The Small Satellite “TSUBAME” for Polarimetry of Gamma-ray Burst


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Abstract

In these decades, many observations and discussions about gamma-ray bursts (GRBs) have carried out, however it is still not clear how to create high energy emissions. Polarimetry in hard X-ray band should be an effective method for understanding the nature of GRBs.

TSUBAME, the fourth small satellite of Tokyo Tech, is designed for the real-time GRB observation. TSUBAME possesses four Control Moment Gyros (CMGs) which enables quite rapid attitude control. Taking the advantage of this rapidity, we are planning polarimetry of prompt emissions of GRBs in hard X-ray band. The X-ray detector system consists of two detectors: Wide-field Burst Monitor (WBM) and Hard X-ray Compton Polarimeter (HXCP). The WBM is always monitoring half the sky and determining the positions of gamma-ray transients with an accuracy of 5 degrees. When a GRB is detected, the onboard CPU calculates the coordinate and then the satellite slews rapidly. Thanks to the high-speed attitude control system, TSUBAME can start polarimetry observations within 15 s after the trigger. Based on the numerical simulation, we expect to detect polarization for two GRBs in a year with TSUBAME.

Key words: X-ray, Gamma-ray burst, Polarimeter, small satellite “TSUBAME”

1. Introduction

1.1. X-ray polarimetry for gamma-ray bursts

Gamma-Ray Bursts (GRBs) are the most energetic explosion in universe. As possible energy sources, collapses of massive stars or mergers of compact objects, such as black holes or neutron stars, are proposed. However it is still not clear how to form collimated blast wave and how to accelerate particles. The X-ray polarimetry that can provide the information of magnetic field around the emitting area is believed to be an effective method for understanding the nature of GRBs. For GRBs, a few observations of X-ray polarimetry have been reported using RHESSI (Coburn et al. 2003) and INTEGRAL (McGlynn et al. 2007). These results are disputable because of uncertainties in possible systematics of the instruments that are not designed and calibrated for polarimetry. Despite a lot of efforts in these decades, observational difficulties prevent us from obtaining significant results. The difficulties are mainly due to the properties of the GRB: the unpredictability when or where it occurs, and its short duration time.

1.2. Overview of small satellite TSUBAME

Tokyo Tech is the one of the pioneers in the Japanese university-built small satellites and have already developed three satellites. Cute-I.7+APD II, the third of them, possesses avalanche photo-diodes (APDs) as radiation detectors for the first time in the world, and observed the distribution of electrons and protons in orbit (Kataoka et al. 2009). TSUBAME is the fourth small satellite of Tokyo Tech. TSUBAME possesses high-speed maneuver system, four Control Moment Gyros (CMGs), which enables quite rapid attitude control, about 90 degrees within 15 s. For long GRB, duration time of its prompt emissions is about several tens of seconds, so TSUBAME has sufficient performance to start the observations soon after the trigger. Specifications of TSUBAME are shown below.

<table>
<thead>
<tr>
<th>Launch</th>
<th>2012~ (Piggyback)</th>
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<tbody>
<tr>
<td>Dimension</td>
<td>50×50×42 cm$^3$</td>
</tr>
<tr>
<td>Total mass</td>
<td>47 kg</td>
</tr>
<tr>
<td>Total power</td>
<td>~100 W</td>
</tr>
<tr>
<td>Mission term</td>
<td>~1 year</td>
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Table 1. Specifications of TSUBAME
always monitoring half the sky and observing the count rate of hard X-ray photons. When a GRB is detected by rapid increase of the count rate, the onboard CPU calculates the coordinate and then the satellite slews rapidly. Thanks to the high-speed attitude control system, TSUBAME can start polarimetry observations by the HXCP within 15 s after the trigger (Fig.2). The HXCP is a polarimeter which utilizes the azimuthal angle anisotropy of Compton scattering. Based on the numerical simulation, we expect to detect polarization for two GRBs in a year with the TSUBAME.

Fig. 1. X-ray detectors of TSUBAME: HXCP and WBM. The HXCP is directed to the opposite direction from the solar cell. The counters of WBM are attached on five walls to direct toward five different directions.

2. Hard X-ray Compton Polarimeter (HXCP)

The Hard X-ray Compton Polarimeter (HXCP) is a Compton polarimeter that utilizes the azimuthal angle anisotropy of Compton scattering. If the incident X-ray is polarized, the photon tends to be scattered into the direction perpendicular to the polarization vector, according to the Klein-Nishina’s equation. Therefore the Compton polarimeter can constrain the polarizations of X-rays with the angular distribution of the scattered photons.

The HXCP consists of pixelated plastic scintillators for scattering X-rays and determining the incident position, and CsI (Tl) scintillators for absorbing scattered photons and determining the direction of scattered photon. In the HXCP, 64 plastic scintillators (6.5×6.5×49 mm³) are placed at the center of the detector and 28 CsI scintillators (6.5×10×49 mm²) surround them. Their signals are read by multi-anode photomultipliers (MAPMTs) and Si avalanche photo-diodes (APDs), respectively. For the TSUBAME mission, we have developed a special MAPMT for space use with quite-high quantum efficiency and mechanically strengthened electrodes that survived the H-IIA QT level. This MAPMT has 16 channel anodes, so 16 signals from multi-pixelated plastic scintillators at a time. On the other hand, the APD is the recently progressed radiation detectors, which possesses excellent properties: compact, lightweight, mechanically hard, low power consumption, and high quantum efficiency, resembling the other kind of semiconductor detectors. In addition, the unique property of the APD is the internal signal multiplication caused by the electron cascades. Thanks to this property, APD has good signal to noise ratio.

For detecting X-ray polarizations, it is essential to reduce the background events caused by the cosmic X-ray backgrounds, atmospheric gamma rays, and trapped charged particles. In order to reject those events, we applied the coincidence technique. An expected Compton event is detected only when the MAPMT and the APD detect a signal simultaneously. By selecting the hit patterns, we can distinguish whether the event is a photon from GRB or an accidental noise. With high performance and ultra low-power analogue VLSIs (PMT: VA32HDR11, APD: VATA462) that can processes multi signals simultaneously, we successfully downsized the signal processing system. The geometrical structure of the HXCP was designed based on the Monte-Carlo simulations to achieve high sensitivity in spite of its small effective area.

In December 2009, we made a prototype of the HXCP for the performance test. For simplicity, the prototype has 16 plastic scintillators with a MAPMT and 8 CsI scintillators with 8 APDs. Utilizing the Photon Factory in KEK, Tsukuba, we irradiated polarized X-ray beam (82.5 keV) to the prototype and obtained a modulation curve. Modulation factor for the X-ray beam derived from modulation curve is 72.3 ± 5.4 %, and this value is exactly consistent with the preceding numerical simulations using Geant4 within 3σ error (Fig.3). This experimental result strongly supports our strategies of designing and evaluating the performance of the HXCP. Expected performances of HXCP is shown in Table.2.

<table>
<thead>
<tr>
<th>Energy range</th>
<th>30 - 100 keV</th>
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<tbody>
<tr>
<td>Field of view</td>
<td>15 deg²</td>
</tr>
<tr>
<td>Effective area</td>
<td>7 cm²</td>
</tr>
<tr>
<td>Modulation factor (MF)</td>
<td>47.8 %</td>
</tr>
<tr>
<td>Minimum detectable polarization (MDP) (3σ)</td>
<td>6.2% (GRB021206)</td>
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Table 2. Expected performance of HXCP

Then we are now developing an engineering model of the HXCP modifying the prototype. The engineering model is designed for mounting to satellite, so the engineering model is smaller and mechanically harder than the prototype. We use Poly Ether Ether Ketone (PEEK) for the structure of detector and achieve to save weight.
1. Burst occurrence

Fig. 2. Sequence of GRB observations of TSUBAME. The WBM monitors hard X-ray count rates (≥30 keV). When a GRB occurs, the WBM detects the GRB by a significant change of count rates. Then, the position of GRB is determined by comparing count rates between five counters. TSUBAME slews rapidly by using CMGs, at the rate of 90° in 15 s. Finally, the HXCP is pointed to the GRB and starts the observation.

2. Detection, Position determination

3. High-speed attitude maneuver

4. Start observation within 15 seconds

Fig. 3. Modulation curve measured at the KEK-PF using prototype of HXCP. The horizontal axis is the azimuthal angle. Black point is data point and gray line is the modulation curve derived from the simulation on the assumption of X-ray beam. The data points at 0-15° and 135-150° had large error due to high noise, and therefore are not used in the analysis. Modulation factor derived from experimental data is 72.3 ± 5.4 %. On the other hand, modulation factor from the simulation is 68.7 ± 1.2 %.

In addition, the engineering model has passive shields, the plate of W (thickness: 2 mm), Cu (0.5 mm), and Sn (1.0 mm), to decrease background events in orbit (Fig.4).

3. Wide-field Burst Monitor (WBM)

The WBM is five scintillation counters which consist of CsI (Tl) scintillator (area: 12×3 cm², thickness: 5 mm) and APD. Each counter is placed on the surface of the satellite. These detectors monitor the count rate of X-ray and gamma-ray photons and triggers if the count rate rises rapidly. In order to determine the position of the transient object, the detectors direct toward five different directions. By comparing the count rate of each detector, we can estimate the source position using the barycentric method. This kind of technique had been already applied to the full-scale gamma-ray observing missions, such as the BATSE aboard the Compton gamma-ray observatory or the GBM aboard the Fermi observatory.

In order to start the polarimetry of a GRB soon after the detection, the obtained count rates are processed by the onboard CPU and determine where the GRB occurs within a few seconds. The target accuracy of the posi-
tion determination of the WBM system is higher than 5 degrees, which is sufficient compared to the FoV of the HXCP and the accuracy of the attitude control. The simulations of the performance of the WBM in position determination assuming various settings, the structures, the detector arrangements, and the algorithms, are on going.

<table>
<thead>
<tr>
<th>Detection count rates</th>
<th>&gt; 10 kHz</th>
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<tr>
<td>Detectable minimum energy</td>
<td>&lt; 30 keV (at 20 °C)</td>
</tr>
<tr>
<td>Accuracy of position determination</td>
<td>&lt; 5 deg</td>
</tr>
<tr>
<td>Weight</td>
<td>260 g / unit</td>
</tr>
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</table>

Table 3. Performance goal of WBM

As for the hardware, we have developed a prototype circuit and already achieved the sufficient performances, the minimum detectable energy of 30 keV at the room temperature, and the high count rate responsivity up to 10 kHz random signals. Now we are developing an engineering model of the WBM based on the numerical simulations. Engineering model has passive shields, W (thickness: 1.0 mm), Cu (0.3 mm), and Sn (0.5 mm), behind the scintillator to decrease background events (Fig.6). Now, we are evaluating the performance of engineering model and developing the position determination algorithm.

![Fig. 5. Spectrum of $^{137}$Cs with the WBM prototype at 20 C°. Dashed line indicates 30 keV and shows that signal and noise can be distinguished. The peak is the photoelectric peak at 662 keV and has the energy resolution of 8.4 %.](image)

4. Summary

The polarimetry in the X-ray band will provide the important information for the astronomy. Actually, various projects for the X-ray polarimetry are in progress.

The small satellite “TSUBAME” has the high-speed maneuver system, so TSUBAME can observe the prompt emission of GRBs. TSUBAME possesses two detectors for the X-ray polarimetry of GRBs: the HXCP and the WBM. We developed the prototypes of these detectors and evaluated the performances of them. The results of evaluations show that the prototypes have sufficient performances to detect the polarization of GRBs. Now, we are developing the engineering models. In the future, we need to evaluate the performance of the engineering models and design the flight model.

References