The CALET Gamma-ray Burst Monitor (CGBM)

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The CALET Gamma-ray Burst Monitor (CGBM) is the secondary scientific instrument of the CALET mission on the International Space Station (ISS), which is scheduled for launch by H-IIB/HTV in 2014. The CGBM provides a broadband energy coverage from 7 keV to 20 MeV, and simultaneous observations with the primary instrument Calorimeter (CAL) in the GeV - TeV gamma-ray range and Advanced Star Camera (ASC) in the optical for gamma-ray bursts (GRBs) and other X-gamma-ray transients. The CGBM consists of two kinds of scintillators: two LaBr$_3$(Ce) (7 keV - 1 MeV) and one BGO (100 keV - 20 MeV) each read by a single photomultiplier. The LaBr$_3$(Ce) crystal, used in space for the first time here for celestial gamma-ray observations, enables GRB observations over a broad energy range from low energy X-ray emissions to gamma rays. The detector performance and structures have been verified using the bread-board model (BBM) via vibration and thermal vacuum tests. The CALET is currently in the development phase of the proto-flight model (PFM) and the pre-flight calibration of the CGBM is planned for August 2013. In this paper, we report on the current status and expected performance of CALET for GRB observations.

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1 Introduction

The gamma-ray burst (GRB) is one of the most energetic events in the universe, with a radiated energy release of $>10^{51}$ erg. For prompt emissions, most of the energies are emitted in an energy range from soft X-rays to GeV gamma-rays. It has been widely believed that electromagnetic radiation in the 10 keV–10 MeV range are probably due to optically thin synchrotron emission from accelerated electrons in relativistic jets. However, Fermi LAT observations have revealed a common feature that there is an additional hard, delayed and long-lived component in GeV gamma-rays for both short and long-duration GRBs, e.g. [1] and [2]. Leptonic and hadronic models are still debated. On the other hand, Beppo-SAX and HETE2 revealed a presence of X-ray flashes (XRF) whose emissions are dominant in X-rays rather than gamma-rays. Judging from spectral and timing properties, the XRFs are considered to belong to the same class as GRBs [3]. Thus, to understand radiation mechanisms of GRBs, the importance of wide-band X-and gamma-ray observations of GRBs are growing.

The Calorimetric Electron Telescope (CALET [4]) is designed primarily for observation of high energy electrons and gamma-rays in the GeV – TeV range. It will be launched by the H-IIB/H-II Transfer Vehicle (HTV), and attached to Exposed Facility of the Japanese Experimental Module (JEM) on the International Space Station (ISS) in 2014. The overview of the CALET mission payload is shown in Figure 1. The primary instrument, calorimeter (CAL), can observe a GRB in the GeV – TeV gamma-ray range. In order to enhance the capability for GRB observations with CAL, we have added a gamma-ray burst monitor (CGBM), which is sensitive to X-rays to soft gamma-rays up to 20 MeV. We also actively utilize the Advanced Star Camera (ASC), which is attached for an accurate localization of gamma-ray sources, to observe an optical flash during the GRB prompt emissions [5] with a limiting magnitude of about 9 in optical (see Table 1). By investigating very broadband coverage from optical, X-rays to GeV–TeV gamma-rays, we will clarify the following issues: 1) radiation mechanisms for GRB prompt emissions including XRFs, 2) search for a coincidence to a gravitational wave (GW) event as expected to start operations of upgraded GW detectors in later 2010s, and 3) presence for absorption features as seen in the Ginga/GBD energy spectrum of GRB 880205 [6]. Furthermore, we emphasize that we can also perform simultaneous X-ray observations with MAXI [7] attached to the same facility JEM-Kibo on the ISS.

2 Instrumentation

2.1 Overview

The CGBM is a secondary scientific instrument which supports a capability for GRB observations by the CAL. It observes a lower energy range which the CAL can not
Table 1: GRB Observations with CALET.

|                      | CAL                  | CGBM               | ASC               |
|----------------------|----------------------|--------------------|-------------------|
| Energy (Wavelength)  | a few GeV–10 TeV     | 7 keV–20 MeV       | 300∼800 nm        |
| Effective area       | ~600 cm$^2$          | 68 cm$^2$(HXM)     | —                 |
|                      |                      | 82 cm$^2$(SGM)     |                   |
| Field of view        | ~2 str.              | ~3 str.(HXM)       | 18.4°×13.4°       |
|                      |                      | 4π str.(SGM)       |                   |
| Angular resolution   | 2.5° @1 GeV          | No capabilities    | —                 |
|                      | 0.35° @10 GeV        |                    |                   |
| Time resolution      | 62.5 µs              | 62.5 µs            | 1/16∼4 sec        |
| Deadtime per event   | 1.8 ms               | 40 µs              | —                 |

Figure 1: Overall picture of the CALET mission payload on the ISS. The CGBM, consisting of HXM and SGM, is attached on the top of the CALET for both sides.

cover and is aimed to obtain GRB spectra over a wide range of X-rays to gamma-rays. In addition to GRB observations, the CGBM will carry out all-sky observations of various gamma-ray transients: soft gamma repeaters, solar flares, terrestrial gamma-ray flashes, and X-ray binaries. It is composed of three sensors and an electronics box (E-box) which processes the signal of sensors. The outputted digitized data from the E-box are formatted by the Mission Data Controller (MDC), and sent as a telemetry to the ground station at NASA.
2.2 Sensors

The CGBM consists of two types of detectors, a Hard X-ray Monitor (HXM) and a Soft Gamma-ray Monitor (SGM), to cover a wide energy range of 7 keV to 20 MeV by its combination. As for the HXM, we utilize a novel scintillator LaBr$_3$(Ce) with excellent performance in terms of light yield, energy resolution, and time response in comparison with NaI(Tl). However, it is used in space for the first time here for celestial gamma-ray observations. Hence, we have been verifying that the performance will not be degraded through proton and gamma-ray irradiation tests. Each of the two LaBr$_3$(Ce) crystals is configured as two cylinders, the front cylinder 66.0 mm diameter and 6.35 mm thick and the rear cylinder 78.7 mm diameter and 6.35 mm thick. The beryllium entrance window with a 410 mm thickness is used for soft X-ray detection below 10 keV. For the SGM, we utilize the BGO scintillator which has a high stopping power for gamma-rays due to its large density ($\rho=7.13$ gcm$^{-3}$) and effective atomic number ($Z_{\text{eff}}=74$). The BGO crystal has a cylindrical shape with 102 mm diameter and 76 mm thickness. The LaBr$_3$(Ce) and BGO crystal units are provided by Saint Gobain Crystals and OKEN Co., Ltd. respectively.

The CGBM sensors are in total three detectors, two identical HXMs and one SGM. Figure 2 shows the HXM and SGM effective area as a function of energy. The unique feature for the HXM is a sensitivity to soft X-rays below 10 keV. The HXM covers a lower energy range of 7–1000 keV, while the SGM covers a higher energy of 100 keV–20 MeV. We aim at operating both detectors at a lower energy threshold. Each sensor mainly contains a scintillation crystal, a photo-multiplier tube (PMT), a high voltage divider, and a charge sensitive amplifier (CSA). The vibration-proof model of Hamamatsu PMT R6232–05 (2.4 inch diameter) and R6233–20 (3 inch diameter) with a high quantum efficiency are used for the HXM and the SGM respectively. All the components are installed in an aluminum housing. The field of view for the HXM is limited by the light collimator within about 58 degrees from the zenith to reduce possible contamination from the cosmic X-ray background and bright X-ray sources. In this configuration, we expect a GRB detection rate of about 30–40 per year by the HXM.

2.3 GBM Electronics-box (E-box)

The CGBM E-box processes three signals from the CSA in the three sensors. It is located apart from both sensors (HXM and SGM) and MDC. The block diagram of signal processing in the E-box is shown in Figure 3. The HXM and SGM signal processing are the same. To ensure a wide dynamic range of a factor of $\sim$1000, the signals are divided into two amplifiers with different gains (high and low), and read out by different sample and hold 16-bit ADCs. The signals from the CSA are bipolar-shaped with a CR-RC$^2$-CR filter where the time constant $\tau$ is 2 $\mu$s. The
ADC conversion timing is produced by a zero-crossing lower discriminator after the shaping with a faster time constant ($\tau=0.5 \mu s$). The dead-time per event is set at 40 $\mu s$. An upper discriminator (UD) is also present in the circuit with the purpose of avoiding malfunction in case of large energy-deposit signals. The digitized data from ADC and comparators are sent to Field Programmable Gate Arrays (FPGAs). The FPGAs implement a trigger sequence, scalers from LDs and UDs, data formatting, a GRB trigger logic, command decoders and so on. The three high voltages S9099, provided by SITAEL, are installed in the E-box for each sensor, and are controlled individually with 8 bit in the 0–+1250 V range.

The CGBM E-box produces two types of the scientific data (see Table 2). One is continuous monitoring data which is always outputted to the telemetry, independent of the GRB trigger status. The monitor data has two kinds of histogram data: Time History (TH) data with a 1/8 sec time resolution and 8 energy channels, and Pulse Height (PH) data with a 4 sec time resolution and 512 energy channels. The other is an event-by-event data which are available only when a GRB triggers the CGBM. It has fine information of an arrival time with 62.5 $\mu s$ time resolution and an energy with 4096 channels for each high and low gain.

On-board trigger system is realized in the FPGA of the E-box. The following criterion for the GRB trigger is installed in the hardware:

$$N_{tot} - \frac{N_{BG}}{\Delta t_{BG}} \Delta t > \sigma \sqrt{\frac{N_{BG}}{\Delta t_{BG}}} \Delta t$$  \hspace{1cm} (1)

where $N_{tot}$ is the GRB plus background counts during the GRB judgment time ($\Delta t=1/4, 1/2, 1$ and 4 seconds), $N_{BG}$ is the background counts during the back-
ground integration time ($\Delta t_{BG}$), and $\sigma$ is the significance level. If the source counts exceeds $\sigma$ times the statistical fluctuation of the background counts, we can regard it as a GRB event. This logic is very simple, and has been successfully applied to the previous GRB instruments such as Ginga/GBD [8] and Suzaku/WAM [9]. When a GRB triggers the CGBM, the energy threshold for CAL will be set lower from 10 GeV to a few GeV, and two ASC optical images will be taken.

Table 2: CGBM Data Types and Contents

| Data Type           | Monitor Data | Event Data                  |
|---------------------|--------------|-----------------------------|
|                     | TH       | PH     | 4096 (for both gains)       |
| Energy channel      | 8        | 512    |                             |
| Time resolution     | 1/8 s    | 4 s    | 62.5 $\mu$s                  |
| Time coverage       | anytime  |        | $\sim1.5\times10^6$ events |
|                     |           |        | around the trigger time      |

3 Bread Board Model of Sensors and E-box

The CALET is currently in the development and verification phase of the proto-flight model (PFM), and the CGBM PFM will be completed till this July. Before starting
productions of the PFM, we have verified mechanical designs and performance using the bread board model (BBM). The BBM was prepared only for SGM since the HXM has similar structure to the SGM.

A picture of the SGM BBM sensor is shown in left panel of Figure 4. The BGO crystal unit was produced by OKEN Co., Ltd and installed in an aluminum housing painted black on the outside and attached to a PMT R6233–20 by optical compound KE1051J (Shin-etsu Chemical Co., Ltd). The vibration and thermal-vacuum test were done at facilities (IMV Corporation and ISAS/JAXA respectively) on this January. After checking resonance characteristics with the modal survey, a random vibration level of 19.8 Grms in the frequency range of 20–2000 Hz was set during 120 seconds for the 3 axes. No critical damages on the sensors were seen during vibration tests. For the thermal-vacuum test, we imposed four temperature cycles to the SGM BBM with a high voltage turned on. The temperature range was –30 to 45 °C with a variation rate of 12 °C per hour. We found that no clear discharge events were seen and the spectral performance was unchanged during the thermal-vacuum test. Finally we disassembled the BBM, then verified by eye that no cracks or anomaly was present in the BGO crystal unit.

The BBM of the pre-amplifier and E-box was also fabricated. A picture of the GBM E-box is shown in right panel of Figure 4. We measured a broadband spectrum with a proto-type 3-inch LaBr₃(Ce) detector irradiated with a ²³²Th source. As can be seen from Figure 5 in addition to the 2.6 MeV gamma-ray line from ²⁰⁸Tl, we clearly see 4.5 keV Lₓ and 32 keV Kₓ lines from ¹³⁸Ba when the radio isotope ¹³⁸La involved in LaBr₃ decays via an electron capture. Therefore a wide dynamic range of the E-box has been verified. The high counting rate tolerance was also verified up to a few 10 kHz which is expected for previous intense GRBs.

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Figure 5: $^{232}$Th broadband spectrum taken by proto-type LaBr$_3$ detector with 220 µm-thickness beryllium window and the BBM of the GBM E-box. The spectrum from high and low gain is shown in red and blue respectively. We can clearly see several lines from 4.5 keV (Ba L$_x$) and 32 keV (Ba K$_x$) in low energies to 1436 keV ($^{138}$La) and 2614 keV ($^{208}$Tl) in high energies.

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