X-ray Transient Localization Experiment aboard a micro-satellite for multi-messenger counterpart search

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Abstract

Short gamma-ray bursts (short GRBs) are likely caused by the coalescence of double neutron star binary and/or neutron star and black hole binary, and therefore they are expected to be promising electromagnetic counterparts of gravitational wave (GW) sources. The joint observation of short GRB and GW, and the identification of the host galaxy and distance of such events will provide not only the definitive observational evidence for the origins of short GRBs but also the insights to the compact object merger model and the explosion mechanism. However, GW sky location is uncertain by tens or hundreds of square degrees, which is not well constrained for the efficient follow-up observation with optical/NIR telescopes. Thus, we are developing X-ray imaging detector that has both fine localization accuracy and wide field-of- view, named Transient Localization Experiment (T-LEX). The energy range, field-of- view, localization accuracy of T-LEX are designed to be 1 - 15 keV, 1 steradian, and 15 arcminutes, respectively. To achieve such capability, we adopted two sets of 1-dimensional coded aperture imaging system, which consists of tungsten mask with random pattern of 1-dimensional strip-like apertures and silicon strip detector with an active area of 50 cm^2 for each dimension. T-LEX is plan to be launched onboard a micro-satellite in late FY 2018, which is being developed at Kanazawa University named as *Kanazawa-SAT*^{3}. The mission life is designed to be more than 1 year. The objective of the satellite mission is to localize X-ray transients including GW sources and to send real time alerts of X-ray transient information about the position and the burst trigger time. We report the imaging performance of a prototype model of T-LEX.

Key words: instrumentation: detectors — micro-satellite - gamma-ray bursts — coded mask imager

1. Introduction

The progenitors and the environment of short duration gamma-ray bursts (GRBs) (< 2 sec) remain elusive despite of their localizations. To test the theoretical argument that short GRBs are produced in the coalescence of binary compact objects such as neutron stars or black holes (Paczynski 1986; Eichler et al. 1989), the observation of short GRBs with gravitational wave (GW) connection gives a decisive evidence.

Recently, the first direct GW detection, GW 150914, was performed by advanced LIGO (Abbott et al. 2016a), and therefore the progress of gravitational astronomy is much expected in the future. To maximize the scientific return from the GW observation, it is essential to observe electromagnetic counterparts and identify the host galaxies of GW sources. However, the GW detectors cannot determine the host galaxy of the GW events by themselves due to their marginal localization ability. For example, the constraint on the position of GW 150914 was an area of about 600 square degrees (Abbott et al. 2016b). Therefore, the observation of short GRBs with a wide field and a fine localization will play a crucial role to serve a bridge from the GW detection to the electromagnetic follow-up observation.

2. Micro-satellite *Kanazawa-SAT*^{3}

Kanazawa-SAT^3 is a micro-satellite with a size of 50 cm cube weighing 50 kg promoted by Kanazawa University, and possesses a wide-field X-ray imaging detector (Yonetoku et al. 2014a). The objectives of that satellite mission are to monitor X-ray transients associated with GW events, and to provide the position and the burst trigger time of X-ray transients to the ground-based telescope community. Thus, *Kanazawa-SAT*^{3} is

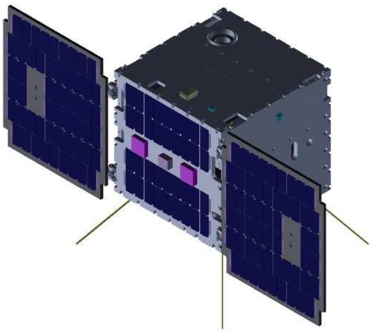

Fig. 1. A schematic view of *Kanazawa-SAT*^{3} designed by Meisei Electric Co., Ltd.

dedicated to contributing to the identification of the electromagnetic counterparts of GW events. Utilizing the advantage of short development time for a micro-satellite, *Kanazawa-SAT*^{3} is planned to be launched in late FY 2018, in which the global network of the second generation GW interferometers will be in operation. Table 1 summarizes configurations of *Kanazawa-SAT*^{3}. The mission life of the satellite is designed for at least one year, and three years are set as the operational goal. The orbit of the satellite is supposed to be a Sun-synchronous orbit due to multiple launch opportunities.

Table 1. Configuration of *Kanazawa-SAT*^{3}

Mission life	> 1 year
	3 years (goal)
Size	50 cm cube
Weight	< 50 kg
Launch target	in late FY 2018
Orbit	Sun-synchronous
Detector	wide-field X-ray imaging detector

Figure 1 shows a schematic view of *Kanazawa-SAT*^{3}. The satellite has two solar paddles, and a three-axis attitude control system for sun-oriented operation. The X-ray imaging detector, T-LEX (Transient Localization Experiment) is installed on the opposite side of the panel on which the solar panel is mounted, for optical light and thermal protections. Therefore, T-LEX will keep pointing at the anti-solar direction, and can monitor and observe the sky on the night side of the Earth.

3. Transient Localization Experiment (T-LEX)

3.1. Detector Overview

T-LEX consists of two (X and Y) sets of 1-dimensional coded aperture systems. Table 2 shows configurations of T-LEX. The energy range of T-LEX is designed to be 1 - 15 keV. The field-of-view is more than 1 sr so as to cover the constraint region of GW events efficiently. The localization accuracy is about 15 arcminutes, which is well constrained for the follow-up observation with optical/NIR telescopes. The effective area of the X-ray sensors for X-/Y- planes is about 100 cm^2 in total.

Table 2. Configuration of T-LEX

Imaging method	X-/Y- 1-D coded mask
Energy range	1 - 15 keV
Field of view	> 1 sr
Localization accuracy	~ 15 arcmin. (geometrical)
Detector size	100 cm^2 in total (X and Y)
Mask aperture fraction	0.5

3.2. Design of Coded Aperture System

The coded aperture system of T-LEX consists of a tungsten mask with random pattern aperture and a silicon strip detector (SSD) with a thickness of 0.5 mm. The pitches of the SSD and the mask pattern are the same, and 0.3 mm. Generally, the localization pitch of the coded aperture system for the line-of-sight $\delta\theta$ yields

$$\delta\theta = \arctan\left(\frac{d}{D}\right), \quad (1)$$

where d is the pitch of the detector and the mask pattern, and D is the distance between the mask and detector planes. Therefore, in order to satisfy the requirement of the localization accuracy, the distance D is set to be about 70 mm.

3.3. Readout Electronics

The charge signals of X-ray events from SSDs are very small (~ 0.04 fC for 1 keV) and therefore they must be amplified in order to discriminate with a proper energy threshold. However, the number of the channels of the SSD is 512 (X) plus 512 (Y), and one cannot implement the readout system with discrete circuits. Therefore, we developed an application specific integrated circuit (ASIC) for readout of small charge from an X-ray sensor, ALEX (ASIC for Low-Energy X-rays) (Yonetoku et al. 2014b). ALEX has 64 analog inputs and digital input/output serial interfaces. The electrodes of ALEX inputs and the SSDs are directly connected with bonding wires for least additional stray capacitance. Each analog input of the ALEX is processed to a charge-sensitive amplifier, two shaping amplifiers with slow and

Fig. 2. A picture of the sensor boards stacking on the readout boards of the T-LEX prototype model.

fast time constants of several microseconds, and a comparator from the fast shaping amplifier output, and an analog-digital converter from the slow shaping amplifier.

A field programmable gate array (FPGA) is used to control the ALEX and process the event data through the digital interfaces of the ALEX. In this way, eight ASICs are used to readout the X- (or Y-) sensor and those ASICs are controlled with one FPGA. To control two (X- and Y-) FPGAs, another FPGA is used for merging the X- and Y- event data and communication with the CPU on the satellite bus system. In the back-end readout FPGA, the logic of one CPU core is implemented so as to manage complicated procedures such as a burst trigger system and the serial communication with the bus system.

3.4. Prototype Model

We developed a prototype model of T-LEX. A picture of the sensor boards stacking on the readout boards of the T-LEX prototype model is shown in Figure 2. The SSD installed on the sensor board in the prototype model comprises 512 strips for each (X- and Y-) dimension, and each strip size is 0.3×16 mm^2. Therefore, the detector area of the SSD for each dimension is ~ 25 cm^2, which is the half of the full configuration at the flight model.

On the other hand, the number of the readout channels is the same as that of the flight model, and thus this prototype model can be characterized as the engineering model of the T-LEX electronics. There are eight ASICs on each (X- and Y-) sensor board, and the FPGA is mounted on the readout board on the back of the sensor board. The FPGA with the implemented CPU is also mounted on the X- readout board. To reduce the changes in the geometrical and functional designs for the flight model, the almost of the all electronics are pin-compatible devices with the space-grade ones.

As a trial piece of the random pattern mask, we made a small tungsten mask with a thickness of 35 microns. The aperture size of that tungsten mask is 76.8×76.8 mm^2 for one dimension, which is a quarter of the flight model. We note that we cannot perform the full-coded imaging test using the all channels of the SSDs because the widths of the sensor and the mask aperture are the same. We made a case of the prototype of T-LEX made of aluminum, where $(d/D)^{-1}$ is designed to be 2.24×10^2.

4. Imaging Performance of T-LEX Prototype Model

4.1. Overview

To confirm the validity of the basic design of T-LEX, we performed an imaging demonstration test with partial channels of the SSDs. The goal of that test is as follows. First, we measure the reconstructed directions of X-ray beams with various incident angles. Second, we compare those experimental data with the ones obtained geometrically. Last, whether the discrepancy of them is acceptable or not is discussed.

4.2. Reconstruction method

To obtain the reconstructed image of the coded mask system, we used a cross correlation method expressed with

$$r_j = \sum_i d_i \cdot m_{i+j}, \tag{2}$$

where the j is the shift index in the cross correlation calculation, r_j is the intensity at the shift index of j in the reconstructed image, d_i is the number of the X-ray events at the detector position of i, and m_{i+j} is the mask weighing design element. In this paper, we used the condition on the mask weighing where m_i is 0 if the mask is opaque at i and 1 if the mask is transparent.

4.3. Setup of Experiment

As the parallel light of X-ray photons, we used a 5.5-meter beam line at the astrophysics laboratory of Kanazawa University. X-ray photons from an X-ray generator with a tube voltage of 40 kV irradiate the molybdenum target with a size of 5×5 cm^2 so as to produce fluorescent X-rays with an energy of 17.5 keV (Kα line). The T-LEX prototype model is placed in a thermostatic bath, which is at a distance of 5.5 meters from the molybdenum target with an ambient temperature of -10 degrees Celsius. A rotation stage is installed on the side of the case of the T-LEX prototype model in order to change the incident angle of the X-ray beam. The divergence of the X-ray beam is calculated to be $(5\,\mathrm{cm}/\sqrt{2})/(5.5\,\mathrm{m}) \approx 0.0064$, or 22 arcminutes, and it is slightly larger than the localization accuracy of T-LEX. This effect causes the peak dilation in the reconstructed image.

As mentioned in Section 3.4., we cannot use the whole channels under the full-coded condition. Thus, we used the data from two ASICs, or 128 channels that are close to the center. Using those 128 channels of X-ray intensity data and 256 strips of the mask patterns, we obtained the reconstructed image according to Eq. 2. We obtained the peak position of the reconstructed image by fitting the data around the peak with a normal distribution function.

4.4. Result and Discussion

Figure 3 and 4 show examples of d_i and r_j, respectively, obtained with the experiment. Figure 5 shows the peak position in terms of the shift index versus the X-ray incident angle (or the rotation angle), where the origin is arbitrary. Ideally, the curve can be modeled with a tangent function because the peak position m yields

$$\tan\theta = \frac{md}{D}, \tag{3}$$

where θ is the rotation angle from the line-of-sight. We fitted this curve with a tangent function and obtained $(d/D)^{-1}$ to be 2.27×10^2 using Eq. 3, which is 1.5% larger than that designed. That means if we use the designed value for $(d/D)^{-1}$, the reconstructed angle for the events with an incident angle of 30 degrees has an error of about 30 arcminutes, which is not acceptable due to the requirement. Therefore the calibration of $(d/D)^{-1}$ by the imaging test will work effective to compensate that systematic error. It is suggested that the imaging test will be mandatory also for the flight model.

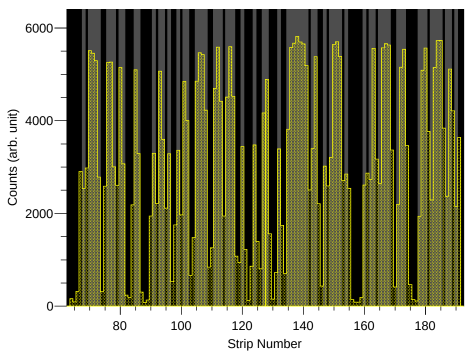

Fig. 3. An example of the X-ray intensity distribution (yellow-filled histogram) representing the mask pattern obtained by the X-ray beam irradiation. Behind the histogram, the best matching position of the mask is shown, where the transparent elements of the mask are represented with the gray color region.

5. Summary

The X-ray transient localization with a wide field-of-view will strongly promote the electromagnetic follow-up observation for the identification of the host galaxy of GW events, contributing to the progress of GW astronomy. The micro-satellite *Kanazawa-SAT*^{3} possesses the wide-field X-ray imaging detector, T-LEX, and the objectives of that satellite mission are to monitor the X-ray transients associated with GW events and to alert to the

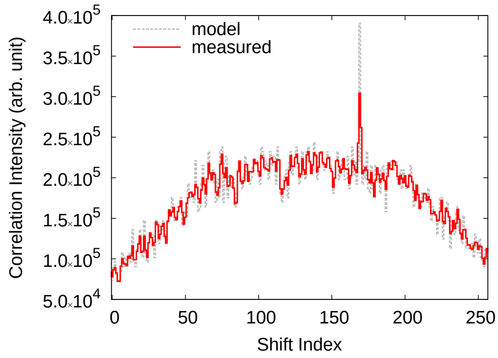

Fig. 4. An example of the one-dimensional reconstructed image within the half-coded region (red solid line). The model image for parallel light is also drawn (gray dashed line).

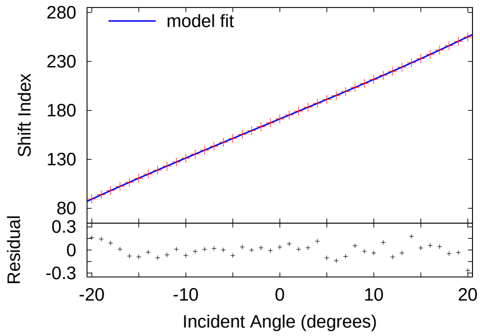

Fig. 5. The peak positions in terms of the shift index in reconstructed image versus the incident angles obtained by the experiment (red cross). The coordinate of the origin is arbitrary. The best estimate of the tangent model function is drawn in the blue solid line. The residuals are also shown.

ground-based telescope community sending the information of the position and the burst trigger time of X-ray transients.

We developed the prototype model of T-LEX and successfully performed the imaging test. We found that the imaging performance test effectively works as the calibration for reconstructing the incident angles. That calibration will be also performed carefully to the flight model of T-LEX to satisfy the requirement for the localization accuracy.

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