Hard X-Ray Detector (HXD) on Board Suzaku

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Abstract

The Hard X-ray Detector (HXD) on board Suzaku covers a wide energy range from 10 keV to 600 keV by the combination of silicon PIN diodes and GSO scintillators. The HXD is designed to achieve an extremely low in-orbit background based on a combination of new techniques, including the concept of a well-type active shield counter. With an effective area of 142 cm² at 20 keV and 273 cm² at 150 keV, the background level at sea level reached ~ 1 × 10^-3 cts s^-1 cm^-2 keV^-1 at 30 keV for the PIN diodes, and ~ 2 × 10^-5 cts s^-1 cm^-2 keV^-1 at 100 keV, and ~ 7 × 10^-6 cts s^-1 cm^-2 keV^-1 at 200 keV for the phoswich counter. Tight active shielding of the HXD results in a large array of guard counters surrounding the main detector parts. These anti-coincidence counters, made of ~ 4 cm thick BGO crystals, have a large effective area for sub-MeV to MeV γ-rays. They work as an excellent γ-ray burst monitor with limited angular resolution (~ 5°). The on-board signal-processing system and the data transmitted to the ground are also described.

Key words: instrumentation: detectors — X-rays: general

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1. Introduction

Suzaku is the fifth in a series of Japanese X-ray astronomy satellites with important US instrument contributions (Mitsuda et al. 2007). Its scientific payload consists of two kinds of co-aligned instruments, the X-ray Imaging Spectrometers (XIS) (Koyama et al. 2007) and the Hard X-ray Detector (HXD). The HXD extends the bandpass of the observatory to much higher energies with its 10–600 keV bandpass. While the bandpass of previous Japanese X-ray satellites was primarily below $\sim 20$ keV, where thermal emission predominates, the energy range of 10 to several 100 keV is where radiation from the high-energy celestial sources is mainly non-thermal. There were several missions that covered this energy range, but sensitive observations were very difficult, since the signal from X-ray sources is much weaker than the detector background, and also because the fluctuations of such background are large at orbital environments in inclined low-Earth orbits.

The main challenge of hard X-rays to gamma-ray spectroscopy is that the signal intensity from the source is usually weaker than the detector background. The main causes of the background include diffuse gamma rays, emission from radioactive nuclei due to activation of the detector, itself, and also cosmic rays, such as protons and other heavy ions. Besides, Compton down-scattering, dominant at higher energies, makes a proper X-ray event appear as background at a lower energy. Based on the experience accumulated through a series of balloon experiments (Kamae et al. 1992; Takahashi et al. 1993), the HXD is designed to minimize the background level by utilizing two concepts: “Well-type active shield”, and “Compound-eye configuration”, and hence to achieve a higher sensitivity than any previous instrument in the energy range between 10 keV and several 100 keV.

Since Suzaku is the recovery mission to the original Astro-E, which was lost in the launch accident in 2000, its basic design is the same as that of Astro-E. We designed and developed the HXD in basically the same manner as the previous HXD on board the lost Astro-E (Kamae et al. 1996; Tashiro et al. 2002). However, we employed a limited range of improvements, particularly concerning the sensor and analog electronics. The HXD fabrication was carried out involving detailed qualification at every step, with a special emphasis on verification of the newly introduced improvements. This paper describes the design of the HXD system and its ground performance. An accompanying paper (Kokubun et al. 2007, hereafter Paper II) considers the in-orbit performance of the HXD. Early reports on the HXD system and ground calibration can be found in previous publications (Kokubun et al. 2004; Kawaharada et al. 2004; Terada et al. 2005; Fukazawa et al. 2006; Yamaoka et al. 2006 and references therein.)

2. The HXD System

The HXD is a non-imaging and collimated instrument. The system is composed of a sensor part (HXD sensor or HXD-S), an analog electronics system (HXD-AE), and a digital electronics system (HXD-DE). A photograph of HXD-S is shown in figure 1. As described in the block diagram (figure 2), HXD-AE receives analog signals from HXD-S, selects the proper events and sends their digitized data to HXD-DE. HXD-DE then formats the data packets to send them to the ground via the satellite data processor (DP). Commands to the HXD are received by the peripheral interface module (PIM) from the satellite data-handling unit, and transmitted to HXD-DE. All power is supplied from a power-supply unit, called HXD-PSU. The operating temperature of HXD-S is designed to be $-20^\circ$C.

The characteristics of the HXD are summarized in table 1.

3. HXD Sensor (HXD-S)

Since the background level sets the sensitivity limit in the hard X-ray band, the HXD is designed to minimize the background by its improved phoswich (acronym for PHOSphor sandWICH) configuration for the energy region above 40 keV and the adoption of newly-developed thick silicon PIN diodes for energies below $\sim 70$ keV. Our detector ensures a low background through the following techniques:

1. Well-type active shield:
   In phoswich counters, two crystals with different decay times, are used for the detection part (faster decay time) and the shielding part (slower decay time), and both signals are extracted by a single photomultiplier. The improvement is that the shield is shaped in a well, so that it also acts as an active collimator (well-type active shield). This narrows the field of view (FOV) of the phoswich counter without any additional passive material, and results in the main detection part having an active shield of almost $4\pi$ of its surrounding (well-type phoswich counter). In the HXD, the well-type shield provides very efficient shielding for the PIN diode, which is read out independently.
2. Compound eye configuration:

HXD is modular, that is, consisting of a number of units. Each well-type phoswich counter unit has a simple shape and operates at a modest count rate by itself. In the HXD, we increase the photon collecting area by placing individual units in a matrix. In this configuration, each unit also becomes an active shield for adjacent units (compound eye configuration). It is also useful to reduce the possible dead time if parallel processing of each unit could be implemented. For additional shielding of the outermost units, thick anti-coincidence counters are placed surrounding the well units.

The main detection part of the phoswich counter in HXD-S is a gadolinium silicate crystal [GSO; Gd2SiO5(Ce)] buried deep in the bottom of a well-shape bismuth germanate crystal (BGO; Bi4Ge3O12) (hereafter we refer it as well-counter unit). As shown in the schematic drawing (figure 3), the HXD-S consists of 16 phoswich counters with 4 silicon PIN diodes in each, and 20 surrounding BGO anti-coincidence shield counters (anti-counter unit). All of the 16 well-counter units and 20 anti-counter units work independently. The numbering of the well-counters and anti-counters, which is frequently referred to in various technical documents, is shown in figure 4.

During operation of the HXD, instead of rocking observations, we plan to perform background subtraction by modeling
Fig. 3. Schematic drawing of HXD-S. It consists of 16 well-counter units and 20 anti-counter units.

the background spectrum, as was done in the LAC detector in Ginga satellite (Hayashida et al. 1989). Thus, the sensitivity will depend on the accuracy of the background modeling. If the background flux can be kept low, any systematic error of the modeling will have little effect on the spectrum of sources with a given flux. Since radioactive contamination in the detection part contributes to the background directly, special care was taken to select materials for the components used in the HXD sensor.

3.1. Well-Counter Units

In the HXD, each well-counter unit consists of five components (figure 5): crystals, PIN diodes, fine collimators, a photomultiplier, and front-end electronics. The mass of each unit is 4.63 kg. The crystals in the well-counter unit are four 5 mm-thick GSO scintillators with dimensions of 24 mm × 24 mm, and BGO scintillators for active shields. A photomultiplier, HAMAMATSU R6231-07, is attached to the counter unit to collect scintillation light from both GSO and BGO scintillators. The dynode signal from the photomultiplier is first processed by a preamplifier mounted in the housing of HXD-S. In the well-counter unit, the BGO scintillator is further divided into two pieces: a block-like section, called “BGO bottom piece”, and a well-shaped long section, called “BGO top piece”. The BGO top piece is not a simple “well”, but has cross-shaped inner BGO plates of 3 mm thickness to divide the “well” into four narrow collimators. The four GSOs are placed on the BGO bottom piece and surrounded by four...
Fig. 4. Numbering of the well- and anti-counter units when HXD-S is viewed from the top. There are 16 well-counter units from W00 to W33 and 20 anti-counter units from T00 to T34. Y direction corresponds to the direction toward Sun when the HXD is mounted to the satellite.

long square tubes of the BGO top piece. The BGO top piece actively restricts the field of view to $4.5^\circ \times 4.5^\circ$. By thus collimating the field of view, and rejecting those events that deposit all, or part, of the energy in BGO, the well-counter unit attains high sensitivity.

In addition to their large stopping power, the reason for having two different types of crystals for the sensors and the shields is their very different rise/decay times of $\sim 706$ ns for BGO and $\sim 122$ ns for GSO, at a working temperature of $-20^\circ$C (Kamae et al. 1992). This allows an easy discrimination of the sensor signal from the shield signals, where a single photomultiplier can discriminate between the two types of scintillators in which an event may have occurred. Any particle events or Compton events that are registered by both the BGO and GSO can be rejected by this phoswich technique. The GSO/BGO phoswich has several advantages over more conventional (e.g., NaI/CsI) combinations. Firstly, both GSO and BGO feature a higher stopping power for $\gamma$-rays. Secondly, they have fast decay times suitable for fast signal processing, and a large difference in the decay times between the two components, which makes pulse-shape discrimination easier. Furthermore, the number of long-lived $\gamma$-rays due to activations caused by charged particles irradiating the detector is smaller compared with other high-light-yield scintillation materials, such as YAP and NaI(Tl), if we normalize by the absorption thickness in the hard X-ray energy range. In table 2, we summarize the properties of the GSO and the BGO scintillators, together with those of NaI and CsI for a reference.

In the HXD, we use GSO crystals made by Hitachi Chemical\(^1\) with highly purified materials supplied by Shin-Etsu Chemical Co Ltd.\(^2\) in order to reduce any possible intrinsic background in the material. This purification is found to be very effective to increase the light output of the GSO scintillator (Kamae et al. 2002).

Since the GSO part covers an energy range of $40$–$600$ keV, another detector element is needed to assure coverage over the energy range down to that of the XIS ($< 12$ keV). The low-energy response of the HXD is provided by 2 mm thick PIN silicon diodes, each placed in front of a GSO crystal to form a PIN-GSO pair as the detection part of the well-counter unit. The diodes absorb X-rays with energies below $\sim 70$ keV, but gradually become transparent to harder X-rays, which in turn reach, and are registered by, the GSO detectors. Such PIN diodes were specially developed jointly with Hamamatsu Photonics K.K.\(^3\) to have 2 mm thickness (Ota et al. 1999). These thick PIN diodes were manufactured from highly purified silicon wafers, and can be fully depleted

\(^1\) [http://www.hitachi-chem.co.jp/english/index.html].
\(^2\) [http://www.shinetsu.co.jp/e/index.shtml].
\(^3\) [http://jp.hamamatsu.com/en/index.html].
Table 2. Properties of the GSO and BGO scintillators, together with those of NaI(Tl) and CsI(Tl) scintillators.

|                    | GSO(Ce) | BGO | NaI(Tl) | CsI(Tl) |
|--------------------|---------|-----|---------|---------|
| Effective decay time (ns) @ 20°C | 86      | 353 | 230     | 1000    |
| Effective decay time (ns) @ −20°C | 122     | 706 |         |         |
| Effective atomic number | 59      | 74  | 50      | 54      |
| Density (g cm⁻³) | 6.7     | 7.1 | 3.7     | 4.5     |
| Radiation length (cm) | 430     | 480 | 410     | 565     |
| Peak emission (nm) | ~10000  | ~4000| 38000   | 32000   |
| Light yield (photons MeV⁻¹) | ~10000  | ~4000|         |         |
| Index of refraction (at λ_em) | 1.9     | 2.15| 1.85    | 1.80    |
| Hygroscopicity | none    | none| yes     | little  |

* Light yield measured with a bi-alkali photomultiplier.

Fig. 6. Typical leakage current of a 2 mm-thick silicon PIN diode developed for the HXD as a function of the bias voltage. Data obtained at three different temperatures are shown.

Fig. 7. Angular transmission function of the fine collimator calculated at an azimuth angle of 0°. The 0° azimuth angle is defined along the positive x-axis in figure 4.

The energy range of the PIN diode, the dominant background component is the cosmic X-ray background. Therefore, having a narrow FOV is the most effective method to reduce the background contamination. For this purpose, passive shields, called “fine collimators”, are inserted in the BGO well-type collimator above the PIN diodes. The fine collimator is made of 50 µm thick phosphor bronze sheets arranged to form a square array of 8 x 8 square channels, each of 3 mm width and 300 mm length. Both the BGO collimator and the fine collimator define the FOV of the well-counter unit. Because of the finite thickness, the FOV changes with the photon energy. Below ~100 keV, the passive fine collimators define a 34° x 34° full-width half-maximum (FWHM) square FOV. Above ~100 keV, the fine collimators become transparent and the BGO active collimator defines a 4.5° x 4.5° FWHM square opening. Figure 7 shows the calculation of the energy dependence of the angular response. The collimator becomes transparent above ~100 keV, approaching the larger FOV of 4.5° x 4.5° (FWHM), defined by the BGO well. The angular response measured with γ-ray lines from radio isotope sources located at a limited distance is consistent with the calculation (figure 8).

A well-counter unit is completed by assembling all of the above and several additional components, and further incorporating several additional attachments. In order to attain a high light-collection efficiency through the better light reflection at the surface, we painted the BGO pieces with BaSO₄ and wrapped them with a Gore-Tex sheet. Similarly, the top and side surfaces of each GSO was wrapped by Gore-Tex sheets for better light reflection. The mechanical support structures at the top and bottom protect each well-counter unit from...
any vibration and shock during the launch. The structures are made of viscoelastic, plastic adapters, and carbon fiber reinforced plastic (CFRP) plates. A detailed description of the construction of the units is provided in Nakazawa et al. (1999).

Figure 9 shows the effective area of 16 well-counter units, which was based on the photo-peak efficiency calculated by Monte Carlo simulations using the EGS4 code (Nelson et al. 1985). The total geometrical area of the PIN diodes is 160 cm$^2$, while that of the GSO crystals is 350 cm$^2$. It is clear that the overlapping energy region between GSO and PIN, 40–70 keV, is well covered.

3.2. Anti-Counter Units

For additional shielding of the outermost well-counter units, 20 anti-counter units, each made of thick (average 2.6 cm) BGO pillars, surround a well-counter matrix. This reduces the cosmic proton flux on the PINs and the GSOs by an order of magnitude. It also serves to reduce Compton-scattered events as well as nuclear activation background events. Each unit is viewed by a photomultiplier (HAMAMATSU R3998-01 MOD). The prime function of the anti-counter units is to provide hit-pattern information to the well-counter units. The anti-counter units have a wedge-like structure for saving their mass while obtaining the same path length of the BGO scintillator viewed from the PIN and the GSO in the well-counter units. The mass of each unit is 4.12 kg for 16 units, except for corner units with a mass of 2.72 kg. The geometrical area of the anti-counter wall is as large as $\sim 800$ cm$^2$ per side, and its effective area is $\sim 400$ cm$^2$, even for 1 MeV $\gamma$-rays. Therefore, they are also utilized as an excellent $\gamma$-ray burst detector in the energy range between 50 keV and 5 MeV. According to a Monte Carlo simulation, if a gamma-ray burst occurs with an intensity of 1 cts s$^{-1}$ cm$^{-2}$ in 50–300 keV, the spectrum with parameters of $\alpha = -1.0$, $\beta = -2.3$, and $E_0 = 250$ keV in Band function (Band et al. 1993), and a duration of 20 s, is captured by two side faces of the anti-counter units, we can determine its one-dimensional position with an accuracy of $\sim 5^\circ$, by comparing signal counts from the four sides. As shown in figure 10, the anti-counter units have the largest effective area compared with other current or future $\gamma$-ray burst (GRB) detectors, including the GLAST/GBM and the Swift/BAT in the MeV range. Above 300 keV, the HXD has the largest effective area. A detailed description of the WAM and its in-flight performance is described in Yamaoka et al. (2006).

3.3. HXD Housing

The housing structure for HXD-S is designed to hold 36 detector units in HXD-S. The function of the housing is to protect the units mechanically, to minimize any temperature gradient among the units, and to reduce the electrical noise. These requirements should be realized within the limited space and mass allowed to the instrument. For this purpose, CFRP and magnesium alloy are adopted for the material to be used. The HXD-S housing is made of three components: the top lid and the center body part made of CFRP, and the
the operating temperature of not give any stress to the detectors once HXD-S is cooled to thermal expansion compared with the BGO crystal, and will not only for its strength and light mass; it also has a lower bottom structure made of magnesium alloy. CFRP is selected S42 T. Takahashi et al. [Vol. 59, its basic role as active shields. The ACU is provided power transient sources (including gamma-ray bursts), in addition to anti-counter units have an additional function of monitoring the well-counter units acquire data from target sources, the latter is broken into two types, four well-processing unit (WPU) boards for the anti-counter units. While each WPU and TPU, respectively, handles four well units and five anti-counter units. All WPU/TPU and ACU boards are connected to the backplane of the AE housing. In order to reject Compton events that occur in the compound eye configuration of the HXD, it is important for each unit to be informed of the presence or absence of hits in the other 35 units. This information, called hit pattern, is shared by all electronics boards through a “hit-pattern bus”, which runs through the backplane. Besides the hit-pattern information, other lines, such as power-lines and clock-lines also run through the backplane.

The signal flow from a well counter unit to a WPU board and a functional block diagram of the signal processing are shown in figure 11 and figure 12, respectively. There are two independent circuit blocks for the PMT and the PIN. Here, we first describe the signal processing for the PMT and then for the PIN.

The signal from a photomultiplier anode is fed directly to a fast amplifier in HXD-AE to generate trigger signals. Unlike the charge-sensitive amplifiers that are contained in the HXD-S front-end electronics and amplify dynode signals, the anode amplifier just simply amplifies the current from the photomultiplier tubes. The power consumptions are 12.8 mW for the anode amplifier and 42.5 mW for the dynode amplifier. This allows us to utilize very short anode pulses, which are required in generating fast pre-trigger signals. This also has a special meaning in the present phoswich configuration: since the GSO

![Fig. 11. Signal flow from a well-counter unit to a WPU board. A pair of anode and dynode signals from the bleeder and four PIN diode signals are processed in one block. A WPU contains four of these blocks, and handles signals from four well-counter units.](https://example.com/fig11.png)
Scintillation has a faster decay time than that from BGO, valid GSO signals produce larger anode output pulse-heights than those from BGO, for the same energy deposit. This allows HXD-AE to preferentially select GSO signals, while rejecting BGO events.

A preamplifier output pulse generated from a dynode signal is split in the HXD-AE into two shaping chains with different time constants: 150 ns (fast shaping) and 1000 ns (slow shaping). Each of the shaped signal is then peak held (activated by the trigger signals) and sent to analog to digital converters (ADCs). Since the decay times of the GSO and BGO are different, the ratio of the fast and slow shaping pulse heights will differ between GSO and BGO. In a fast-shaping processing chain, the charges from a BGO event are only partially integrated, while the GSO signal is fully integrated. In a slow-shaping processing chain, in contrast almost all of the charges are integrated for both crystals. By comparing the fast and slow pulse heights, we can thus discriminate GSO pulses from BGO events. This “double integration method” is the basis for pulse shape discrimination (PSD).

We have developed an application specific integrated circuit (ASIC) with this PSD function (Ezawa et al. 1996). When a dynode signal is fed to this ASIC and a trigger is received from the anode, the ASIC gives two peak-held analog outputs, corresponding to the two shaping time constants. The power consumption of the ASIC is 230 mW. These outputs can be arranged as in figure 13, called “fast–slow diagram” or “two-dimensional spectrum”, where the vertical and horizontal axes represent the slow and fast shaping pulse heights, respectively. In this way, we can see two lines with different inclinations, or branches, demonstrating the separation of signals from GSO and BGO. A bridge connecting the two branches is formed by Compton-scattered events, which hit both GSO and BGO. A bridge connecting the two branches is formed by Compton-scattered events, which hit both GSO and BGO. A bridge connecting the two branches is formed by Compton-scattered events, which hit both GSO and BGO. A bridge connecting the two branches is formed by Compton-scattered events, which hit both GSO and BGO. A bridge connecting the two branches is formed by Compton-scattered events, which hit both GSO and BGO. A bridge connecting the two branches is formed by Compton-scattered events, which hit both GSO and BGO. A bridge connecting the two branches is formed by Compton-scattered events, which hit both GSO and BGO. A bridge connecting the two branches is formed by Compton-scattered events, which hit both GSO and BGO. A bridge connecting the two branches is formed by Compton-scattered events, which hit both GSO and BGO. A bridge connecting the two branches is formed by Compton-scattered events, which hit both GSO and BGO. A bridge connecting the two branches is formed by Compton-scattered events, which hit both GSO and BGO.
energy range of $\sim 600\text{keV}$ are those events scattered between the adjacent units. Since a Hit Pattern Selection using too many detector units will increase accidental coincidence, and hence reduce the signal acceptance, it is generally adequate to consider the 4 adjacent units, or 8 surrounding units. The rejection pattern can be selected by software, either in HXD-DE, or in the course of ground analysis.

The signals from the four PINs inside the well-counter unit are separately read out and fed individually to low-noise charge-sensitive preamplifiers (PIN preamplifiers) mounted underneath the preamplifier for the PMT and fed into the circuit in HXD-AE. Analog electronics for the PIN is designed to achieve an energy threshold of 10 keV and an energy resolution of $3\text{keV}$ (FWHM) in the orbit under power consumption of $107\text{mW}$ for the preamplifier per each PIN diode. Since a PIN diode has a typical leakage current of $\sim 2\text{nA}$ at $-20^\circ\text{C}$, and a relatively large capacitance of $\sim 50\text{pF}$ (including the capacitance of the cable), we developed a low-noise preamplifier with a capacitance gradient of $\sim 15\text{eVpF}^{-1}$. Since as many as 64 channels of PIN diodes need to be processed, reduction of the size and the power consumption is very important in the AE electronics. We therefore integrated the last step of the amplification, the peak-hold-circuit and the lower discriminator into the PIN as a variant to the PSD ASIC (Ozawa et al. 1997).

By combining the preamplifier with the PIN diode and operating them at $-20^\circ\text{C}$, we achieved an energy resolution of $2.9\text{keV}$ at 59.5 keV, and an energy threshold of $\sim 10\text{keV}$, as shown in figure 14. The energy resolution of the PIN preamplifier is $1.0\text{keV}$ in a load-free condition; this degrades to $1.6\text{keV}$ due to capacitive noise, and another $1.0\text{keV}$ is due to the current noise. The remaining $\sim 2.1\text{keV}$ is possibly caused by electronic noise in the HXD-S or the HXD-AE.

**Fig. 13.** (top) Fast–slow diagram for the $^{22}\text{Na}$ and $^{133}\text{Ba}$ irradiation, taken from a single unit. (bottom-left) PSD selection effect on the GSO spectrum. (bottom-right) Separation of GSO/BGO events at the lower energy.
The trigger signal for the well-counter unit is generated from the anode signal, and for the PIN diodes, the output of the gain amplifier is fed into a comparator to generate the triggers. When any one of the trigger sources, including the pseudo-trigger, is activated, gate signals for peak holding and ADCs are generated. The trigger rate in a single WPU could be as high as several hundred Hz, if we turn off the on-board PSD selection. Therefore, careful design was adopted for the digital circuits that handle the triggering. By using the PSD information, the trigger is issued for events that deposited all of their energy in GSO or PIN. Signals with energies out of the energy range of the detector are also rejected based on the upper discriminator information. Hit-pattern information is used later in an offline analysis. The details of trigger sequence are described by Takahashi et al. (1998).

A significant fraction of these trigger events are charged particles, including geomagnetically trapped particles (mainly protons) and primary cosmic rays. Because the energy loss of a charged particle is proportional to the density and size of the detector, it becomes very severe in the HXD, which employs large and heavy scintillators for active shielding. In fact, the energy loss by a charged particle onto a HXD unit is estimated to be typically $\sim 100\,\text{MeV}$, which is 3 to 5 orders of magnitude larger than the target energy. Since this is well above the saturation level of the amplifying system, a long electronic recovery time would affect the subsequent signals, produce spurious events, and/or increase the dead time. In order to avoid these problems and make the system tolerant to these large pulses with high counting rates, we designed all of the electronics, from front-end to HXD-AE, to quickly recover these large pulses with high counting rates, we designed all of the electronics, from front-end to HXD-AE, to quickly recover from every energetic pulse. The recovery time for a 100 MeV pulse is about 50 $\mu$s for the dynode amplifier (Tanihata et al. 1999). Furthermore, we inhibit any subsequent trigger until the circuit has fully recovered from disturbance caused by large pulses (Tanihata et al. 1999). The treatment for large pulses is also implemented in bleeder circuits in the photomultipliers for the well-counter units (Tanihata et al. 1999) and the anti-counter units (Yamaoka et al. 2006).

Measuring the dead time is one of the most important tasks of the electronic system. This is because the spectrum of a celestial object is obtained by subtracting the background spectrum from the observed one, and an accurate live time is especially required when the source is faint. In the HXD, a dead-time measurement is done individually for each well unit by counting the number of pseudo event pulse. The pseudo event pulses are electronic pulses generated in the ACU module, periodically with a selectable period. These pulses are fed into the trigger-handling block, and activates the trigger logic in the same way as other trigger sources, but with a specific flag in the trigger pattern. Since the pseudo-trigger is randomly vetoed by normal events, we can accurately estimate the dead-time fraction by comparing the total number of injected pseudo-pulses and those actually recorded in the data. Another way to estimate the dead time is to count up to 10 MHz (selectable by command) by clock pulses when the system is busy, and hence the the trigger is inhibited. A verification of these methods in orbit is described in Paper II. The dead-time counters are edited into the monitor data and sent to HXD-DE every second. While the dead time cannot measure dead times caused by the HXD-DE capability or by a telemetry limitation, it can handle fast changes in the dead time.

The anti-counter units, which surround the 16 well-counter units, have two functions. One is to provide hit-pattern information to the well-counter units, and the other is to monitor celestial transient events, such as gamma-ray bursts and solar flares. Signals from each of the 5 anti-counter units on the same side of HXD-S are handled by one TPU module. In the TPU, hit-pattern signals from each counter are generated with an energy threshold of 40 keV. At the same time, a TPU module accumulates event pulses from the 5 anti-counter units, and produces their summed pulse-height spectrum, which is sent to HXD-DE every 1 s. If a sudden increase in the counting rate, due, e.g., to a gamma-ray burst, is detected, the TPU records four-energy-band light curves with a finer (15.625 ms or 31.25 ms) timing resolution for a certain length of time.
4.2. Data Packet from HXD-AE

When an event from a well-counter unit satisfies the pre-specified trigger conditions, and is hence judged to be valid, all analog outputs from the relevant well unit (those of the slow shaper, the fast shaper, and the four diode shapers) are digitized by ADCs and edited into event data. For the signals of the PIN diodes, the upper 8 bits are used, because the dynamic range of the PIN diode is small (10 to 70 keV). Also recorded are the occurrences of any hits in four PIN diodes and GSO in the well unit as a trigger pattern. The pseudo-trigger and the output from the discriminator that senses any overshoot of the charge-sensitive amplifier of the PIN also provides triggers, which are recorded in the trigger pattern. Any hits in the slow discriminator output from 16 well units and 20 anti-counters are also recorded as a hit pattern. The output of the PSD flags to monitor the pile-up events, and the upper discriminator outputs are also recorded. All arrival times are recorded with a resolution of 61 µs during the normal operation mode. The data, formatted as shown in table 3, are sent to the HXD-DE on an event-by-event basis. Thus, one valid event occupies 16 Bytes. In addition to the well-event data, a number of additional data in the HXD system used to monitor its proper function and to estimate of the background and dead time are collected.

4.3. Digital Electronics (HXD-DE)

HXD-DE is the CPU-based signal processing part of the HXD. It is designed: (1) to provide the primary interface with the satellite data processor for command and telemetry, (2) to control the acquisition and formatting of the data from HXD-AE, and (3) to react to events such as γ-ray bursts. HXD-DE is based on a CPU 80C386 running at 12 MHz. It has two CPU boards, with one board working while the other is idling for backup purposes. Mounted on the CPU board is 512 KB of SRAM used for a programmable area, another 512 KB of SRAM serving as direct memory access (DMA) buffer, and 512 KB of EEPROM for program storage.

One of the baseline requirements of HXD-DE is to acquire data without loss from sources that are several times as bright as the Crab Nebula. This means that HXD-DE should be capable of an acquisition rate of at least several hundred events per second. If we loosen the electronics parameters, such as the level of PSD discrimination and low-level discriminator, the rate goes up quickly. Therefore, we set our rate tolerance of the system to be 4000 events per second. In order to achieve this high acquisition rate with limited hardware resources, we use a fast real-time operating system specially designed for this experiment, in conjunction with a circuit capable of receiving data from HXD-AE by the DMA mode. When data are sent or received in the DMA mode, the I/O adaptor accesses the DMA buffer directly, without interrupting the CPU.

In orbit, irradiation by charged particles can cause bit errors in the memory. In order to prevent these errors from causing malfunctioning, the process called Memory-Patrol is always running to verify the contents of memory byte by byte. In addition, the HXD-DE data are accompanied by an error correction code, which repairs 1-bit errors, and reports the occurrence of 2-bit (or more) errors.

4.4. PI PROGRAM

A process called “PI program” is an important addition to the HXD-DE software, and is used to realize high signal throughput while keeping a low-background capability. Its task, for example, is to filter out those background events that leak through the hardware selection in WPU, and to compress the “transient” data sent from the TPU. These functions become particularly important when the telemetry bandwidth is limited. Additional tasks of the PI program are to collect calibration data, and to notify γ-ray burst triggers to the TPU modules. The PI program is activated when the data arrives from the DMA buffer with the data type, as input. According to the data type, the main routine of the PI program calls the corresponding function that handles the data.

Although the hardware PSD in the WPU module is very powerful, the PI program provides more flexible ways to further select events. The PI program does the event selection via several different algorithms, which can be chosen by commands. Several examples of these algorithms are given below:

hit pattern: The program performs event selection based on the hit-pattern information of the surrounding units. Using this, we can reject Compton-scattered events and particle-interaction events.

pulse shape: In HXD-AE, pulse-shape discrimination is performed by comparing the pulse heights between the slow and fast shaping amplifier outputs. In HXD-DE, finer and more flexible selections can be applied on the fast–slow diagram.

delta-t: In some inorganic scintillators, such as CsI(Tl), a train of pulses with random shapes occur during 400 µs — a few ms after a large energy deposit (at least $E \geq 60$ MeV) in the crystal (Takahashi et al. 1993). This leads to a number of false triggers in a very short time. These false events can be removed in the HXD-DE, because the PI program can measure the time difference between successive events and remove them if the difference is shorter than a certain threshold.

5. Ground Calibration and Tests

Before the launch, the HXD performance was studied extensively on the ground. Since the HXD is a highly sophisticated experiment involving a large number of components, a comprehensive data base has to be prepared before launch in order to construct a set of software required to deduce scientific results from the observational data. In ground pre-launch tests, we first qualified the basic system functions, including the pulse-shape discrimination, hit-pattern generation, and the methods of dead-time measurements. Subsequently, we placed HXD-S in a low-temperature environment (−20 °C), irradiated it with various gamma-ray emitting radio isotopes, and acquired data via HXD-AE and HXD-DE. We thus measured the basic characteristics of individual well-counter and anti-counter units, including the gain linearity and energy resolution, as well as their angular responses. The background spectrum was also measured to verify the low background performance of the HXD.
5.1. Alignment

The alignment of the 64 fine collimators has been measured by means of optical light and a $\gamma$-ray source. Figure 15 shows their angular offsets, measured by scanning a $^{133}\text{Ba}$ source in front of HXD-S at some distances. These two independent measurements confirm that the collimators are aligned with an accuracy of $3'5$ (FWHM). This ensures an effective transparency of 90%, when a target is placed at the mean direction of the optical axes of the 64 fine collimators. We verified that the angular offsets did not change after the vibration test of HXD-S. The effective area shown in figure 9 has to be collected with this effective transparency. The overall calibration for the absolute normalization in orbit is described in Paper II.

5.2. Spectral Performance

Calibrations of the gains and the offsets and measurements of the energy resolution are essential in constructing the instrumental response function, which in turn is needed to reconstruct incident spectra from the observed pulse-height distributions. Before assembling HXD-AE, we measured the linearity and dynamic range of its individual signal-processing circuits using electronic test pulses. After some iterative electronics gain and offset adjustments, the relations between the test pulse amplitude and the resultant ADC values of individual signal channels were measured, and were registered as gain parameters in a calibration data base.

When mono-energetic gamma-rays are incident on the PIN or GSO detector, the output pulse height distribution primarily consists of a roughly Gaussian peak formed by full-energy-deposit events. Although the Gaussian centroid is roughly proportional to the gamma-ray energy, we must consider the measured electronics non-linearity (see above). Furthermore, the GSO scintillator is known to exhibit some non-linearity of the energy deposit and light output, particularly toward lower energies (Uchiyama et al. 2001); this has to be calibrated. The pulse-height distributions also very often show secondary features with lower pulse heights. In the GSO spectra, the strongest secondary feature is produced by gamma-rays that undergo Compton scattering in the detector and escape from it. In the PIN spectra, guard-ring structures in the diode produce a spectral sub-peak with $\sim2/3$ of the main-peak pulse height (Sugiho et al. 2001). Since these secondary features generally depend on the detector geometry, we use a Monte Carlo simulation code, either EGS4 (Nelson et al. 1985) or Geant4 (Allison et al. 2006; Agostinelli et al. 2003), to compute the response of the HXD detector as a continuous function of energy (Terada et al. 2005; Kokubun et al. 2007). These codes allow us to handle the detailed detector geometry, such as the guard ring and housing of the PIN diodes. These Monte Carlo simulations refer to the data base, which summarizes the parameters of individual GSO and PIN detectors such as the linearity and the energy resolution, measured at discrete energies using isotopes by fitting the spectrum with a Gaussian profile. Sub peak structures seen in the PIN spectrum are properly taken into account in the code.

After HXD-S and HXD-AE were assembled, we measured the linearity and energy resolution, including both the sensor and electronics properties, utilizing gamma-ray lines from the radio isotopes listed in table 4. The obtained PIN and GSO spectra are shown in figure 16 and figure 17, respectively. The GSO spectrum clearly reveals the $31$ keV $\alpha$ line from $^{133}\text{Ba}$, indicating that the lower threshold energy of GSO has been made sufficiently low. The phoswich configuration successfully prevents the Compton events from contaminating the GSO spectra, and makes the full-energy peaks much more prominent than in the spectra taken with conventional scintillators. Figure 18 and figure 19 show linearity plots of one representative PIN and GSO, respectively, obtained from the $\gamma$-ray line measurements. Below $\sim100$ keV, the GSO results show the slight non-linearity mentioned above, which can be corrected by analysis software.

As can be inferred from figure 16, and summarized in figure 20, the typical energy resolution of the PIN diodes has been obtained as $\sim3.3$ keV at $-20^\circ\text{C}$. This meets our design goal, because then the low-energy threshold of PIN can be lowered to $\sim10$ keV, ensuring an overlap with the energy range of the XIS (Koyama et al. 2007). Similarly, figure 21 shows...
the distribution of the energy resolution of the GSO scintillator in the 16 well-counter units, while figure 22 shows the energy resolution of unit W01 as a function of energy. Thus, the energy resolution is 12% at 511 keV (or 10% at 662 keV), which again meets our design goal. The corresponding value of a single GSO of 5 mm thick read directly by a PMT is typically 7% at 662 keV, and its degradation to ~10% is caused by the phoswich configuration: about 30% of the GSO scintillation photons are absorbed when they penetrate the BGO bottom piece, and another ~20% is reflected into the BGO top piece.

5.3. Background Level and Expected Sensitivity

It is of vital importance to confirm that the HXD achieves a sufficiently low background level, after the event selections implemented in the HXD are applied. Figure 23 left shows an on-ground background spectrum of a typical well-counter unit, acquired in these pre-launch tests. It is presented in the same fast–slow diagram as figure 13. Again, we clearly observe the separation of the GSO and BGO branches. Below the GSO branch, we can see a narrow line. Because of the very fast time constant attributed to these events, they are thought to be due to Cherenkov light produced in PMT glass. Figure 23 right shows the events selected by the PSD in the data analysis; the selection here is somewhat tighter than is implemented in HXD-AE as hard-wired function (subsection 4.1), but comparable to those that will be employed in actual observations. It is apparent that all of the BGO and Compton events are effectively rejected by the PSD cut. Further details on the selection...
Fig. 20. Distribution of the energy resolution among the 64 PIN diodes in the HXD, measured at −20°C using the 31.5 keV γ-ray line from $^{133}$Ba.

Fig. 21. Distribution of the energy resolution of GSO in the 16 well-counter units, measured using the 511 keV γ-ray line from $^{22}$Na.

The remaining background events are further reduced by taking anti-coincidences among the 16 well-counter and 20 anti-counter units, employing the hit-pattern information attached to individual GSO events (subsection 4.2). The solid line in figure 24 shows the background spectrum after hit-pattern selection by adjacent 4 units for both GSO and the PIN diodes. For the PIN diodes, the events that hit the BGO or GSO in its own well unit are also rejected. The effect of anti-coincidence among units by utilizing hit-pattern information reduces the background level by 30–50%. In the GSO selected spectrum (figure 24), it is apparent that while the background level under 100 keV is determined by off-aperture X-rays from the FOV, it is dominated by the intrinsic radioactivation above 100 keV. A peak around 360 keV is clearly seen. This is due to the intrinsic radioactivity of the $^{152}$Gd in the GSO crystal (abundance 0.2%, 2.14 MeV α-rays, half-life $1.1 \times 10^{14}$ yr) (Kamae et al. 1993). The number of photons of the peak is counted to be $0.2 \text{cts s}^{-1}$ per well, which is consistent with the calculated value. Though this intrinsic peak cannot be removed, we utilize it as an in-orbit calibration source, while we use activation lines of GSO and BGO for PIN (Paper II). The resulting background level at the sea level was $\sim 1 \times 10^{-4} \text{cts s}^{-1} \text{cm}^{-2} \text{keV}^{-1}$ at 30 keV for the PIN diodes, and $\sim 2 \times 10^{-5} \text{cts s}^{-1} \text{cm}^{-2} \text{keV}^{-1}$ at 100 keV, and $\sim 7 \times 10^{-6} \text{cts s}^{-1} \text{cm}^{-2} \text{keV}^{-1}$ at 200 keV for the phoswich counter. This is the lowest background level we have reached throughout our development, including balloon experiments (Takahashi et al. 1993).

In orbit, the background level is expected to increase because charged particles penetrating through the scintillators will produce various unstable nuclear isotopes. We have thus carried out proton irradiation experiments using particle
accelerator facilities, in which a flight-equivalent well and anti-counter units were both irradiated by protons accelerated up to typical energies (100–200 MeV) of the geomagnetically trapped cosmic-rays in orbit. Figure 25 represents the expected background spectrum in orbit, obtained by adding together the measured on-ground background and the expected increase due to radio-activation. The latter was calculated assuming a proton flux in an orbit of altitude of 550 km and an inclination of 31° at the solar maximum (Kokubun et al. 1999).

The sensitivity of a detector for a weak continuum source is generally determined by statistical and systematic uncertainties in the background, the effective area in the relevant energy range, and the observation time. The very low background level demonstrated by the ground calibration ensures a high sensitivity for the HXD, even with its relatively small effective area. The expected sensitivity will be presented in the companion paper (Paper II), taking into account the actually measured in-orbit background and its variation.

In order to achieve a high sensitivity, precise modeling of the background is important. For this purpose, we turn on the PIN diodes even in the SAA passage to count the number of energetic charged particles that have passed through the PIN diodes. By utilizing the count rate of upper discriminators attached to each analog processing chain for the PIN diode, the information about the nature of non X-ray background can be obtained by measuring any variation and distribution of such high-energy particles. Detail results of measurements and their application to the modeling are described in Paper II.
6. Summary

The HXD has been designed to achieve an extremely low in-orbit background (≈ 10^{-4} cts s^{-1} cm^{-2} keV^{-1}), based on a combination of novel techniques: (1) five-sided tight BGO active shielding; (2) the use of 20 shielding counters made of thick BGO crystals that surround the 16 main GSO/BGO counters; (3) sophisticated onboard signal processing and onboard event selection, employing both high-speed parallel hardware circuits in the Analog Electronics, and CPU-based signal handling in the Digital Electronics; and (4) a careful choice of materials that do not become strongly radio-activated under in-orbit particle bombardment. Finally, (5) the narrow field of view below ≈ 100 keV, defined by the fine collimator, effectively reduces both the CXB contribution and any source confusion. A detailed pre-flight calibration confirms that the performance of the HXD meets the design goal of the experiment, including a threshold of ≈ 10 keV of the PIN diode, and the very low on-ground background of 1–5 × 10^{-5} cts s^{-1} keV^{-1} cm^{-2}.

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