A portable Si/CdTe Compton camera and its applications to the visualization of radioactive substances

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ABSTRACT

Gamma-ray imagers with the potential for visualizing the distribution of radioactive materials are required in the fields of astrophysics, medicine, nuclear applications, and homeland security. Based on the technology of the Si/CdTe Compton camera, we have manufactured the first commercial Compton camera for practical use. Through field tests in Fukushima, we demonstrated that the camera is capable of hot spot detection and the evaluation of radioactive decontamination.

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1. Introduction

A gamma-ray imaging system that can visualize the distribution of radioisotopes is extremely useful in many fields such as scientific research, non-destructive inspection and homeland security. For example, in the case of Fukushima, the visualization of the radioactive contamination by the gamma-ray imager is expected to accelerate the prioritization and verification processes of the decontamination. Based on recent development of high-quality room temperature semiconductor devices and readout analog ASICs, gamma-ray imagers have been improved [1–4] to realize sufficient angular resolution to locate the sources as well as sufficient energy resolution to reject background.

A Compton camera is regarded as powerful technology since it can directly locate sources without collimators, i.e. it can obtain a wider field of view (FoV) than coded aperture gamma cameras. The wider FoV is advantageous in real-world situations since radioactive substances can be distributed over large patches of ground. It is difficult to precisely track the scattering gamma-rays with traditional scintillation detectors. Therefore, a semiconductor Compton camera is desirable to meet requirements in practical use. Since the early 2000s, we have been developing a new Compton camera which consists of Si and CdTe semiconductor detectors [5,6]. Original technologies of low-noise silicon devices, high resolution Schottky CdTe diodes and dedicated low-noise analog ASICs allow the tracking of low energy gamma-rays,

yielding a wide energy band from 100 keV to a few MeV. In the Si/CdTe Compton camera, the events involving the incident gamma-ray being scattered in the Si detector and then fully absorbed in the CdTe detectors are used for Compton imaging. Since the effect of Doppler broadening is smaller in the Si devices than in other semiconductor devices, the camera allows the difference between the measured and actual scattering angles to be constrained, meaning that higher angular resolution is expected. CdTe works very nicely as an absorber thanks to its large atomic numbers (48, 52) and high density (5.8 g/cm³).

ASTROCAM 7000HS (see Fig. 1) is the first commercial Compton camera based on the Soft Gamma-ray Detector (SGD) [7] onboard the ASTRO-H satellite [8] planned for launch in 2015. The camera unit is 445 mm in depth, 340 mm in width and 235 mm in height, and the weight is approximately 10 kg. All measurements can be controlled on the user interface screen of a PC via a control box that houses a camera control circuit, a temperature control circuit, a high voltage control circuit, a power supply circuit, etc. In addition to its portability, ASTROCAM features scalability, that is, the efficiency can be optimized by customizing the number of detectors according to requirements of each application.

2. Design of ASTROCAM 7000HS

In early 2012, we developed a prototype Si/CdTe Compton camera and tested its feasibility in the evacuation zone [9], situated around 20 km from Fukushima Daiichi Nuclear Power Plant. The

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prototype consists of 2 layers of Si double-sided strip detectors (Si-DSDs) and 3 layers of CdTe double-sided strip detectors (CdTe-DSDs), which have a detector area of 3.2×3.2 cm and a strip pitch of 250 μ m. Its imaging capabilities such as a good angular resolution of 3.8° (FWHM) at 662 keV, an excellent energy resolution of 2.2% (FWHM) at 662 keV, and a wide FoV corresponding to 2π steradian ($180^\circ \times 180^\circ$) have been reported [10]. Hot spots above the environmental radiation level of a few μ Sv/h were clearly visible in exposure times of around 60 min.

The efficiency obtained by the prototype was 0.035 cps/MBq at 1 m (^{137}Cs , 662 keV). This refers to the count rate in the full energy peak at 662 keV for a ^{137}Cs point source (1 MBq) located 1 m from the camera. Because this prototype required 60–120 min for visualization on a few μ Sv/h background, improvement of the efficiency was highly desirable in order to shorten the exposure time to around 10 min.

Fig. 1. Photo of the ASTROCAM 7000HS.

To improve the efficiency in ASTROCAM, the detector size was increased to 5×5 cm wide and the camera has the capability to have larger numbers of layers. This type of detector is used in the SGD onboard ASTRO-H, and the details of each detector and their modularization are reported in Watanabe et al. [7]. The standard model of the camera consists of 8 layers of Si detectors and 4 layers of CdTe detectors. An efficiency of 0.16 cps/MBq at 1 m (^{137}Cs , 662 keV), about 5 times higher than that of the initial prototype, is measured, which agrees well with design value.

It is possible to integrate more detectors, up to 32 layers of Si and 8 layers of CdTe detectors. In addition, all four horizontal directions of the accumulated detectors are covered by 2 layers of CdTe modules. In this enhanced model, the efficiency is improved to 2.8 cps/MBq at 1 m (^{137}Cs , 662 keV), which is about 16 times higher than that of the standard model.

The energy resolution of the camera is measured to be 2.2% (FWHM) for 662 keV gamma-rays. A moderate angular resolution of 5.4° (FWHM) in ARM (Angular Resolution Measure) is obtained, meaning that it has about 1 m spatial resolution at 10 m from the camera. The basic specifications of ASTROCAM are summarized in the technical review [11].

3. Demonstrations in Fukushima

Tests of ASTROCAM have been performed several times in the 20 km zone. Here, we show two examples that clearly demonstrate the power of gamma-ray imaging. Data were taken with the standard model using an exposure of 30 min.

In order to suppress image noise, only the parts which have a certain significance are shown in the camera image. As described in the previous work [9], this is realized by quantifying the statistical uncertainty of the signal and an offset component due to back-grounds appeared in the sky region of the back-projection image.

One potential use of gamma-ray imagers is to visualize the effect of decontamination efforts. An example for “before and after” clean-up is shown in Fig. 2. The environmental radiation levels in this area were around 0.5 – 1.0 μ Sv/h. The camera was located at the same position, both (left) before and (right) after clean-up. As clearly seen, extended hot spots were detected before clean-up, while one cannot recognize any accumulation of radioactive substances in the image after clean-up. This result means that ASTROCAM is capable of not only hot spot detection but also being utilized for the verification of decontamination.

Another desired capability is to be able to visualize the distribution of radioactive substances spread on a wide area, because a

Before decontamination (Jun. 2013)

After decontamination (Jan. 2014)

Fig. 2. One example demonstration in the 20 km zone of the nuclear plant. ASTROCAM was located at the same position, both (left) before radioactive clean-up in June 2013, and (right) after radioactive clean-up in January 2014.

manual survey with survey meters takes a large amount of time and sometimes misses hot spots. However, an intense hot spot near the camera could potentially prevent detection of distant hot spots. In order to avoid this, we mounted the camera on a bucket truck and then elevated it. With this setup, the contamination by the near-field hot spots is reduced. One scene of this demonstration is shown in the left panel of Fig. 3. The camera was raised to a height of 6 m. As shown in the right panel, we confirmed that the distribution of the hot spots existing at 20–30 m from the camera can be visualized.

4. Detectable hot spots in background

Quantifying the hot spot detection capability in an environment with background radiations is important for estimating the exposure time and the detection limit in practical situations. We evaluate the hot spot detection capability, hereafter the sensitivity, in terms of the minimum detectable signal counts on an image which is defined as

$$S_{\text{RoI}} > z \sqrt{(\Delta B_{\text{RoI}})^2 + (\Delta S_{\text{RoI}})^2} \quad (1)$$

where B_{RoI} and S_{RoI} are the background and the signal counts in Region of interest (RoI), respectively, ΔB_{RoI} and ΔS_{RoI} are their

uncertainties and z is the significance. In this section, we describe details of methods to calculate above quantities and associate the sensitivity with a $\mu\text{Sv/h}$ unit.

The appropriate RoI in this calculation should be the typical size of a point-like source in the reconstructed image. The RoI is defined as a circle with a radius of 10° in this study.

The back-projection image produced by simply accumulating Compton cones is suitable for the sensitivity calculation since the count in each image pixel directly reflects photon statistics, which makes it easy to calculate statistical uncertainties of the signal and background counts compared with other image reconstruction methods (e.g. List-Mode Expectation Maximization). It should be noted that since the integral of a single Compton cone is normalized to 1 to conserve the number of measured photons on the image, the total counts of the single cone in the RoI are smaller than 1. Consequently, the background counts in the RoI, B_{RoI} , given by integrating all contributions from each isotropic background gamma-ray could not be simply interpreted by the Poisson distribution.

Analytical approaches to predict the uncertainty of B_{RoI} on the measured full energy peak events N_B are difficult since B_{RoI} is the sum of partial probabilities of the Compton cones which depends on the incident energy, detector configuration, event reconstruction and so

Fig. 3. One scene in the 20 km zone. In order to visualize the radioactive substances spread on a wide site, ASTROCAM was mounted on a bucket truck and raised to a height of 6 m. The environmental radiation level in front of the camera was $1.3 \mu\text{Sv/h}$. The distribution of the hot spots existing at 20–30 m from the camera is visualized within an exposure of 30 min.

Fig. 4. (Left) The distribution of B_{RoI} (4000 samples) for $\overline{N}_B = 200$ with the best fitted Gaussian function. (Right) Plots of ΔB_{RoI} , defined as the RMS of B_{RoI} , with respect to $\overline{B}_{\text{RoI}}$. The red line is the best fitted modeling function. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

on. We take an empirical approach employing Monte Carlo simulations [12] based on Geant4 to account for situations close to real observations. In the simulation, we simply assume an isotropic background of 662 keV gamma-rays coming to the camera to calculate the sensitivity for a point like source that emits 662 keV gamma-ray photons in the background environment. In order to study the relation between ΔB_{Rol} and B_{Rol} , N_B events of isotropic backgrounds are generated with a Poisson distribution at a mean value of $\overline{N_B}$ events. And then, the back-projection image is produced to count the number of counts in the Rol. The left panel of Fig. 4 shows the distribution of B_{Rol} for 4000 samples with $\overline{N_B} = 200$. It indicates that the distribution can be modeled with a Gaussian with a mean value of $\overline{B_{\text{Rol}}}$. In the right panel of Fig. 4, ΔB_{Rol} defined as the RMS of B_{Rol} is shown as a function of $\overline{B_{\text{Rol}}}$ corresponding to $\overline{N_B} = 100, 200, 800$ and 2000. The relationship between them is well expressed as $\Delta B_{\text{Rol}} = p_b \times (\overline{B_{\text{Rol}}})^{0.5}$, where p_b is an arbitrary parameter determined by a fit. Given a measured event N_B , we could deduce ΔB_{Rol} by using this modeling function.

The uncertainty of the source signal S_{Rol} can be evaluated in a similar manner as ΔB_{Rol} by generating simulation samples for different values of $\overline{N_S}$. We confirmed that the distribution of S_{Rol} is also well expressed by the Gaussian, and ΔS_{Rol} can be also modeled by the function, $\Delta S_{\text{Rol}} = p_s \times (\overline{S_{\text{Rol}}})^{0.5}$. The effect of an offset component of the point spread function to the sensitivity calculation is negligible since the situation we consider here is background dominant.

In order to suppress misdetection of the fluctuation of background events as a signal for the large FoV of the Compton camera, the misdirection probability should be less than 0.1%. Since the distribution of $(B_{\text{Rol}} + S_{\text{Rol}})$ is considered to be approximately expressed by the Gaussian distribution, the misdirection probability of 0.1% corresponds to $z \approx 3$.

In the field, it is useful to associate the background and source count rates with the equivalent radiation dose rate in a $\mu\text{Sv/h}$ unit. As shown in Fig. 5, using real data taken in the 20 km zone in Fukushima, the background count rates at 662 keV in the camera were found to be linearly correlated with the environmental radiation dose rate measured by a calibrated survey meter around the camera. We assumed a linear function between them and obtained a conversion factor from the count rate to the radiation dose rate. On the other hand, the count rate of the point-like source can be converted into the radiation dose rate in the camera, using the camera's efficiency of 0.16 cps/MBq at 1 m (^{137}Cs , 662 keV) and the dose-rate constant of $1.0 \times 10^{-13} [\text{Sv m}^2 \text{ Bq}^{-1} \text{ h}^{-1}]$ of ^{137}Cs . For example, a 62 kBq source located at 1 m gives the count rate of 0.01 cps and the radiation dose rate of $0.006 \mu\text{Sv/h}$ in the camera.

The detection sensitivities for a point-like source in terms of the dose rate in the camera with a misdirection probability of 0.1% are shown for the standard and enhanced models of ASTROCAM as a function of the environmental radiation dose rate in Fig. 6, for exposure times of 30 min, 60 min and 90 min. For the enhanced model, a curve for an exposure of 2 min is also drawn. The sensitivity for the enhanced model is calculated by assuming 16 times higher efficiency than the standard model (see Section 2). Fig. 6 indicates that, for example, a point-like source that gives $0.006 \mu\text{Sv/h}$ of the dose rate in the camera is visible with an exposure of 60 min in an environmental radiation dose rate of $0.3 \mu\text{Sv/h}$. For the same detectable source level, the exposure time for the enhanced model can be shortened to 1/16 of the standard model. For the same exposure time, the enhanced model can detect about 4–5 times weaker sources than the standard model.

We carried out a measurement using the standard model of ASTROCAM within the 20 km zone in Fukushima in order to verify the above sensitivity obtained using the simulation. An Rol is selected in the part of the reconstructed image, where there is no strong concentration of radioactive materials. The radiation dose rate measured by a calibrated survey meter around the camera was about $0.32 \mu\text{Sv/h}$. In order to create a hot spot that increases

Fig. 5. The count rates of ASTROCAM for 662 keV gamma-rays with respect to the environmental radiation levels measured by a calibrated survey meter. All data were taken in the 20 km zone with the standard model.

Fig. 6. The sensitivity for ^{137}Cs point-like source detection, based on Monte Carlo simulation, on a misdirection probability of 0.1% estimated for (red) the standard model and (blue) the enhanced model. The simulation is performed under a simple assumption of isotropic background distribution. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

the radiation level by $0.01 \mu\text{Sv/h}$ at the position of the camera, we placed a point source of ^{137}Cs with an intensity of 2.7 MBq at 5.2 m from the camera surface. As predicted by the simulation (Fig. 6), the point source was detected with an exposure of around 30 min.

The distribution of radioisotopes in the real-world is very complicated and highly location-dependent. Here, we are limited to a simplified set of conditions in our simulation, which is still useful in designing this kind of visualization system that meets requirements for practical applications.

5. Conclusion

Based on the detector technologies advanced for the ASTRO-H mission, the first commercial Compton camera, ASTROCAM, was developed. The camera consists of a combination of Si and CdTe semiconductor devices which can achieve both good angular resolution and excellent energy resolution. In addition to portability, a key feature of ASTROCAM is scalability which enables a cost-effective performance tailored to requirements of any desired application. For example, the enhanced model incorporates 4 times more Si detector and 2.5 times more CdTe detectors than the standard model while providing 16 times better efficiencies. Through field tests performed in the 20 km Fukushima zone, we demonstrated that the camera is

capable of hot spot detection and evaluation of decontamination effectiveness.

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References

- [1] M. Gmar, et al., Nuclear Instruments and Methods in Physics Research Section A 652 (2011) 638.
- [2] F. Zhang, et al., IEEE Transaction on Nuclear Science NS-59 (1) (2012) 236.
- [3] O. Limousin, et al., Nuclear Instruments and Methods in Physics Research Section A 647 (2011) 46.
- [4] S. Watanabe, et al., IEEE Transactions on Nuclear Science NS-56 (3) (2009) 777.
- [5] T. Takahashi, et al., New Astronomy Reviews 48 (2004) 309.
- [6] S. Watanabe, et al., IEEE Transactions on Nuclear Science NS-52 (5) (2005) 2045.
- [7] S. Watanabe, et al., Nuclear Instruments and Methods in Physics Research Section A 765 (2014) 192.
- [8] T. Takahashi, et al., Proceedings of the SPIE 9144 (2014) 914425.
- [9] T. Takahashi, et al., in: IEEE NSS/MIC 2012 Conference Record, 2012, pp. 4199–4204.
- [10] S. Takeda, et al., Physics Procedia 37 (2012) 859.
- [11] Mitsubishi Heavy Industries Technical Review, (<http://www.mhi-global.com/company/technology/review/pdf/e511/e511068.pdf>).
- [12] H. Odaka, et al., Nuclear Instruments and Methods in Physics Research Section A 624 (2010) 303.