G
amma rays, which are classified as the most energetic electromagnetic waves (photons), are generated and emitted due to the decay of radioisotopes and/or non-thermal phenomena of high-energy particles. Gamma-ray imaging at energies of approximately 1 MeV has progressed considerably recently owing to Compton camera technology,1,2) which has been used for the visualization of radioactive cesium release from the Fukushima Daiichi nuclear power plant accident,3) in nuclear medicine,11) in gamma-ray telescopes in astrophysics,14–16) and in gamma-ray telescopes in astrophysics. A Compton camera typically includes scatterers in the first layer and absorbers in the second layer. Compton kinematics can be used to calculate the scattering angle of incoming gamma rays, $\theta_{\text{scat}}$, from the energy deposited in the scatterer ($E_s$) and absorber ($E_a$) at each detected event. The gamma-ray source direction can then be reconstructed by back projection as a smeared ring shape with a radius of $\theta_{\text{scat}}$ for each event, depending on the angular resolution of the detector [Fig. 1(a)].

Recently, a low-cost, high-sensitivity, omnidirectional gamma-ray imaging Compton camera was proposed and developed based on the two-fold coincidence within six CsI (Tl) scintillator cubes of 3.5 cm (i.e., scattering length of sub-MeV gamma rays) that act as either scatterers or absorbers. The purpose of this technique is to easily achieve high detection efficiency for sub-MeV gamma rays with an angular resolution, $\sigma$, of $\sim 10^\circ$ or less. This resolution is adequate for an environmental monitoring intended to visualize low-level gamma radiation sources with a surface and/or an air dose rate of only a few $\mu$Sv h$^{-1}$ or less for use in nuclear medicine, in accelerator facilities, and in the field at Fukushima. The high efficiency is accomplished by applying an image sharpening technique [Fig. 1(b)] based on a filtered back-projection algorithm,20–22) which applies a convolution filter that is typically used in image reconstruction for computed tomography to the Compton ring reconstruction.

One major disadvantage of the Compton camera technique is that the reconstructed images have artificial uneven structures (called “ghosts”) except for when using gamma-ray sources [Fig. 1(c)]. Thus, a reconstructed gamma-ray image is a shift variant owing to “ghosts”. This effect depends on a small number of back projection ring patterns in the image reconstruction caused by using a small number of counters. To counteract this, the virtual number of scintillators needs to be increased, i.e., the accumulation of various rings with different hit patterns can naturally reduce the ghosts. If the detector is rotated during the measurement, the number of crystals can be virtually increased. Thus, it is expected that “ghosts” will be evenly distributed in the entire field of view and can be further removed by applying an image sharpening technique. In this study, we focused on a rotation of the Compton camera during the measurement as a method to reduce the “ghosts” [Fig. 1(c)]. We used the omnidirectional Compton camera technique that we previously developed and described.17)

Figure 1(d) shows a schematic view of the CsI(Tl) scintillator arrangement. Six scintillators were placed at the vertexes of an octahedron with a side length of 10 cm to obtain uniform acceptance and angular resolution in all directions, even with a small number of elements. Each CsI (Tl) scintillator (cube, $3.5 \times 3.5 \times 3.5$ cm in size) was read out with a super-bialkali photo-multiplier tube (PMT) assembly (Hamamatsu Photonics H11432-100). The signals were fed into a 16-channel flash ADC board (operated at 2.5 MHz) using SiTCP technology. When two hits are coincident above some threshold, a gate signal is generated, and the waveform data stored in the FPGA registers are transferred to a PC via an Ethernet connection. The timing resolution ($\sigma$) between two hit counters was 60 ns when 511 keV gamma rays were measured from the $^{22}$Na-sealed source. An online program, which was created using Visual
C++ with a ROOT library, was operated on a Windows PC. The details of the fundamental techniques of the system and the data selection for image reconstruction are described in Kagaya et al. (2015) and Watanabe et al. (2018).

The Compton camera was fixed to a motorized rotation stage (Sigma Koki, OSMS-60YAW), as shown in Fig. 1(e). The detector rotation stage is controlled by an online computer via USB using an independent program that was
also created using Visual C++. The online program that controls the Compton camera can save the rotation angle of a detector for each event by referring to the shared memory when saving the waveform data for each two-fold coincidence event. A gamma-ray image was reconstructed on a spherical surface with accumulating rings with a radius of $\theta_{\text{scat}}$, which is the scattering angle calculated from Compton kinematics for each two-fold coincidence event. Figure 1(b) shows the cross section of the smeared ring with a Gaussian profile (solid line) and with a multiple-Gaussian profile used as the image sharpening technique (dashed line). In this study, the standard deviation of the Gaussian profile shown in Fig. 1(b) was assumed to be 6° based on consideration of the geometrical effect due to the crystal size (3.5 cm) and the interval of the crystals (10 cm).

Performance tests were carried out using a 1.6 MBq $^{22}$Na-sealed source placed 1 m ahead of the detector in the direction of azimuth $= 0°$ and elevation $= 0°$. First, the measurement was performed for 30 min without rotating the Compton camera. For this measurement, the average trigger rate and dead time were 64 Hz and 1.2%, respectively. Here, the dead time was attributed to the data transfer speed from the SiTCP to the online computer. Figure 2(a) shows the reconstructed image of 511 keV gamma rays from $^{22}$Na without detector rotation in the Aitoff projection, where the back projection was performed with a smeared ring with a single Gaussian profile, as in Fig. 2(a). Some ghosts shown in Figs. 2(a) and 2(b) disappeared, and only the gamma-ray source at the center of the field of view was successfully reconstructed as a single peak. This was due to the increase in the back-projection ring patterns owing to detector rotation. However, it was difficult to obtain a shift-invariant reconstruction image because the peak was broadened, and the background region was larger than 0.

The measurement was then performed for 30 min with rotation of the Compton camera from $0°$ to $360°$ every 5 s at angular intervals of $1°$, assuming temporal continuous detector rotation. The result is shown in Fig. 2(c), where the back projection was performed with a smeared ring with a single Gaussian profile, as in Fig. 2(a). Some ghosts shown in Figs. 2(a) and 2(b) disappeared, and only the gamma-ray source at the center of the field of view was successfully reconstructed as a single peak. This was due to the increase in the back-projection ring patterns owing to detector rotation. However, it was difficult to obtain a shift-invariant reconstruction image because the peak was broadened, and the background region was larger than 0.

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using the image sharpening technique are plotted by black and gray symbols for the measurement with and without detector rotation, respectively. More uniform sensitivity was achieved in all directions, except it was slightly reduced in the polar directions due to shielding of the PMT and electronics. Here, it would be interesting to investigate the contrast to noise ratio (CNR) as an index for the quantification of ghost reduction. Now, assuming that the peak value in the reconstructed image is $P$ and that the average and standard deviations of the pixel values in regions other than at a radius of 30° centered on the radiation source position are $M_{BG}$ and $\sigma_{BG}$, respectively, the CNR can be calculated by $\text{CNR} = (P - M_{BG})/\sigma_{BG}$. The results are shown in Fig. 4(b), where black and gray symbols represent the results for the same conditions as in Fig. 4(a). The CNR improved by approximately five times in all directions except for the polar directions when the rotation function was added.

Next, to investigate how multiple gamma-ray sources are reconstructed, performance tests were also carried out using two 0.8 MBq $^{22}\text{Na}$-sealed sources in different directions at a distance of 1 m from the detector. The measurements were done for 60 min with rotation of the Compton camera from 0° to 360° every 10 s at angular intervals of 1°, assuming continuous detector rotation at a constant speed as in the case of the one radiation source mentioned above. The results are shown in Figs. 5(a)–5(h), where the image sharpening technique was also applied to the back projection as in the cases of Figs. 2(d) and 3. When the distances between the two sources were 60° [Figs. 5(a), 5(e)] and 40° [Figs. 5(b), 5(f)], two sources were successfully reconstructed as a superposition of independent point sources. This implies that a shift-invariant gamma-ray imaging is well achievable. Additionally, when the two sources were 30° apart [Figs. 5(c), 5(g)], their partial regions were reconstructed...
Fig. 4. Peak intensity (a) and contrast to noise ratio (CNR) (b) as a function of incident elevation angles of the gamma rays. The values were obtained from the images reconstructed using the image sharpening technique with detector rotation (black circles) and without detector rotation (gray circles, triangles, and diamonds). The measurement conditions are the same as those of Figs. 2 and 3.

Fig. 5. (Color online) Same as Fig. 3 but with two $^{22}$Na-sealed sources for various directions (radioactivity: 0.8 MBq each; measurement time: 60 min). (a) (azimuth, elevation) = (0°, 30°), (0°, −30°). (b) (0°, 20°), (0°, −20°). (c) (0°, 15°), (0°, −15°). (d) (0°, 10°), (0°, −10°). (e) (30°, 0°), (−30°, 0°). (f) (20°, 0°), (−20°, 0°). (g) (15°, 0°), (−15°, 0°). (h) (10°, 0°), (−10°, 0°). (i) (5°, 0°), (−5°, 0°) © 2020 The Japan Society of Applied Physics.
by overlapping, but the peak positions were separable. Furthermore, when the distance between the two sources approached 20°, it became difficult to separate the two sources; instead, they were reconstructed as a distribution with one peak spread in the elevation [Fig. 5(d)] and azimuthal [Fig. 5(h)] directions, respectively. Thus, the angular resolution of this system was slightly less than 30° in FWHM. In fact, the angular resolution (σ) obtained from 2D Gaussian fitting of the measurement result with one source [Fig. 2(d)] was 11.7° in the azimuth and 11.0° in the elevation direction, which is in good agreement with the above estimation.

We demonstrated that by rotating the Compton camera, shift-invariant gamma-ray images with reduced artificial uneven structures, including some “ghosts” in the entire field of view, can be easily acquired in conjunction with an image sharpening technique. The decrease in sensitivity in the polar direction shown in Fig. 4(a) will be considerably improved by replacing the PMT with a metal package PMT or multi-pixel photon counter as the photodetector and by reducing the size of the lower electric box so that it can be mounted on a tripod. The high-sensitivity omnidirectional gamma-ray Compton camera with the rotation function introduced in this study will be useful to visualize low-level gamma radiation sources with surface and/or air dose rates of a few μSv h⁻¹ or less in nuclear medicine or acceleration facilities and in the field at Fukushima. In particular, this method is expected to be useful for radiation decontamination work in a large area in eastern Japan; this work aims to reduce the air dose rate down to 0.23 μSv h⁻¹ [26] as set by the Ministry of the Environment, Japan.

Other Compton cameras often employ the iterative image reconstruction using the maximum likelihood expectation maximization (MLEM) algorithm based on a statistical approach. [27] The advantage of MLEM is that it is relatively easy to obtain images that are free of artificial uneven structures attributed to ghosts, even when the acquired data are missing. However, the disadvantage of this method is that the shape of the reconstructed image changes with increasing number of iterations; thus, it difficult to obtain an accurate image when the gamma-ray source has complex structures and continues to become increasingly difficult depending on the amount of missing data. In this study, we have shown that it is possible to obtain shift-invariant images using a filtered back-projection algorithm based on an analytical approach if the missing data are compensated for by rotating the detector. Other Compton cameras can also improve the accuracy of the reconstructed images by compensating for the loss of acquired data by rotation. Moreover, the accuracy of the reconstructed images by MLEM is expected to improve; we will discuss this point in our next study.

Recently, high-light-yield and high-density scintillators with ultrafast decay times on the order of ns have been discovered. [28–32] Furthermore, pixelated TIBr detectors with a high atomic number, high density, and wide bandgap are being developed as a next-generation semiconductor detector material to replace CdZnTe. [33] New gamma-ray detector materials with these excellent features will also facilitate further advancement of Compton camera technology when combined with our proposed technique.

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