**SSC23-WIV-06**

# NinjaSat: 6U CubeSat Observatory for Bright X-ray Sources

Toru Tamagawa, Takao Kitaguchi, Yo Kato, Tatehiro Mihara, Kentaro Taniguchi
RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan; +81-50-3502-2477
tamagawa@riken.jp

Teruaki Enoto
Kyoto University, Kitashirakawa Oiwake-cho, Kyoto, Japan

Tomoshi Takeda, Yuto Yoshida, Naoyuki Ota, Syoki Hayashi, Sota Watanabe, Arata Jujo,
Amira Aoyama, Yuanhui Zhou, Keisuke Uchiyama
Tokyo University of Science, 1-3 Kagurazaka, Shinjuku, Tokyo 162-8601, Japan

Wataru Iwakiri
Chiba University, 1-33 Yayoi-cho, Inage-ku, Chiba, Chiba 263-8522, Japan

Masaki Numazawa
Tokyo Metropolitan University, 1-1 Minami-Osawa, Hachioji, Tokyo 192-0397, Japan

Hiroki Sato
Shibaura Institute of Technology, 307 Fukasaku, Minuma, Saitama, Saitama 337-8570, Japan

Chin-ping Hu
National Changhua University of Education, Changhua, 50007, Taiwan

Hiromitsu Takahashi
Hiroshima University, 1-3-1 Kagamiyama Higashi-Hiroshima, Hiroshima 739-8526, Japan

Hirokazu Odaka
Osaka University, 1-1 Machikaneyama, Toyonaka, Osaka 560-0043, Japan

Tsubasa Tamba
ISAS/JAXA, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan

## ABSTRACT

NinjaSat is a 6U CubeSat observatory designed for long-term monitoring of bright X-ray sources, such as binary systems between normal stars and black holes or neutron stars. NinjaSat is the first Japanese CubeSat dedicated to astronomical observation, and it is also a mission to demonstrate that even a small satellite, which can be developed quickly and inexpensively, unlike large satellites, can perform excellent scientific observations. NinjaSat realizes the world's highest X-ray sensitivity in CubeSat missions by using gas X-ray detectors filling the entire space allocated for science payloads. The fabrication of the flight model payloads began in 2021, and testing at the payload component level was completed in August 2022; as of April 2023, the payloads were integrated into the NanoAvionics 6U bus (M6P) in Lithuania. After four months of testing, the payload will be stored in the Exolaunch deployer in August and launched by the SpaceX Transporter-9 mission in October 2023. This paper will describe the scientific objectives, satellite structure, payloads, and operations of NinjaSat.

## INTRODUCTION

The universe contains various sizes of objects, such as normal stars, black holes, neutron stars, galaxies, galaxy clusters, etc. Today, it is known that almost all the objects in any hierarchy emit X-rays. High energy (X-ray) astrophysics is the study of the properties of these objects through the observations of X-rays, gamma-rays, and other messengers. Since X-rays from celestial objects are absorbed by the atmosphere of the Earth, X-ray astrophysics requires an X-ray detector on board a satellite to be carried out in space. Therefore, X-ray astrophysics is a relatively new field in astronomy pioneered in the 1960s when satellites and rockets became easy to use.

In recent years, scientific satellites have continued to grow bigger as observational instruments have become larger and more complex. While some science themes can only be done with such large satellites, even small satellites with limited resources can conduct scientific research and make new discoveries. The commercial use of low Earth orbit is progressing, and the basis for less expensive X-ray astrophysics studies using small satellites and CubeSats is being established. Under these environments in space missions, we aimed to develop an X-ray astronomical satellite to demonstrate that good science can be achieved with CubeSats.

Scientific CubeSats for X-ray or gamma-ray observations have already begun to be launched; for example, HaloSat,[1] PolarLight,[2] and GRBAlpha.[3] They have unique science objectives, but the satellites and detectors specialize in specific purposes. These satellites with either a small effective area of onboard detectors or no capability for pointing observations of specific celestial objects: no CubeSat has been launched for general-purpose X-ray astronomical observations. For this purpose, sufficient energy bandwidth and an effective area to collect photons are essential. We started the NinjaSat project in 2020, intending to develop a general-purpose X-ray satellite.[4]

## THE NINJASAT PROJECT

NinjaSat is an X-ray observatory that can monitor X-ray sources with a flux brighter than a few $10^{-9}$ erg cm$^{-2}$ s$^{-1}$. With a time-tagging resolution of 61 $\mu$s, we can capture the fast variation of X-ray flux in mass accretion from companion stars to black holes or neutron stars. Related to time-domain astronomy, NinjaSat can perform agile observations of transient X-ray objects within a day or so when X-ray or gamma-ray monitors, e.g., X-ray all-sky monitor MAXI[5] on board the International Space Station (ISS) or the Neil Gehrels Swift Observatory,[6] detects such sources.

In addition to independent X-ray observations with the NinjaSat, the mass accretion and relativistic jets in blackhole or neutron star binary systems will be studied through joint observations with ground-based and space-based optical and radio instruments. As an extra success, by detecting the rotation period of fast-spinning neutron stars through observing quasi-periodic oscillation, we can help the detection of coherent gravitational waves from the neutron stars by gravitational wave observatories such as LIGO. Taking advantage of the operational flexibility, we are also planning to use NinjaSat for educational purposes. The NinjaSat team logo and the artist's impression of the satellite in orbit are shown in Figure 1.

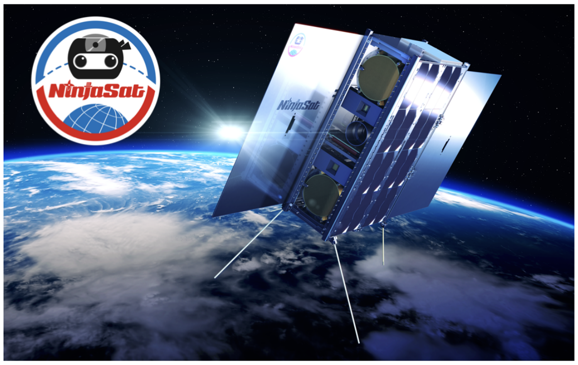

**Figure 1: NinjaSat image in space and logo (modified from Enoto, *et al.*[4])**

We started the NinjaSat project in 2020, fabricated the Engineering Model (EM) payload in 2021, and conducted various functional and environmental tests from 2021 to 2022. Four GMC and four RBM Flight Models (FMs) were fabricated and tested from late 2021 to early 2022, and two GMC and two RBM FM payloads were shipped to NanoAvionics in August 2022. The payloads were integrated into the NanoAvionics M6P and tested by March 2023. After four months of qualification and verification, the payload will be stored in the Exolaunch deployer in August. Then the satellite is scheduled to be launched in October 2023 from Florida by SpaceX Falcon-9 Transporter-9 to a Sun Synchronous Orbit (SSO) at an altitude of 550 km.

## THE SPACECRAFT AND PAYLOADS

### *Overview*

NinjaSat is a 6U CubeSat. To accommodate an X-ray detector with a sufficient effective area, the payload requires at least 2U of size. Since a 3U satellite bus is too small to realize NinjaSat, a 6U size was chosen. We had no plan to build a satellite bus ourselves but considered procuring it from a private company. The satellite bus should be as reliable as possible and should be a proven one launched in the past and operated in space. We also considered keeping reliability with as little special customization as possible to accommodate the project. After investigating various possibilities, we selected a general-purpose commercial satellite bus with sufficient space experience, and a contract was signed with Kongsberg/NanoAvionics of Lithuania through Mitsui Bussan Aerospace (MBA) to build NinjaSat using the M6P bus. The specifications of NinjaSat are summarized in Table 1.

**Table 1: NinjaSat Specifications**

| **Item** | **Value or Note** |
|---|---|
| Units | 6U (NanoAvionics M6P) |
| Power | 16.4 W daily average |
| Weight | 8.14 kg |
| Orbit | SSO, LTDN 10:00, 550±25 km |
| Launch | Oct. 2023 (SpaceX Transporter-9) |
| Downlink | 60 MB/day in normal operation |
| Payloads | 2×GMC and 2×RBM |
| GMC | Gas Multiplier Counter (X-ray detector)<br>1U, 1.2 kg, 1.8 W each<br>Energy Band 2–50 keV<br>Timing Resolution 61 $\mu$s<br>Effective Area 32 $\text{cm}^2$ at 6 keV for 2GMCs<br>Field of View 2.3° (FWHM)<br>$^{55}$Fe onboard calibration source (5.9 keV X-rays) |
| RBM | Radiation Belt Monitor<br>0.07U, 70 g, 1 W each |

NinjaSat carries two Gas Multiplier Counters[7] (GMCs) to detect X-rays from celestial sources and two Radiation Belt Monitors (RBMs) to monitor charged particles in orbit, mainly electrons and protons. Figure 2 shows the configuration of payloads mounted on the M6P satellite bus. One of the solar panels is mounted along the payload field of view, jutting out in front of the payload, and serves to prevent X-rays from the sun from entering the payload directly from the sides. This panel does not obstruct the field of view of GMC1 and GMC2 (2.3° FWHM) nor the field of view of the star tracker ($\phi$21°). The RBM1 and RBM2 windows (5×5 $\text{mm}^2$ each) are located far side from the panels to avoid the influence of the solar panel. Photographs of GMC and RBM are shown in Figure 3.

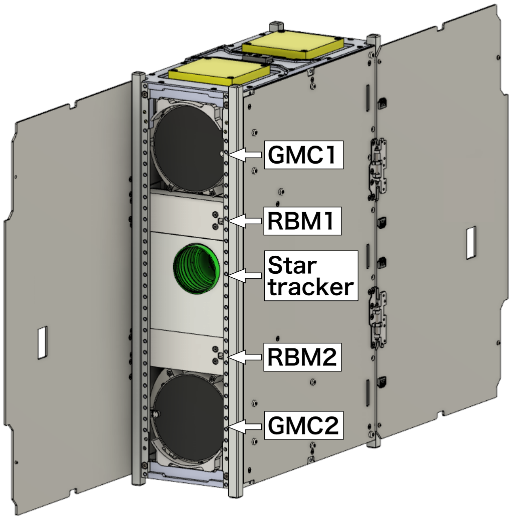

**Figure 2: The NinjaSat observatory viewed from the side without solar panels.**

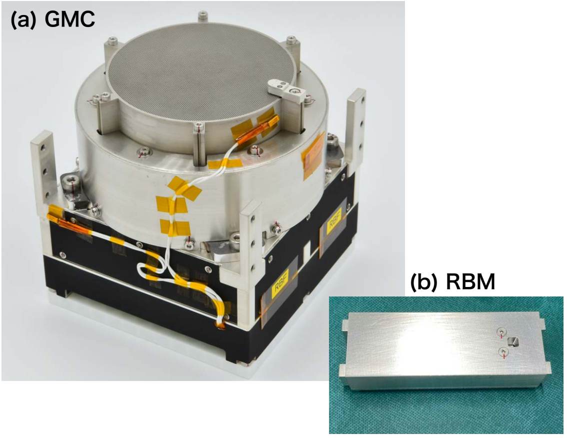

**Figure 3: Photographs of the NinjaSat payloads.**

### *Platform*

Figure 4 shows the functional block diagram of the satellite bus M6P, which is equipped with the necessary functions for NinjaSat with minimal customization. The onboard computer (OBC, aka Flight computer; FC) is a SatBus 3C2. FC includes the attitude determination control system (ADCS) functionality, which works by combining six sun sensors, a star tracker, four RW01 reaction wheels, one 3-axis magnetorquer, an inertial sensor, 3-axis magnetometers, and a GNSS (GPS) receiver. The power for the entire satellite and payloads is controlled by an Electric Power System (EPS), which contains Li-ion batteries.

Internal communication of the satellite uses the CubeSat Space Protocol (CSP) over Controller Area Network (CAN), the M6P satellite bus standard. The CAN bus of NinjaSat consists of CAN1, which is used only by the satellite bus, and CAN2, which payloads can use. CAN2 is isolated from CAN1 not to interfere with the satellite system by commanding payloads. Some exception packets, such as time information data/commands are allowed to pass mutually between CAN1 and CAN2. Each X-ray event must be tagged with the absolute arrival time, obtained by correcting the time counter implemented in the FPGA of GMC with the absolute time obtained from the Real-Time Clock (RTC) of the satellite in sync with the GPS-PPS signal every second. The time resolution is 61 $\mu$s for event data, well below our requirement.

To observe celestial objects, the pointing accuracy of the satellite is required to be less than 0.1°. This is derived by considering the collimator field-of-view (2.3° FWHM) of GMC. At this level, the effect of pointing errors on the X-ray light curve of the objects can be kept below the required observation accuracy. A simulation with pointing error budgets has confirmed that the pointing accuracy of NinjaSat is 0.06° at $2\sigma$ confidence level after calibration.

### *Gas Multiplier Counter*

Gas Multiplier Counters (GMCs) are the only X-ray detectors onboard NinjaSat observing the 2–50 keV X-rays with effective areas of 32 cm$^2$ per two GMCs. They are non-imaging gas proportional counters with passive collimators whose field-of-view is 2.3° to detect X-rays only from an observing target source. The one unit of GMC is designed to fit into a 1U size. A mixture of Xeon, Argon, and dimethyl ether gases is contained in an aluminum chamber with a volume ratio of 75%, 24%, and 1%, respectively. The filled gas pressure is 1.2 atm at 0°C. The gas leakage over two years is designed to be less than 1%, and the actual gas leakage rate is negligible. Two GMCs with the same functionality are installed, and their boresight is aligned with each other. Each GMC operates independently to ensure redundancy.

An incident X-ray kicks out a photoelectron by the photoelectric effect in the gas, and the photoelectron produces electron-ion pairs proportionate to the incident X-ray energy. The electrons drift toward the readout electrode at the bottom of the aluminum chamber. They are amplified by a Gas Electron Multiplier (GEM) placed just before the electrode by a factor of approximately 400. The charges induced at the electrode are converted to a voltage signal through the Amptek A225 preamplifier. The signals are fed into the amplifier circuit in the subsequent stage: CR-RC filters are implemented in the amplifier circuit to eliminate signals other than the X-ray signals. Then, the amplified signal through the amplifier circuit is digitized by a 25 MHz analog-to-digital converter, and the digitized waveform is processed in the FPGA on the data acquisition (DAQ) board placed at the bottom of the GMC housing.

Analog signal processing is mainly performed on the front-end card (FEC) attached to the bottom of the gas chamber, which also applies a high voltage of about +1800 V to the gas volume with the UMHV0520 DC-DC converter (HVM Technology). A chain of resistors of approximately 300 M$\Omega$ mounted on FEC is used to reduce the voltage and bleed the necessary high voltage to each electrode. All high-voltage circuits are designed to follow the standard, 1 kV/2mm or better, to avoid discharges from high voltages. When the pulse height of a digitized wave signal exceeds a threshold value, a trigger is fired, and signal processing starts. The time of the trigger is assigned to the event using a time counter value in the FPGA, and a waveform is extracted from a ring buffer implemented in the FPGA. The STM32H7 Micro Control Unit (MCU) processes the waveform at a later stage. See SSC23-WIII-01 for detail of the GMC design and performance.

A state machine has been assembled to avoid damage by unexpected commanding because high-voltage is applied to GMC. GMC is in one of the following operational modes (or states): OFF, SLEEP, IDLE, STANDBY, OBS, or EMERGENCY. The GMC state diagram is shown in Figure5a. When the GMC power is turned on from the satellite EPS, the DAQ and FEC boards of GMC are activated, and GMC goes to the SLEEP state. High voltage cannot be applied in the SLEEP state for safety; only after entering the IDLE state can high voltage be applied. Once operational, GMC goes to the OBS state in which GMC is observing stellar objects. In the high radiation region such as South Atlantic Anomaly (SAA) or Auroral regions near the poles, the high voltage of GMC is reduced and transits to the STANDBY state where the observation

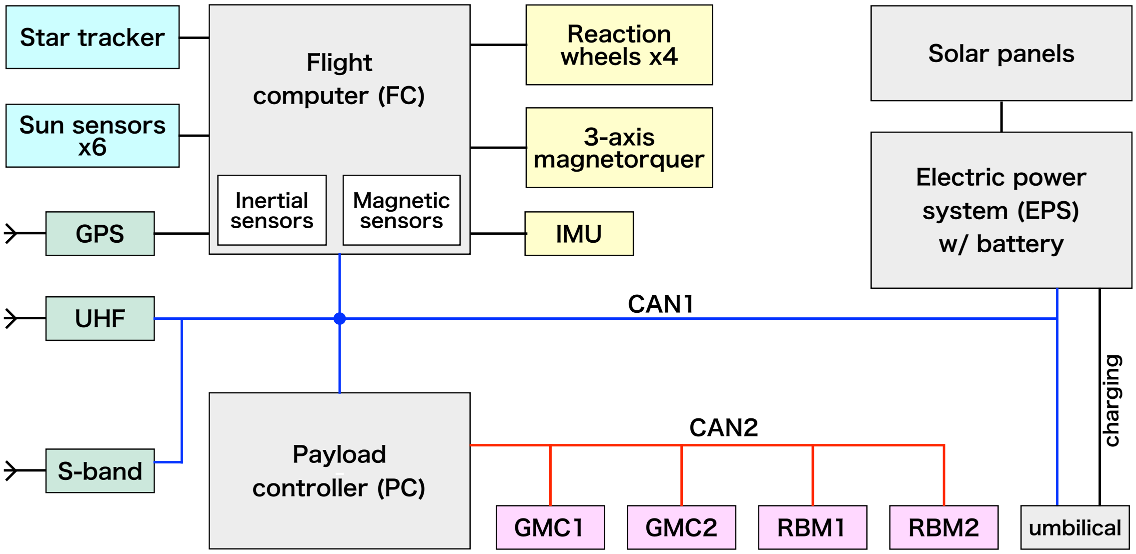

**Figure 4: NinjaSat functional block diagram.**

is stopped. If the event rate exceeds a threshold value or discharges are observed in GMC, the state is automatically transited to EMERGENCY. The firmware update function is implemented, and the BOOT mode is used.

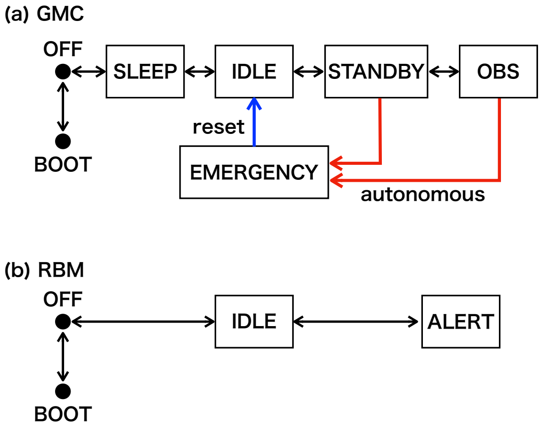

**Figure 5: NinjaSat payload state diagram.**

### *Radiation Belt Monitor*

Radiation Belt Monitors (RBMs) measure the rate of charged particles (electrons and protons) in the orbit. The main role of RBMs is sending alerts to GMC in areas of the high flux of charged particles in SAA or Aurora regions. The overall size of one RBM is $9.5 \times 3.2 \times 2.1$ cm$^3$ and uses a $1 \times 1$ cm$^2$ Si-PIN detector with a thickness of 500 $\mu$m as the particle sensor. The circuit board of RBM contains the Si-PIN detector, Amptek A225 preamplifier, comparator and STM32H7 MCU. When the count rate of charged particles captured by the RBM exceeds a preset threshold value, an alert is sent to GMC through CAN2. RBM is sensitive to electrons above 150 keV and protons above 300 keV. In normal operation, GMC stops operation in SAA or Aurora regions by scheduled commands or is shut down by its own count limiter, even in a case of commanding error. In addition to those safeties, RBM can forcibly shut down GMC by issuing the alert. This will work in the case of an unexpected increase in the charged particle count rate by Solar flares. See SSC23-WIII-03 for detail of the RBM design and performance.

The RBM has two states, IDLE and ALERT, as shown in Figure 5b. The IDLE state is used only for initial operation and parameter setting. During normal operation, RBM is in the ALERT state, where RBM can send alerts to two GMCs. RBMs are always powered on and are expected to continue monitoring charged particles throughout the mission. The MCU firmware of RBM can be uploaded in the BOOT mode like GMC.

## CONCEPT OF OPERATIONS

NinjaSat was originally intended for release from the Japanese module of the International Space Station. However, the orbit life at an altitude of 400 km could be shorter than our request (at least one year) if solar activity increases. We will instead launch the NinjaSat into a Sun Synchronous Orbit (SSO)

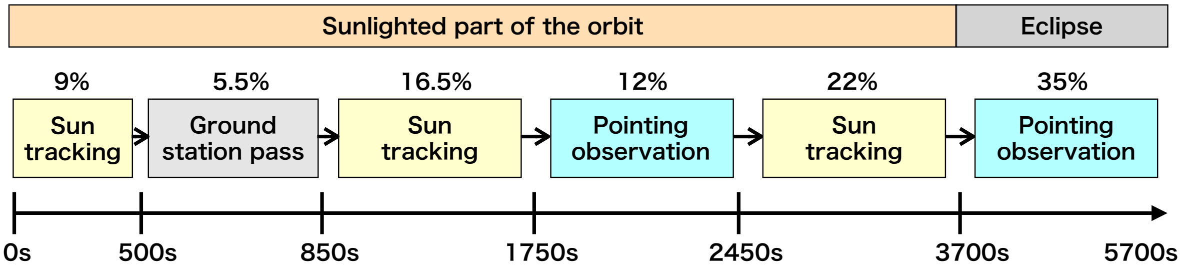

**Figure 6: An example of an operation in a path includes a ground contact. In this example, 47% of the orbit can be used for astronomical observations.**

at 550 km altitude by SpaceX Falcon 9. There are pros and cons of the SSO orbit for X-ray satellites. Since a satellite passes through the Auroral region, a charged particle belt, the time to turn off the X-ray detectors becomes longer. On the other hand, using a ground station near the poles increases the number of contact opportunities per day and is good for target-of-opportunity observations.

### *Normal operation*

NinjaSat is operated in three repetitive modes: ”charging mode,” ”pointing mode (astronomical observation mode),” and ”ground communication mode. The solar panels face the sun in the charging mode, and no astronomical observations are made. When the satellite reaches a certain depth of charge in batteries, it switches to pointing mode to perform astronomical observations. In pointing mode, the satellite faces a pre-planned celestial object and continuously observes the target as long as the orbital environment and charge in batteries permit. In the communication mode, neither charging nor observation is performed, and downlinks of data stored in the satellite and uplinks of commands are performed. Figure 6 shows an example of the operation, including ground contact, charging, and observations. The duty cycle of observations is expected to be between 30–50%, depending on the location of the target sources.

### *Verification phase*

NanoAvionics will perform functional verification of the satellite bus immediately after launch. This process is expected to take about one month. After confirming the function of the satellite, the initial operation of the payloads will begin.

The charged-particle environment in the orbit varies depending on the altitude of the satellite and solar activity. RBM will start initially and monitor the charged-particle environment in the orbit of NinjaSat. During the one-week start-up period of RBM, a map of the charged particles in orbit will be mapped, and the allowable area of the GMC operation will be determined based on the map. This activity is essential to efficiently avoid high-radiation regions such as SAA and Auroral belts and maximize the observation time of GMC.

Then, the initial on-orbit function tests of GMC will be performed. Although applying high voltages in a vacuum is risky, all functional tests must be completed in about one week. After launch in October 2023, NinjaSat can observe the Crab Nebula, a standard calibration source in X-ray astrophysics, until May 2024. The flux and spectrum of this object are well-known from previous X-ray missions, and reproduction of them by GMC is a good validation of our detector response.

The pointing accuracy of the satellite will be tested using Crab Nebula. Mutual alignment of two GMCs is essential, and the alignment of two GMCs with respect to the star tracker will also be verified. For this purpose, we will conduct a dithering observation in which the pointing direction of the satellite will be systematically shifted around Crab Nebula. Scorpius X-1, the brightest object in the sky and one of our main targets, will be available for observation starting in January 2024. (Until then, it cannot be observed due to the solar angle limitation of the star tracker.) All on-orbit calibrations will be completed by December 2023.

## Acknowledgments

The NinjaSat project is funded by RIKEN Cluster for Pioneering Research (CPR) and partially supported by JSPS KAKENHI Grant Number JP17K18776 and MEXT KAKENHI Grant Numbers JP18H04584 and JP20H04743. The satellite bus is assembled and tested by Kongsberg NanoAvionics through Mitsui Bussan Aerospace. We acknowledge the support for the payload tests at the Photon Factory of KEK (2021G127), HIMAC of QST (21H442), the thermal-vacuum test facilities of ISAS/JAXA and Nagoya University, the proton test facility at WERC.

## References

[1] A. Zajczyk, P. Kaaret, D. L. Kirchner, D. LaRocca, W. T. Robison, W. Fuelberth, H. C. Gulick, J. Haworth, R. McCurdy, D. Miles, R. Wearmouth, K. White, K. Jahoda, T. E. Johnson, M. Matthews, L. H. Santos, S. L. Snowden, K. D. Kuntz, S. Schneider, C. Esser, T. Golden, K. Hansen, K. Hanslik, and D. Koutroumpa, "HaloSat: a search for missing baryons with a CubeSat," *Proceedings of the 32nd Annual AIAA/USU Conference on Small Satellites*, pp. SSC18–WKIX–01, 2018.

[2] H. Feng, W. Jiang, M. Minuti, Q. Wu, A. Jung, D. Yang, S. Citraro, H. Nasimi, J. Yu, G. Jin, J. Huang, M. Zeng, P. An, L. Baldini, R. Bellazzini, A. Brez, L. Latronico, C. Sgrò, G. Spandre, M. Pinchera, F. Muleri, P. Soffitta, and E. Costa, "PolarLight: a CubeSat X-ray polarimeter based on the gas pixel detector," *Experimental Astronomy*, vol. 720, pp. 1 – 19, 2019.

[3] A. Pál, M. Ohno, L. Mészáros, N. Werner, J. Ripa, M. Frajt, N. Hirade, J. Hudec, J. Kapuš, M. Koleda, R. Laszlo, P. Lipovský, H. Matake, M. Šmelko, N. Uchida, B. Csák, T. Enoto, Z. Frei, Y. Fukazawa, G. Galgóczi, K. Hirose, S. Hisadomi, Y. Ichinohe, L. L. Kiss, T. Mizuno, K. Nakazawa, H. Odaka, H. Takahashi, and K. Torigoe, "GRBAlpha: a 1U CubeSat mission for validating timing-based gamma-ray burst localization," vol. 11444, p. 114444V, 12 2020.

[4] T. Enoto, T. Tamagawa, T. Kitaguchi, W. Iwakiri, Y. Kato, M. Numazawa, T. Mihara, H. Takahashi, H. Odaka, C.-P. Hu, H. Uchiyama, T. Takeda, Y. Yoshida, H. Sato, K. Uchiyama, J. Toeda, Y. Kojima, Y. Nambu, and Y. Itoh, "NinjaSat: an agile CubeSat approach for monitoring of bright x-ray compact objects," in *Space Telescopes and Instrumentation 2020: Ultraviolet to Gamma Ray* (J.-W. A. den Herder, S. Nikzad, and K. Nakazawa, eds.), vol. 11444, p. 114441V, International Society for Optics and Photonics, SPIE, 2020.

[5] M. Matsuoka, K. Kawasaki, S. Ueno, H. Tomida, M. Kohama, M. Suzuki, Y. Adachi, M. Ishikawa, T. Mihara, M. Sugizaki, N. Isobe, Y. Nakagawa, H. Tsunemi, E. Miyata, N. Kawai, J. Kataoka, M. Morii, A. Yoshida, H. Negoro, M. Nakajima, Y. Ueda, H. Chujo, K. Yamaoka, O. Yamazaki, S. Nakahira, T. You, R. Ishiwata, S. Miyoshi, S. Eguchi, K. Hiroi, H. Katayama, and K. Ebisawa, "The MAXI Mission on the ISS: Science and Instruments for Monitoring All-Sky X-Ray Images," *Publications of the Astronomical Society of Japan*, vol. 61, pp. 999 – 1010, 10 2009. 10.1093/pasj/61.5.999.

[6] N. Gehrels, G. Chincarini, P. Giommi, K. O. Mason, J. A. Nousek, A. A. Wells, N. E. White, S. D. Barthelmy, D. N. Burrows, L. R. Cominsky, K. C. Hurley, F. E. Marshall, P. Mészáros, P. W. A. Roming, L. Angelini, L. M. Barbier, T. Belloni, S. Campana, P. A. Caraveo, M. M. Chester, O. Citterio, T. L. Cline, M. S. Cropper, J. R. Cummings, A. J. Dean, E. D. Feigelson, E. E. Fenimore, D. A. Frail, A. S. Fruchter, G. P. Garmire, K. Gendreau, G. Ghisellini, J. Greiner, J. E. Hill, S. D. Hunsberger, H. A. Krimm, S. R. Kulkarni, P. Kumar, F. Lebrun, N. M. Lloyd-Ronning, C. B. Markwardt, B. J. Mattson, R. F. Mushotzky, J. P. Norris, J. Osborne, B. Paczynski, D. M. Palmer, H.-S. Park, A. M. Parsons, J. Paul, M. J. Rees, C. S. Reynolds, J. E. Rhoads, T. P. Sasseen, B. E. Schaefer, A. T. Short, A. P. Smale, I. A. Smith, L. Stella, G. Tagliaferri, T. Takahashi, M. Tashiro, L. K. Townsley, J. Tueller, M. J. L. Turner, M. Vietri, W. Voges, M. J. Ward, R. Willingale, F. M. Zerbi, and W. W. Zhang, "The Swift Gamma-Ray Burst Mission," *The Astrophysical Journal*, vol. 611, p. 1005, 08 2004.

[7] T. Takeda, T. Tamagawa, T. Enoto, T. Kitaguchi, Y. Kato, T. Mihara, W. Iwakiri, M. Numazawa, Y. Zhou, K. Uchiyama, Y. Yoshida, N. Ota, S. Hayashi, S. Watanabe, A. Jujo, H. Sato, C. Hu, H. Takahashi, H. Odaka, T. Tamba, and K. Taniguchi, "Gas selection for Xe-based LCP-GEM detectors onboard the CubeSat X-ray observatory NinjaSat," *Journal of Instrumentation*, vol. 18, p. C06020, 06 2023.