational commands for payloads. Contacts are made three times daily, primarily using Svalbard, with Awaruwa serving as backup. Downlinked data is automatically processed by developed ground software for quick look assess-

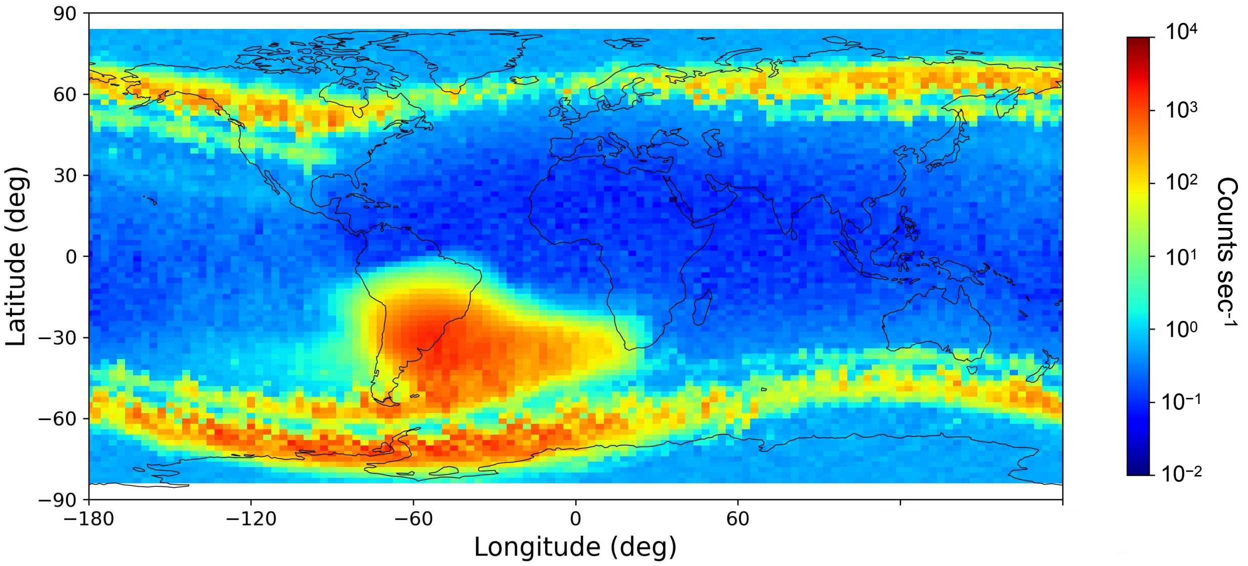

Figure 3: Average count rate map of RBM1 observed between 5 and 22 April.

ment of payload and satellite health. Furthermore, observation data undergoes automatic processing by pipeline software incorporating ground and in-orbit detector calibration results, adding event timings and energy information, and is archived in a format suitable for analysis using the standard X-ray astronomy analysis software HEASoft/FTOOLS.[10] For further details, please refer to Ota et al (2024).[11]

Communication with NinjaSat is primarily conducted via the Svalbard ground station. The high latitude of the Svalbard station offers frequent communication opportunities for NinjaSat in its polar orbit. NanoAvionics operators manage the communications between the satellite and the ground stations. The RIKEN team determines the pointing intervals for sources to be observed, which are then verified by the ADCS team at NanoAvionics before the attitude file is uploaded to the satellite. To create the pointing intervals for celestial sources, we first extract time periods when (1) the satellite is not in communication with the ground station, (2) the source is visible, and (3) the high voltage of the GMC can be applied. Subsequently, the observation time is adjusted to ensure that the efficiency of battery charging exceeds 50% of the total orbit. The efficiency is estimated by multiplying the charging time by $\cos\theta$ to account for the times when the angle θ between the satellite's solar panels and the sun is not 90°. The efficiency of observing each object depends primarily on the extent of Earth occultation and the requirement set by the star tracker that the solar separation angle must be greater than 40°. These factors are influenced by the celestial position of the object in the sky and the time of observation. Therefore, to maximize overall observation efficiency, operations sometimes involve dividing the observed targets between the daytime and nighttime portions of the satellite's orbit.

Under nominal operations, new attitude files are uplinked approximately twice a week. On the other hand, if an X-ray transient discovery is reported and deemed scientifically significant, a new attitude file can be uplinked within a few hours to a day, enabling prompt follow-up observations. This flexible communication and operation strategy ensures that NinjaSat can quickly respond to transient X-ray events, maximizing its scientific output.

INITIAL OPERATION RESULTS

Satellite commissioning and payload verification

After launch on November 11, 2023, NinjaSat communicated with the ground station via UHF and S-band, followed by functional verification of the satellite, such as the electric power system (EPS) and ADCS. Satellite commissioning by NanoAvionics was completed by mid-January 2024, after which the RIKEN team started the initial payload verification.

RBMs have been mapping the charged particle flux in orbit, and the results are used to determine and adjust the region in which GMCs conduct astronomical observation. Figure 3 shows the average count rate map observed with RBM1 Counter 2 (corresponding to kinetic energies of about 5–200 MeV for protons) between 5 to 22 April. The SAA and the auroral belts surrounding the North and South Poles are clearly visible, with maximum count rates exceeding 1000 counts sec^{-1}. The sun-synchronous orbit with an orbital inclination of 97° provides particle count rate maps for almost the entire planet approximately every six days. We regularly update the operational region of GMC using count rate maps of RBM that reflect the impact of increasing or decreasing solar activity. Currently, the astronomical operational area of the GMCs covers approximately 37% of the total area, and this percentage could increase in the future with an improved understanding of the orbital radiation environment.

After the start-up of the GMCs, housekeeping data such as detector temperature and noise levels were checked. Subsequently, a test pulse acquisition test was carried out to verify the functionality of the FEC and DAQ board in signal processing, confirming that there were no issues. The high voltage application area of the GMC was then defined based on the RBM observations. Figure 4 shows the energy spectrum for the iron-55 calibration source, which is a radioactive isotope emits mainly 5.9 keV X-rays. We used this emission line to calibrate the detector energy response, finding a gain increase of about 20% before and after launch. The energy resolution, however, remained approximately 20% at 5.9 keV in full width at half maximum, consistent with the error range of the pre-launch measurements. No significant variations in detector gain have been observed since then.

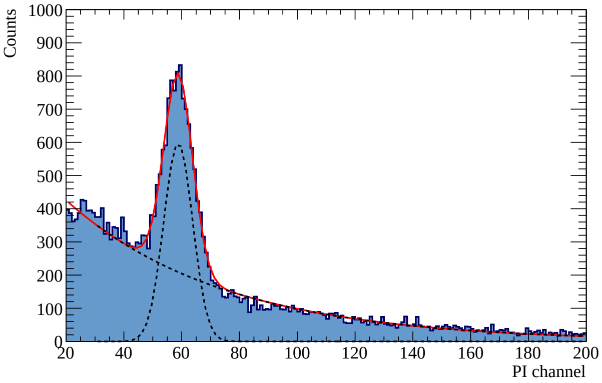

Figure 4: Energy spectrum for iron-55 calibration source mearsued with GMC1. The conversion factor from PI channels to X-ray energy is approximately 0.1 keV ch^{-1}. The spectra were fitted with a Gaussian + exponential model. The best-fit model is indicated by the solid red line.

Observation results to date

After the initial payload verification, NinjaSat first observed the Crab Nebula to perform a timing and energy calibration. The Crab Nebula is a standard candle in X-ray astronomy because of its well-known X-ray pulse period and energy spectrum. As shown in figure 5, NinjaSat correctly detected a 33.8 ms pulsation from the X-ray pulsar located at the center of the Crab Nebula, which confirmed that the relative time information was properly assigned to the X-ray photons. The absolute time was then verified by correcting the phase of each photon using the regularly updated Crab ephemerides observed by the Jodrell Bank Observatory.[12] The results were found to be consistent with other X-ray satellites. The detailed analysis is outside the scope of this Letter and will be reported elsewhere. With this observation, NinjaSat met the minimum success criteria and proceeded to the planned scientific observations.

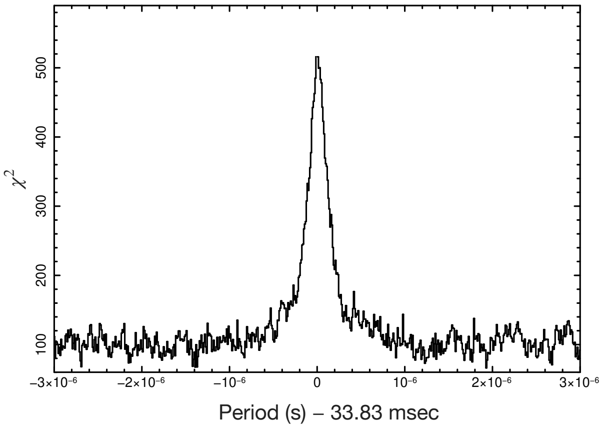

Figure 5: Periodogram of Crab pulsar obtained from approximately 1 ks observation by GMC1.

The first science target of NinjaSat was a newly discovered X-ray transient SRGA J144459.2−604207[13] (hereafter SRGA J1444). SRGA J1444 was initially detected by the Mikhail Pavlinsky ART-XC telescope on Spectrum Roentgen Gamma on February 21, 2024,[14] and subsequently confirmed by the Monitor of All-sky X-ray Image (MAXI)[15] and The Neil Gehrels Swift Observatory.[16] The follow-up observations with NICER revealed the presence of 447.9 Hz pulsations and type I X-ray burst, identifying SRGA J1444 as an accretion-powered millisecond X-ray pulsar.[17,18] NinjaSat also observed SRGA J1444 on February 23 and started a monitoring campaign on February 26. NinjaSat detected three X-ray bursts by February 28. We reported these results to The Astronomer's

Table 2: Source list observed with NinjaSat by June 20, 2024

Source name	Dates in 2024
Crab Nebula	February 9–11, 22–2, March 17–29, April 2–11, 18–19
SRGA J144459.2−604207	February 23–24, February 27 to March 18
Cygnus X-1	February 24–27
Scorpius X-1	April 19, June 11–12
Hercules X-1	March 30 to April 2, April 24 to May 2, June 7–10
4U 0115+63	April 13–14
GX 310−2	April 15–17
MXB 1730−335	June 11–13
EXO 0748−676	June 13–23
SMC X-1	June 13–14, 19–20

Telegram,[19] an internet-based short-notice publication service for the rapid sharing of new astronomical observational information to researchers worldwide. To the best of our knowledge, this is the first observation of X-ray bursts with a CubeSat, enabled by the large effective area of NinjaSat.

MXB 1730−335 is known as one of two sources exhibiting type II X-ray bursts and is commonly referred to as a rapid burster.[20] Unlike type I X-ray bursts, which are caused by thermonuclear runaway on the surface of the neutron star, type II X-ray bursts are thought to be caused by sudden changes in the accretion rate onto the neutron star. This could occur due to instabilities in the accretion disk or sudden releases of accumulated material from the disk. These bursts are characterized by their rapid onset and short duration, typically lasting from a few seconds to a few minutes.[21] NinjaSat observed this object from June 11, 2024, at 13:00 UT to June 13, 2024, at 11:01 UT, with a net exposure time of 16.7 ks. Figure 6a shows the entire X-ray light curve observed with GMC1 in the 2-20 keV band. The shaded grey region corresponds to the observation interval shown in figure 6b. Persistent emissions, including background events, were approximately 5 count s^{-1}, whereas the count rate frequently increased up to a maximum of around 30 count s^{-1}, indicating that more than 100 bursts were clearly detected.

Since the observation of Crab Nebula on February 9, NinjaSat has observed 9 X-ray sources by 20 June. The list of sources observed with NinjaSat and their observation periods are summarised in table 2. As originally planned, NinjaSat demonstrated that many X-ray sources can be observed even with a CubeSat, where space for detector and development costs are limited. NinjaSat continues observations to achieve full success and extra success.

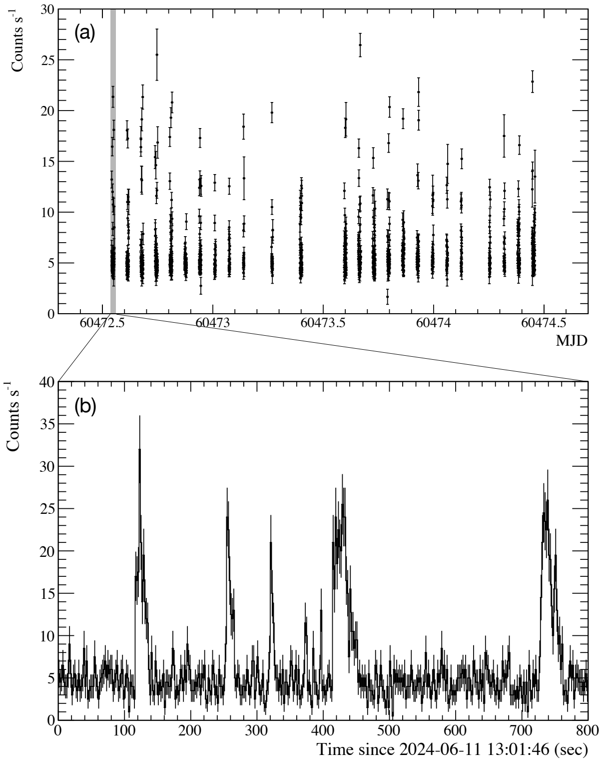

Figure 6: (a) 2–20 keV light curve of MXB 1730-335 observed by GMC1 with 20 s bin. The shaded grey region corresponds to the observation interval in (b). (b) Example of burst light curve with 2 s bins.

SUMMARY

NinjaSat is the first Japanese 6U CubeSat X-ray observatory launched into a sun-synchronous orbit at an altitude of 530 km on November 11, 2023, by the SpaceX Transporter-9 mission. After the payload verification in orbit, NinjaSat observed the Crab Nebula on February 9 and successfully detected the 33.8 ms pulsation. With this observation, NinjaSat met the minimum success criteria. NinjaSat observed 10 X-ray sources by June 20. In particular, NinjaSat conducted the follow-up observation of the newly discovered X-ray transient SRGA J144459.2−604207 two days after its discovery, detecting multiple type I X-ray bursts. NinjaSat also observed type II X-ray burster MXB 1730−335. To the best of our knowledge, these are the first observations of X-ray bursts with a CubeSat. Although NinjaSat's X-ray detection sensitivity is inferior to that of large satellites, it is the highest ever achieved by CubeSat missions. By taking advantage of its large effective area, NinjaSat successfully demonstrated that many X-ray sources can be observed even with a CubeSat. This large effective area also enabled the capability to accurately measure millisecond-order time variations in sources with X-ray fluxes on the order of Crab Nebula with about 1 ks observations.

Acknowledgments

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