Visualization of Radioactive Substances with a Si/CdTe Compton Camera

Tadayuki Takahashi, Shin'ichiro Takeda Shin Watanabe, and Hiroyasu Tajima

***Abstract*—Dust containing radioactive materials dispersed following the Fukushima nuclear power plant accident in March 2011. Gamma-rays are emitted in the process when unstable nuclei in the materials decay. Based on the technology of Si/CdTe Compton Camera, we have manufactured a quick prototype model for the use in the field. The camera, now called a "Ultra-Wide-Angle Compton Camera" was successfully applied to visualize the distribution of radio-active substances in the Fukushima area.**

***Index Terms*—Gamma-ray imaging, Semiconductor Compton camera, Silicon double-sided strip detector, CdTe double-sided strip detector , Hotspot monitoring**

I. INTRODUCTION

The Great East Japan Earthquake of March 11, 2011 caused significant damage to Japan. The radioactive materials released from the Fukushima nuclear power plant have had a huge impact on the Japanese people. The removal of these radioactive materials is of very high priority for Japan.

In early April 2011, we received an e-mail from Tokyo Electric Power Company containing the request of possible contribution to provide a detector which can broadly and at once identify areas where strong or weak radiation exists on the ground. Because of the accident at the nuclear power plant, dust containing radioactive materials such as ^{134}Cs and ^{137}Cs dispersed over a broad area [1]. Gamma rays are emitted in the process when unstable nuclei in the materials decay to become stable. Quick removal of dust with radioactive materials (decontamination) is essential. To decontaminate, we need to know where the radioactive materials are. A gamma-ray imaging system which is capable of directly locating radiation sources, which enables monitoring of hotspots in otherwise inaccessible radiation sites and with considerable radiation exposure, and is namely more effective than manual surveys, if such a detector exists.

Over the past 15 years, we have been working on the next generation gamma-ray detector, "Si/CdTe semiconductor Compton camera," with the aim of high-sensitivity observations for gamma-ray astronomy. The Soft Gammar-ray Detector (SGD) onboard the 6th X-ray Astronomy satellite, ASTRO-H, is now being built to cover the soft gamma-ray region up to 600 keV [2], [3]. In order to lower the background dramatically and thus to improve the sensitivity as compared to the HXD of Suzaku, the SGD design combines a stack of Si and CdTe pixel detectors to form a Compton camera (Si/CdTe Compton Camera) [4], [5]. SGD measures soft gamma-rays via reconstruction of the Compton scattering in the Compton camera and covers an energy range of $40 - 600\,\text{keV}$. By combining another new concept, "narrow FOV Compton telescope", SGD will have sensitivity at $300\,\text{keV}$ of more than 10 times better than that of the Suzaku Hard X-ray Detector [6], [7], [8].

Upon receiving a consultation from Tokyo Electric Power Company, we swiftly constructed a prototype of the ultra-wide-angle Compton camera for imaging tests in Fukushima prefecture based on the SGD concept combined with elemental technology for another device onboard ASTRO-H, the Hard X-ray Imager (HXI) [9].

II. REQUIREMENTS OF GAMMA-RAY CAMERA

Prior to the measurement by our Compton camera, we visited the site carrying dosimeters and portable gamma-ray detectors. Then we found that there were places with a strong ambient dose as publicly reported and, at 5 cm above those areas, there were hot spots with a dose approximately 10 times the ambient dose. Our on-site observations also revealed that, in addition to the constant-energy gamma-rays directly emitted from ^{134}Cs and ^{137}Cs, the sites were dominated by low-energy gamma rays (gamma rays that had been scattered by the ground, buildings, etc., and changed to lower-energy ones).

According to the on-site experiences, we realized that the followings are requirements for gamma-cameras to be used for visualization of gamma-ray emitting radioactive substances;

1) Spectral Resolution:
   In order to take a gamma-ray image by using gamma-rays directly emitted from radioactive material such as ^{134}Cs and ^{137}Cs, it is important to avoid possible contamination from scattered components, the camera should have a spectrum resolution capable of distinguishing individual lines. Thus energy resolution better than 3 % ($\Delta E/E$) is necessary.
2) Field of View (FOV):
   Urgent tasks at the region close to or inside the evacuation zone is to decontaminate the radioactive substances. In order for this, efficient survey of hot spots that could contribute the increase of the environmental radiation level, is useful for the decontamination operation. In order to make a map of hot spots in short time, wider field of view is better.

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Manuscript received Nov. 16, 2012.

3) Angular Resolution:
   In order to identify radioactive substances that emit gamma-ray lines, it would be useful to have an angular resolution of <5 degrees that corresponds to about 1 m's size at 10 m away from the camera.
4) Efficiency:
   The sensitivity should be sufficient to pick up hot spots in the area where the radiation level is 0.5–a few $\mu\mathrm{Sv/h}$.
5) Portability: The detector should be easily handled and could be carried by hand, because people would like to use detectors in the various environment, in forest or in mountain areas.

Gamma-rays emitted directly from ^{137}Ce and ^{134}Ce have energies ranging from 600 to 800 keV. A conventional gamma camera uses a simple pinhole for imaging observations in this energy range[1] . By limiting the direction of incident gamma-rays beforehand, the camera captures images of the radioisotopes. The maximal field of view is limited to 40 to 60 degrees due to the aperture angle of the pinhole. This imaging method is effective when the surrounding background radiation is low, and when the pinhole mask is thick enough to block gamma-rays that fall outside the pinhole. However, when gamma-ray energies exceed several hundred keV, the shielding turns transparent, and, even if one can visualize radioisotopes, it could be difficult to obtain a clear contrast. In order to improve imaging performance, the camera has to be made heavier for sufficient shielding.

In order to meet the requirements listed above, we decided to construct a new detector which utilizes the Compton scattering effect.

III. Si/CdTe Compton Camera

Compton scattering typically plays a dominant role in the energy band from a few keV s to 10 MeV. It entails elastic collision between an incident photon and an electron in the scattering medium. In conventional Compton cameras, the incident gamma-ray is identified by successive interactions in two detector layers. The ideal case would be that a gamma-ray photon emitted from the source is Compton-scattered in the first layer and then photo-absorbed in the second layer. Once the locations and energy deposites of both interactions are measured, Compton kinematics allows us to calculate the energy and direction (as a cone in the sky) of the incident gamma-ray by using the following Compton equations:

$$E_{\rm in} = E_1 + E_2, \tag{1}$$

$$\cos\theta = 1 - m_{\rm e}c^2\left(\frac{1}{E_2} - \frac{1}{E_1+E_2}\right), \tag{2}$$

where E_1 denotes the energy of the recoil electron, E_2 the energy of the scattered gamma-ray photon, and θ the scattering angle. For every event, a cone can be reconstructed as an opening angle of 2 θ. The source is somewhere on the cone surface. Compton cameras offer the advantage of needing only small number of photons to recover the position of sources without mechanical collimators in front of the camera. If the direction of a recoil electron can be measured, the Compton cone is reduced to a segment of the cone, the length of which depends on recoil electron measurement accuracy.

[1]Coded masks that extend the idea of a pin hole camera are often used for hard X-ray observations in space. But the situation listed here is almost same

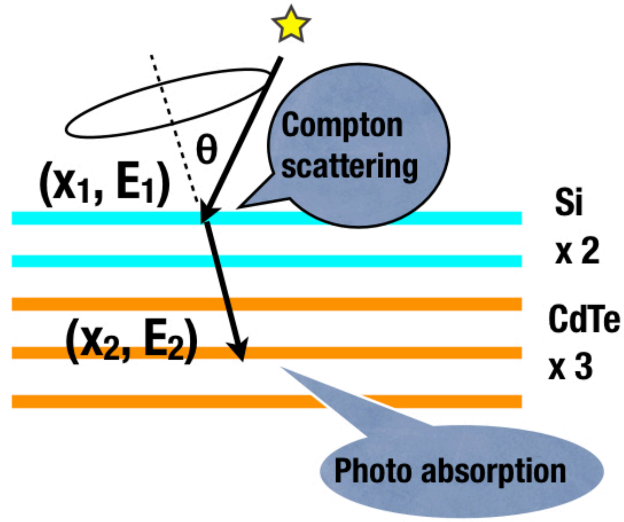

Fig. 1. Principle of a Si/CdTe Compton Camera Gamma rays are scattered through the Si semiconductor detector and then absorbed by the CdTe semiconductor detector. Based on the values measured by semiconductor detectors, we can retrace the initial direction of incoming gamma rays. .

Semiconductor imaging detectors are desired for Compton imaging. As expressed in Equations (1) and (2) above, the energy and position resolution provided with semiconductors should improve the angular resolution and hence the sensitivity of Compton cameras. From this perspective, several semiconductor-based Compton cameras have been proposed. However, most of these cameras have been developed based on combining a semiconductor such as silicon with scintillators. Taking advantage of significant progress, we have performed in CdTe technology [10], [11], [14], we have been developing a new generation of Compton telescope [4], [15], [16], the semiconductor Compton telescope by combining Si and CdTe, as the Si/CdTe semiconductor Compton camera. Since CdTe has large atomic numbers (48, 52) and high density (5.8 g/cm^3), it offers the potential to replace scintillators and to form a full-semiconductor Compton camera.

Figure 1 shows the conceptual design of the Si/CdTe semiconductor Compton camera. In the Si/CdTe Compton camera, events involving the incident gamma-ray being scattered in the Si detector and fully absorbed in the CdTe detectors are used for Compton imaging. The direction of the gamma-ray is calculated by solving the Compton kinematics with information concerning deposit energies and interaction positions recorded in the detectors. In principle, each layer could act not only as a scattering part but also as an absorber part.

A very compact, high-angular resolution (fineness of image) camera could be realized if we were able to fabricate successfully semiconductor imaging elements made of Si and CdTe, which have excellent performance in position resolution, high-energy resolution, and high-temporal resolution. The field of view of the camera is determined from the gap between each layers, because events coming from large angle with resect to the detector plane, if we can cover the large angle scattering

The effect of the doppler broadening, which degrades the angular resolution of the imaging system, is smaller in the Si devices than other semiconductor devices [23], allowing the difference between the measured and actual scattering angles to be constrained. The effect of the Doppler broadening becomes smaller as the incident energy becomes higher, because the binding energy and momentum of electrons in materials become relatively small for gamma-ray photons with higher energies.

In our previous work, we developed a prototype Si/CdTe Compton camera, and verified its performance. The camera consists of a single layer of double-sided silicon strip detector (DSSD) and four layers of CdTe pice detectors. The stacked CdTe module is placed 14.5 mm under the DSSD module. Each CdTe layer contains four CdTe detectors in a 2×2 arrangement. The Compton reconstruction was successfully performed and the gamma-ray images of point sources were obtained from 662 keV down to 59.5 keV. The resolution of catering angle (Angular Resolution Measure or ARM) was 3.5 degree (FWHM) and 2.5 degree (FWHM) at 356 keV and 511 keV, respectively. The performance and the responses of the camera has been studied quite intensively and reported in other literatures [16], [17], [18], [19].

IV. The prototype camera for hot spot monitoring

Although the principle of a Compton camera is well established for some time, no working model has been manufactured that is both relatively easy to use and also able to shoot images on site with sufficient efficiency and resolution. The ASTRO-H program was in the detailed design phase at that time and the design of its Compton camera was complete. Furthermore, we had begun partial fabrication of the prototype model. It was technically difficult to use the model in its existing condition in Fukushima, however, so we had to build a new model dedicated to observations there. We decided to secure the research budget and manufacture the dedicated model. This was considered to be a project that could drive our future astronomy research and, eventually, also drive the development of space technology that would contribute to the national disaster. We promptly established a team for prototype-model manufacture and on-site imaging. The proto-type model assembly started in October 2011 and was completed in January 2012.

According to the measurements we performed with a dosimeter, we decided to fabricate the prototype which is suitable for gamma-ray monitoring in the area where the environment background level is 2−3 μSv/h. The ultra-wide-angle Compton camera, we brought to Fukushima, is structured in a way that gamma-rays scattered by Compton scattering are unlikely to escape from the system; therefore, it can achieve an ultra wide angle view. We fabricated a hybrid camera by utilizing the ASTRO-H HXI structure (i.e., a 5-layer sensor), but a change was made to the mix of layers: from 4 layers of Si and 1 of CdTe used in HXI to 2 and 3 layers, respectively. For the analog read-out LSI (Large Scale Integrated circuit), we employed the one developed for SGD with large dynamic range. We prepared two cameras and installed them into a portable refrigerator.

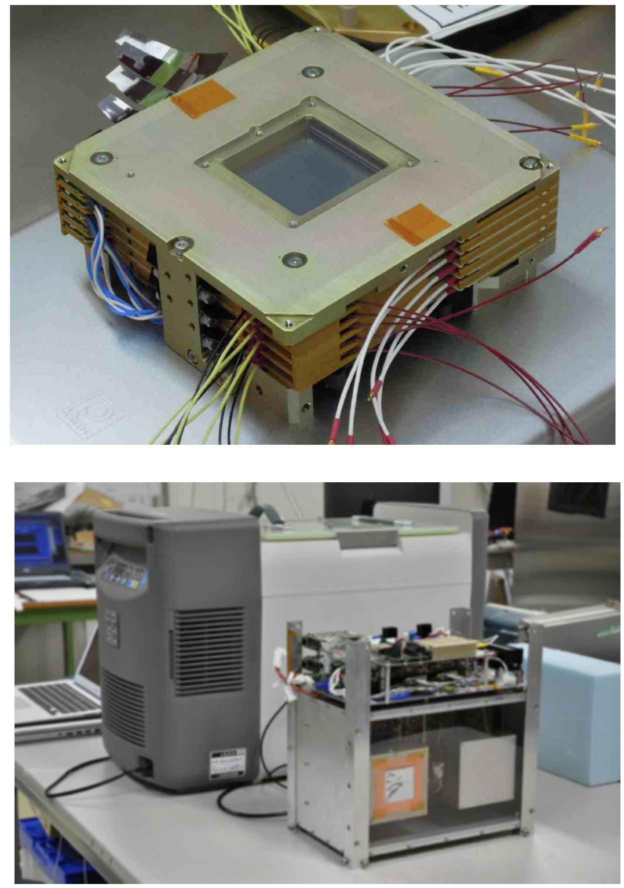

Fig. 2. Photo of the prototype Compton camera. (top) five-layers of Si and CdTe imagers (bottom) two camera modules and readout electronics with a portable refrigerator.

Figure IV shows a photograph of the gamma-ray camera, which was brought to Fukuhshima. The top detector module consists of a 0.5 mm thick Si-Double Sided Detector (DSD). The Si-DSD used here has strip electrodes with pitch of 250 μm on the P- and N-sides, respectively. The 0.75 mm thick CdTe-DSDs are stacked under the Si-DSD module. The CdTe-DSD has been developed based on the technology of high resolution CdTe diode detector [10], [12], [13]. On the CdTe-DSD, electrodes with a strip pitch of 250 μm are placed orthogonally on both sides. Details of the CdTe-DSD are reported in Watanabe et al. [14] and Ishikawa et al. [20].

The direction of the incident gamma-ray is back-projected as a cone by using the measured scattering angle θ and scattering direction $\vec{s}$. The coordinate for the back-projection is selected by taking account of the distance between the camera and targets. Cases for the near-field, such as medical imaging, are reported in some papers [21], [22]. In astrophysical observations, where the source is located in extremely far-field, a 2-dimensional celestial sphere is generally used as the back-projection coordinate. If the angle of the Compton camera as viewed from the targets is much smaller than the angular resolution of the imaging system, the celestial

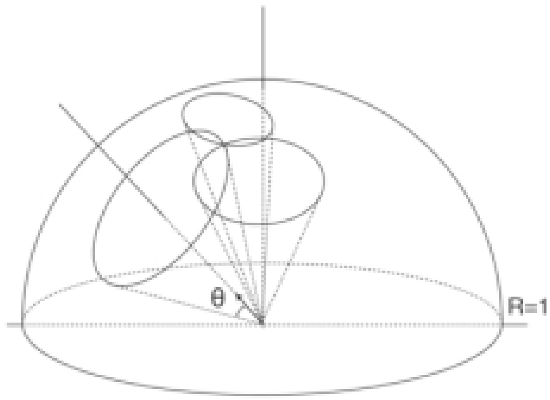

Fig. 3. Concept of image reconstruction by the back projection method

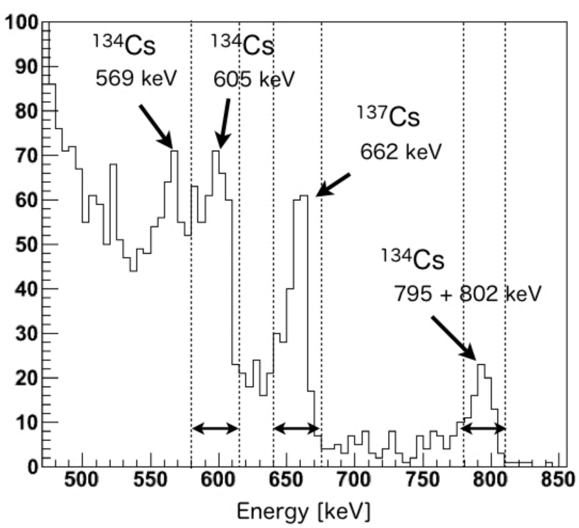

Fig. 4. Gamma-ray spectrum taken together with an image during the imaging test in Iidate Village, Fukushima.

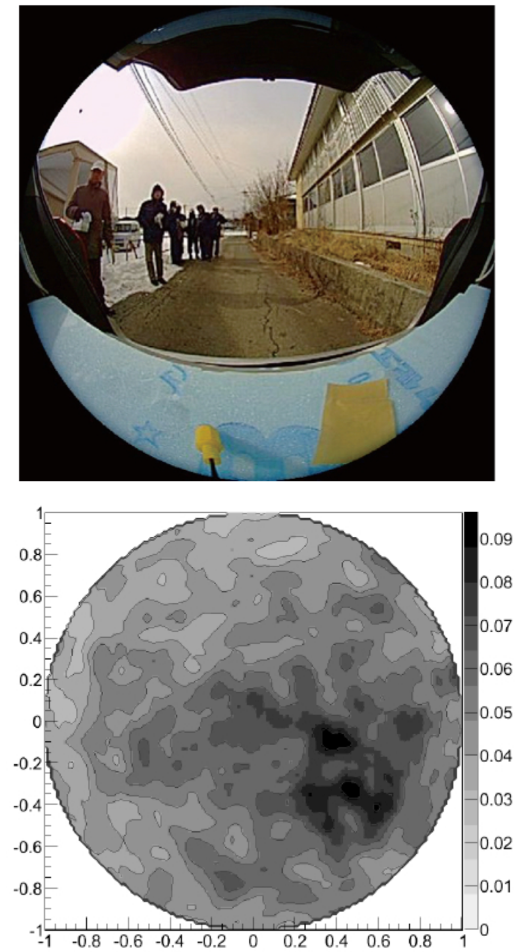

Fig. 5. Imaging test in Iidate Village, Fukushima. (top) Optical image taken with a digital camera with a fish-eye lens. (bottom) Contour plot generated from the back projection image by Compton reconstruction from the data obtained at the site.

sphere is regarded as an appropriate coordinate, even for other applications. For hotspot monitoring, the sources typically exist within the range of a few meters to several tens of meters. When the source is located at 5 m, the camera angle as viewed from the source becomes 0.37 degrees in our system, which is small enough when compared with the typical angular resolution of a few degrees, hence the celestial sphere is used for the back-projection [18]. The probability distribution of the estimated position by a single event becomes a circle, as in Fig. 3. The location of the sources is determined by accumulating many cones.

The camera has a wide field of view, about 180 deg., and was thus named the Ultra-Wide-Angle Compton Camera. The camera has an angular resolution of several degrees in the energy range of 500 to 800 keV. This means that we can localize hot spots to several tens cm size at a distance of 10m.

V. Measurement

After we carried out initial performance tests in our laboratory, we performed an imaging experiment at Iidate Village in Fukushima in cooperation with the Japan Atomic Energy Agency (JAEA) and Tokyo Electric Power Company in Feb. 2012 [24].

Figure 4 shows the spectrum obtained with the Ultra-wide-angle Compton Camera at the site. Four lines from ^{134}Cs and ^{137}Cs are seen in the spectrum. One crucial point of the Si/CdTe Compton camera is that the sum of the two energies measured by the first and second reaction in the detector is equal to the gamma-ray energy directly emitted from the radioactive materials (e.g., 662 keV released from ^{137}Cs). Such agreement guarantees that the gamma rays come directly from the materials, without being scattered on the ground, buildings, etc.

Since the Ultra-wide angle Comptin Camera has a FOV of 180 degrees, it is convenient to superimpose the image on to the optical image taken with a camera with a fisheye lens (Figure 5 (top)). Figure 5 (bottom) shows the simple image of back projected cones calculated from events taken by the Compton camera. In order to obtain the image, we extracted events obtained from energy regions that contain these lines,

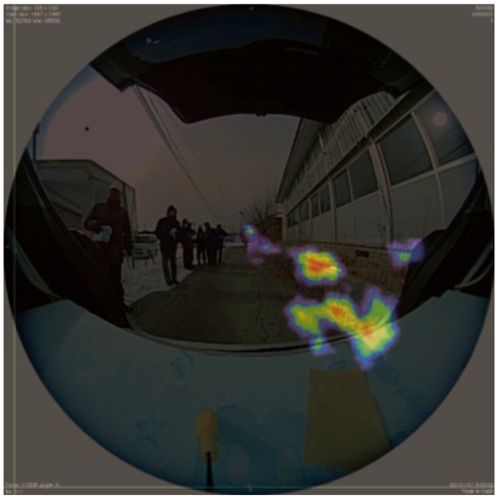

Fig. 6. The intensity (flux) distribution of gamma rays with energies of 605, 662, 796, and 802 keV directly emitted from cesium-134 and 137. The color image is extracted by requiring above three sigma excess from our statistical analysis. Red is high intensity while blue is low, superimposed on an image taken with a digital camera with a fish-eye lens. The exposure time is 60 min.

with energies of 605, 662, 796, and 802 keV. Smoothing algorithm is applied to draw contours.

We can clearly see the high intensity region in the image of the back projection. In order to extract peaks from the image, we have developed a peak-finding algorithm based on our experiences of source finding in the astronomical application. We have also studied statistical significances of the excess by studying the offset components appeared in the sky region of the back projection image. The resultant image that corresponds to the concentration of radio active substances is shown in Fig. 6. The independent measurements of the radiation level at 5cm cm away from the surface of the ground was carried out by using the detector developed by JAEA. Both results are consistent with each other [24].

VI. Conclusion

Based on the technology of Si/CdTe Compton Camera, we have manufactures a prototype model for the use in the site, in order to verify whether this type of camera is useful to decontaminate the radio active material. With this prototype, named Ultra-Wide-Angle Compton Camera, we have succeeded to visualize the distribution of radio-active substances in areas where the background radiation level ranges from 1 μSv/h to $\sim$30 μSv/h. The camera has an angular resolution of a couple of degrees in the energy range of 500 to 800 keV. This means that we can localize hot spots to several tens cm size at a distance of 10 m.

The challenge with future decontamination work is to improve the sensitivity of the camera several times over, up to 10-fold, in order to enable fast imaging in a few minutes, and so facilitate the operatorfs work at on-site decontamination. The SGD for ASTRO-H has a multiple-layer structure (32-layer Si detector and 8-layer CdTe detector) to detect faint gamma-ray signals coming from celestial bodies. If we can apply that structure to the gamma-ray camera used in Fukushima, the sensitivity should be improved by about 30 times. We expect that the 20 to 30 minutes required for "gamma-ray imaging" with the current prototype could be significantly shortened. To introduce a new model to visualize the distribution of radioactive materials in Fukushima, a plan to create a new camera based on the design of ASTRO-H SGD is underway with the support of the Japan Science and Technology Agency (JST), jointly with Mitsubishi Heavy Industries.

Space science observations require the most advanced technology. By realizing our own cutting-edge space observation technology, we were able to contribute to current and future radioactive decontamination, and widely expand the role of ASTRO-H from space to the earth.

Acknowledgment

The keys to realization of the prototype Ultra-Wide Angle Compton Camera were detector technology employing CdTe semiconductors with excellent energy resolution and extremely high-density packaging technology. These were jointly developed with Acrorad Co. Ltd. and Nagoya Guidance Systems Works of Mitsubishi Heavy Industries, Ltd. over 15 years. The HXI and SGD for ASTRO-H are under incessant development toward launch in 2014 by the same team that developed hard X-ray/gamma-ray observation instruments for Suzaku. The team consists of JAXAfs ISAS, University of Tokyo, Nagoya University, Hiroshima University, Waseda University, et al.

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