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Automatic data processing on the ground for the 6U CubeSat X-ray observatory NinjaSat

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ABSTRACT

NinjaSat is a 6U CubeSat X-ray observatory that observes time variations in X-ray flux through long-term monitoring of black holes or neutron stars and performs follow-up observations of unexpected objects discovered by other observatories. NinjaSat is equipped with gas X-ray detectors (GMCs) sensitive to 2–50 keV. The satellite is operated in cooperation with NanoAvionics (NA) responsible for satellite operation. As a science team, we need to process GMCs' data and cross-check the power system and attitude of the satellite. We are developing data processing software, consisting of Quick Look software for satellite bus and GMC health checks, and calibration software to process the GMC data and perform energy and time calibration. These software are run automatically when NA ground operators contact with the satellite and data is downlinked.

INTRODUCTION

NinjaSat is a 6U CubeSat X-ray observatory launched into a sun-synchronous orbit at an altitude of 530 km in November 2023 by SpaceX Transporter-9. NinjaSat observes time variations in X-ray flux through long-term monitoring of black holes or neutron stars, or performs follow-up observations of unexpected objects discovered by other observatories.[1] NinjaSat is equipped with gas X-ray detectors (GMCs) sensitive to 2–50 keV.[2] The satellite is operated in cooperation with NanoAvionics (NA), the Lithuanian small satellite bus manufacturer and mission integrator. NanoAvionics is responsible for satellite operations and NinjaSat team of RIKEN is responsible for science operations. NinjaSat data is downlinked three times a day. NinjaSat team cross-checks the power system and attitude of the satellite and performs scientific analysis of observed data. We develop data processing software consisting of quick look (QL) software to monitor the status of the satellite bus and GMCs, and calibration software to process data of GMCs and calibrate X-ray energy and detected time.

OPERATION AND DATA SHARING

Figure 1 shows an overall ground system. The NanoAvionics operator handles satellite communications and attitude control. 3 duty scientists of NinjaSat team are assigned to daily operation of payloads. They send a pointing list one day before uplink and payload operation commands 2–3 hours before uplink to operators of NanoAvionics. NanoAvionics operators uplink and execute these commands in addition to data downlink during satellite contact.

We use Amazon Web Service (AWS)[3] to share satellite data between NanoAvionics and RIKEN. Data downlinked from the satellite by the NanoAvionics ground system is stored in AWS endpoints in JavaScript Object Notation (JSON) format for each type of data, such as satellite power systems, Flight Computer attitude control systems, GMC House Keeping (HK) data and observed X-ray data. The communication schedule with the satellite is updated on AWS in the same way. Data download software developed by NinjaSat team automatically compares the current time with the AWS schedule every minute using cron,[4] a Unix-like Operating System job scheduler and downloads data on the AWS to the RIKEN local machine when communication with the satellite is over. The satellite file system numbers all data acquired on the satellite in orbit and by the NanoAvionics ground system respectively. When downloading data from AWS, the data download software compares it with the number of data stored on the local machine in the previous contact pass and downloads the increment of new data.

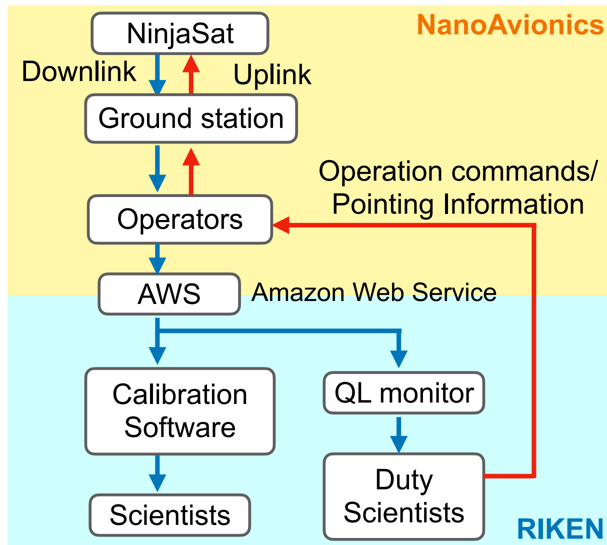

Figure 1: Flowchart of NinjaSat operations and data proccessing.

QUICK LOOK SOFTWARE

Satellite bus data and GMC HK data are archived in InfluxDB,[5] a time series database. We use Grafana,[6] an interactive visualization web application, for monitoring. Grafana sends queries to InfluxDB and plots the latest data every 5 seconds. Plotted data are, for example, the pointing direction and position of the satellite, current consumption of GMCs, temperature on the satellite, and High voltage value applied to GMCs. The plots are monitored by duty scientists in the operations room where the RIKEN ground data processing machine is located. The plots are shared with the NinjaSat team simultaneously. Snapshots of the monitor generated by a Grafana function are automatically sent to the NinjaSat team mailing list by an emailing function of QL software This allows team members other than the scientist on duty to check the status of the satellite and enables mobile operation via smartphone. With the alert function of Grafana, QL software alerts when values such as current consumption, attitude and temperature balance exceed configured thresholds and state anomalies are detected.

Satellite attitude information is downlinked as quaternions in the raw data. QL software converts it to celestial coordinates and the Grafana plot shows the plot. We monitor it and check whether the pointing direction of the satellite is the expected object position.

In measuring X-ray flux variations, loss of X-ray event data during communication between GMCs and the satellite bus or data downlink is critical because it causes pseudo-variations. QL software immediately detects data loss by comparing the number of events counted by GMCs, the satellite bus, and itself. It checks leaps in the numbers attached by the file system of the satellite bus during download from the AWS to detect data loss during data downlink from the satellite. GMCs have a function to count the number of detected X-ray events and output this count value data. QL software also counts the number of X-ray events and compares it with the count value from the GMCs to detect event losses between the GMCs data output and the satellite FileSystem.

CALIBRATION SOFTWARE

To realize long-term observation cooperated with other observatories, it is important to provide data qualified for scientific analysis quickly and continuously. The data processing software archives the calibrated data in Flexible Image Transport System (FITS) file[7] format that can be analyzed by HEASoft/FTOOLS,[8] a common data analysis tool for X-ray astrometry scientists. This makes it easy to analyze X-ray fulx variations and energy spectra observed by NinjaSat and compare them with data from other observatories.

Figure 2 shows the flowchart of the calibration software. Raw data downloaded from AWS are not ready for scientific analysis and need to be calibrated. Analysis by HEASoft mainly requires energy and time information. The calibration software automatically processes X-ray energy and time measurement results. As the level 1 process, the calibration software converts the raw data in JSON file format to FITS format and then calibrates it by referring to the Calibration Database, which records the information required for calibration as the level 2 process. As the level 3 process, from the calibrated data, the software performs a screening to cut out time intervals that are not suitable for scientific analysis, for example, the time interval in which the voltage applied to the GMC is reduced and observations are stopped.

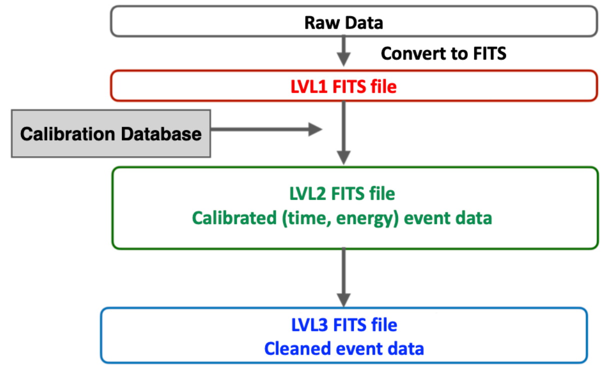

Figure 2: Flowchart of a calibration software.

Energy Calibration

GMCs acquire electrical signals corresponding to the X-ray energy.[2] The signal fluctuates with the ambient temperature. The relationship between energy and the electrical signal pulse height is linear if the temperature is constant, but the conversion coefficient is temperature dependent, with energy as E and pulse height as PHA, which is PHA [ch] $= a(T) \times E$ [keV] $+ b$. T is the temperature, $a(T)$ is the slope and b is the constant term. The PHA is acquired by a 12 bit ADC from a signal with a dynamic range of 2 V.

The calibration software converts the signal to energy with temperature correction based on the temperature data obtained as GMCs HK data. Figure 3 shows temperature variations on the orbit. One orbital period is 5700 seconds and Temperature fluctuates about 10 K around 300 K during it. The temperature fluctuations of $a(T)$ have been investigated during pre-launch ground tests of the satellite, and the experimental and simulated results are shown in Fig 4. From the results, we modeled $a(T)$ with a cubic function of temperature, which is consistent between experiment and simulation, before launch. During NinjaSat mission, the calibration function is modified based on data obtained in orbit. The values of the coefficients used in the function of $a(T)$ and b are recorded in the calibration database. This means that any calibration updates can be simply added to the calibration database and the data processing is automatic; the energy calibration is performed based on the conversion equations described above.

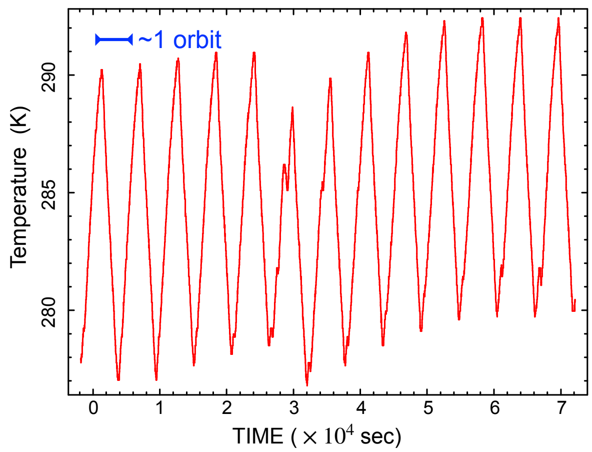

Figure 3: Temperature drift of GMC chamber in orbit.

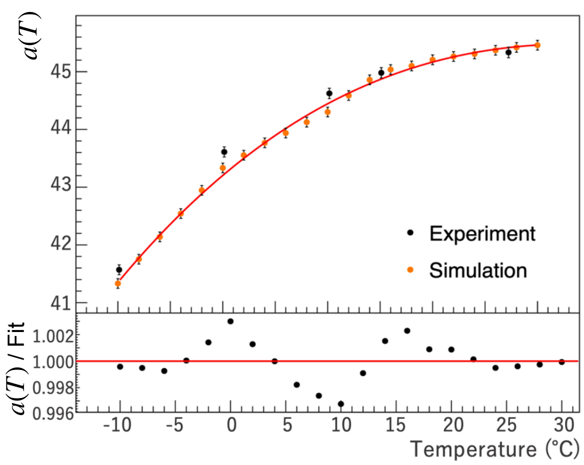

Figure 4: Energy calibration results of ground experiment and simulation.

Time Calibration

To monitor the temporal variation in X-ray flux, precise timing of each X-ray detection is essential. GMCs measure times of X-ray events with an internal FPGA time counter and record them with 61 μs resolution. The GPS module is onboard NinjaSat[1] and it receives absolute time from GPS satellites and stores it in the flight computer. The GPS module sends pulse-per-second signals (PPS) to the flight computer and GMC. GMCs acquire PPS signals from the satellite bus and transmit their own FPGA time counter with 15 μs resolution synchronized with GPS time at the timing. As time information of GMC, it outputs X-ray events and GPS data packets and these data are used for time calibration on the ground. Figure 5 shows a schematic diagram showing how to assign an absolute time to an event from a time counter and GPS time. The time calibration part of calibration software interpolates the GPS absolute times acquired in synchronization with the GMC time counter and assigns absolute timestamps to X-ray events.

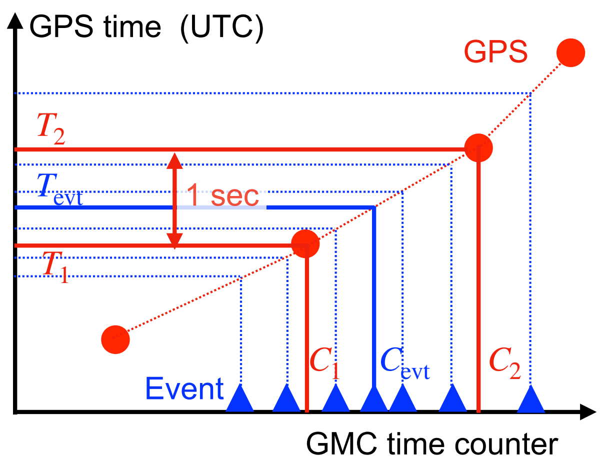

Figure 5: A schematic diagram showing how to assign an absolute time to an event from a time counter and GPS time. Details are written in the main text.

SUMMARY

NinjaSat is a CubeSat that observes time variations in X-ray flux from celestial bodies. Data from the satellite is shared using AWS between the NA members accountable for the satellite and the NinjaSat team accountable for the main instruments, the GMCs NinjaSat team developed a data processing software on the ground that automatically downloads data from AWS and processes the data at the time of contact with the satellite. We needed to check the health of GMCs, their data quality, and the pointing direction of the satellite so developed QL software using InfluxDB and Grafana. Data acquired by the GMC requires energy and time calibration and the processing is also performed automatically. The energy calibration is based on thermometer measurements to correct for the temperature dependence of the detector. As time calibration, time counter of GMCs are calibrated using GPS absolute time.

Acknowledgments

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