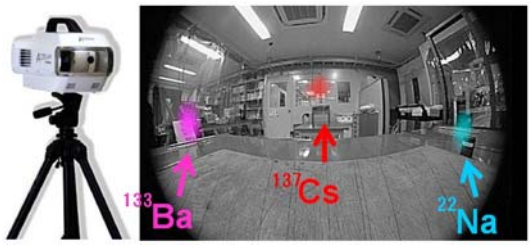
"ASTROCAM 7000HS" Radioactive Substance Visualization Camera



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Mitsubishi Heavy Industries, Ltd. (MHI) released the ASTROCAM 7000HS, a radioactive substance visualization camera, in March 2013, following the accident at the Fukushima Daiichi Nuclear Power Plant caused by the Great East Japan Earthquake. The ASTROCAM 7000HS incorporates the technologies for the gamma-ray detector used for the ASTRO-H satellite, which we have been developing under entrustment from and together with scientists at the Institute of Space and Astronautical Science (ISAS) at the Japan Aerospace Exploration Agency (JAXA), and the design was modified for use on land to commercialize the product. We performed on-site tests in June 2013 in the area where living is restricted in Fukushima Prefecture and succeeded in the visualization of hot spots. The outline of the ASTROCAM 7000HS, the measurement principle and the test results are reported below.

1. Introduction

The contamination of a wide range of areas with radioactive substances, which is attributable to the accident at the Nuclear Power Plant caused by the Great East Japan Earthquake, is a serious problem today. The removal of radioactive substances is essential, but the substances that need to be removed are not visible to the naked eye, which is one of the issues preventing the easy removal of such substances. Cesium 134 and cesium 137 (^{134}Cs, ^{137}Cs), which are particularly problematic at present, release gamma rays featuring a high amount of energy ranging from approximately 600 kilo electron volt (keV) to 800 keV. Conventionally, the air dose rate was normally measured by survey meters to detect the existence of hot spots where radioactive substances are concentrated. However, there are some issues in using survey meters to measure every corner of the wide range of areas that may be contaminated. For example, it is difficult to measure high areas that cannot be reached, the individuals that perform measurement could be exposed to radiation for a long time and some of the hot spots could be overlooked.

MHI has been manufacturing X-ray and gamma-ray detectors onboard ASTRO-H satellite[1,2], which is the next X-ray astronomical satellite by Institute of Space (ISAS) and Astronautical Science in JAXA. The detector, called "Si/CdTe Compton Camera", is based on silicon (Si) semiconductors and cadmium telluride (CdTe) semiconductors and has functions to image gamma rays. The technology of the camera has been developed in ISAS/JAXA for more than 10 years aiming at future astronomical satellites, including ASTRO-H[3]. By incorporating the technologies for space development in the device for use on land, we commercialized the ASTROCAM 7000HS, the first camera that can visualize radioactive substances including ^{137}Cs, in March 2013[4,5,6]. Issues regarding gamma ray measurement and the key technologies to solve such issues, as well as the results of on-site tests performed in Fukushima Prefecture, are introduced in this report.

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2. Interaction between gamma rays and substances

Rays are classified into infrared rays, visible rays, ultraviolet rays, X-rays, etc., depending on the wavelength and the formation principle (**Figure 1**). Gamma rays are one type of rays (electromagnetic waves). The visualization of gamma rays released from radioactive substances, which are the targets of removal, was difficult for the following two reasons. (1) It is difficult to concentrate gamma rays using a lens, etc., and (2) Gamma rays are characterized by a high amount energy ranging from several hundred keV to several thousand keV, which is approximately 100,000 times the energy of visible rays, and penetrate CCD elements used in digital cameras.

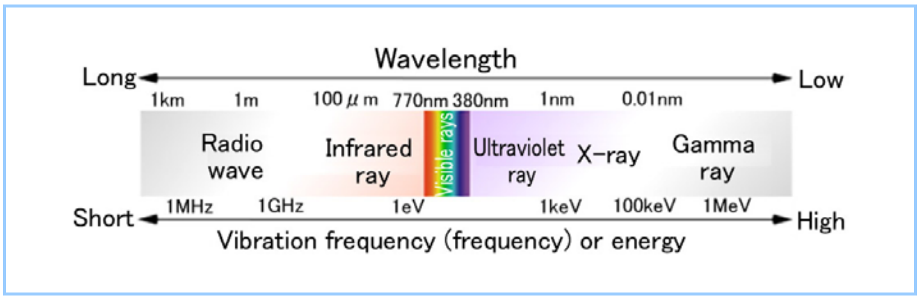

Figure 1 Classification of rays

The following three types of physical phenomena are observed as interactions between gamma rays and substances. The gamma ray visualization camera is works using these principles. Examples of the application of such principles to the camera are introduced in section 3.

(1) Photoelectric absorption

Photoelectric absorption is the reaction where gamma rays are absorbed completely in the detecting portion and disappear in a single cycle of interaction. Gamma rays have a high amount of energy and easily penetrate the detector, and the rate of reaction to the interaction is low.

(2) Compton scattering

Incident gamma rays scatter, without being absorbed completely in the detecting portion, and create a scattering gamma ray and a recoil electron, like billiard balls, as shown in **Figure 2**. The reaction is called Compton scattering. The interaction is the highest in terms of the rate of reaction against gamma rays.

(3) Pair production

The pair production is a reaction where gamma rays generate pairs of electrons and positrons. For pair production, the energy needs to exceed two times 511 keV, which is the rest mass of electrons, and the reaction is caused by gamma rays featuring energy higher than 600 keV to 800 keV, which are released from ^{134}Cs and ^{137}Cs, the targets of removal.

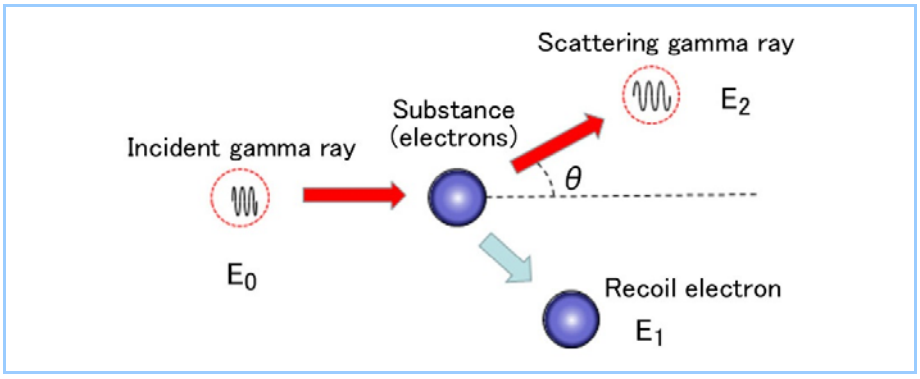

Figure 2 Compton scattering

3. Imaging principle of gamma ray camera

Usually pinhole system is used to image gamma rays. The comparison with the Compton Camera method is summarized below. The methods are compared in **Table 1**, and the outline of the imaging principle is shown in **Figure 3**.

Table 1 Comparison of pinhole camera with Compton camera

Imaging method	Pinhole camera	Compton camera
Major interaction	Photoelectric effect	Compton scattering
Disadvantages	・Detected portion needs to be enclosed by a heavy shield, and the equipment is large and heavy. ・View angle is limited to 40 to 60 degrees. ・Increase in noise due to gamma rays that pass through the shield. The noise is especially remarkable near pinhole collimator where the shield is thin.	・Production of an gamma-ray image requires calculation based on Compton reconstruction kinematics. Dedicated analysis code should be prepared.
Advantages	・The structure at the detecting portion is comparatively simple. ・Gamma image can be created comparatively easily from the obtained data.	・No need to use a shield because the direction of incoming gamma rays can be identified, making it possible to downsize and reduce the weight of the equipment. ・View angle is extremely large at 180 degrees (half sphere). ・By requiring the condition of Compton kinematics, signal to noise ration becomes high. ・High background rejection capability.

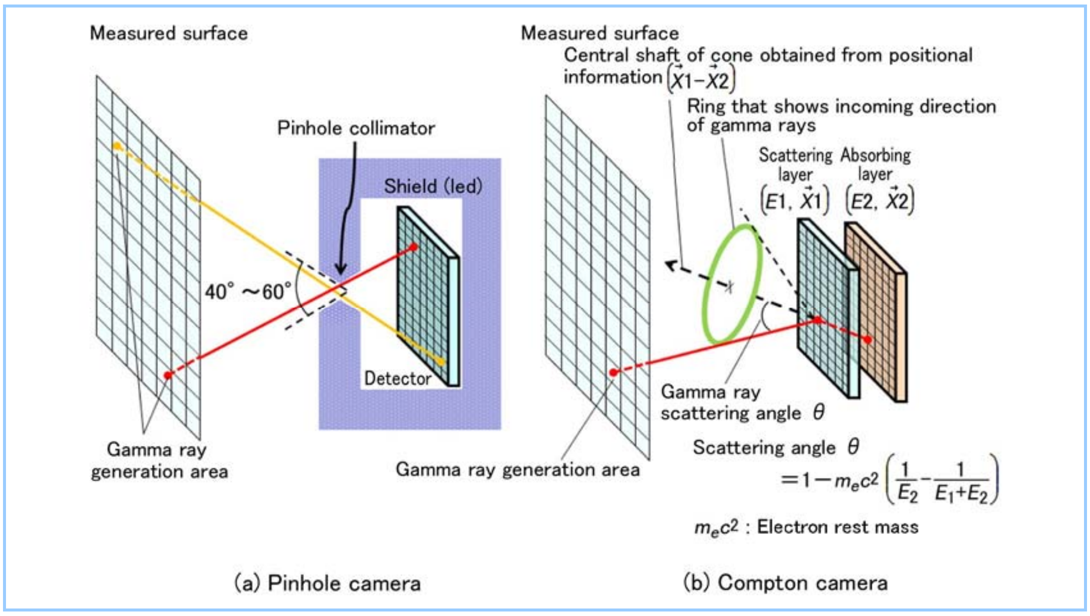

Figure 3 Imaging principles of pinhole camera and Compton camera

(1) Pinhole camera method

In the pinhole camera method, the photoelectric effect is utilized to image gamma rays. The detector of the camera is covered by a pinhole collimator and a shield, as shown in Figure 3 (a). Gamma rays that pass through the pinhole collimator and enter the camera are detected by the pixel detector. The direction of incoming gamma rays is identified from the geometrical relationship between the measured detector position and the pinhole.

(2) Compton camera method[3]

In the Compton camera method, Compton scattering is utilized to image gamma rays. The ASTROCAM 7000HS released by MHI incorporates this method. The camera has a pixel detector consisting of the scattering layer and the absorbing layer, as shown in Figure 3(b). Gamma rays that enter the camera go through Compton scattering at the scattering layer, and the scattered gamma rays undergo photoelectric absorption at the absorption layer. The energy measured at the scattering layer is defined as (E1), the 3D coordinate position on the detector surface where Compton scattering occurred is defined as position vector ($\vec{X}1$), the energy measured at the absorbing layer as (E2), and the position where photoelectric absorption occurred as ($\vec{X}2$). The energy of gamma rays that enter is obtained by E1+E2. As for the direction of incoming gamma rays, it is estimated that they pass through one of the points along the ring of the cone shown in Figure. The ring is obtained from the scattering angle (θ) calculated from the energy information and the central axis of the cone calculated from the positional information.

If multiple gamma rays are detected from the same gamma ray source, the direction of incoming gamma rays can be obtained from the intersection point where the rings overlap. The intersection point of the rings is emphasized in red as the events of detected gamma rays increase from three to 16 and more and the images of gamma rays become clearer, as **Figure 4** shows.

The Compton camera can narrow down the direction of incoming gamma rays by the method explained above, and there is no need to limit the direction of incoming gamma rays using a pinhole collimator, etc., realizing a super wide-angle measurement field covering all directions in a hemisphere.

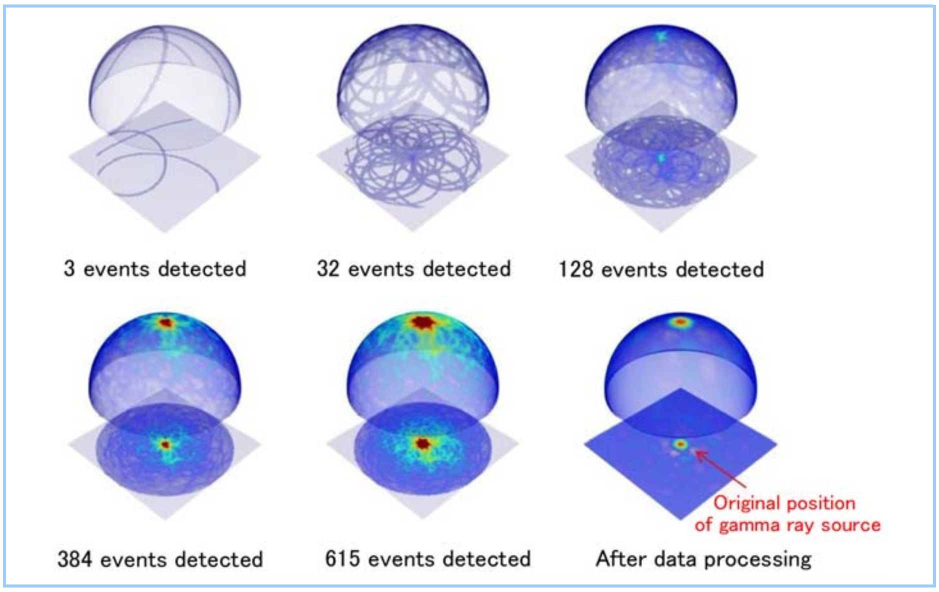

Figure 4 Number of detected gamma ray events and change in gamma image

4. Outline of ASTROCAM 7000HS

4.1 Configuration of the product

Figure 5 shows the overall structure of the ASTROCAM 7000HS and the basic specifications are shown in **Table 2**. The components are explained below.

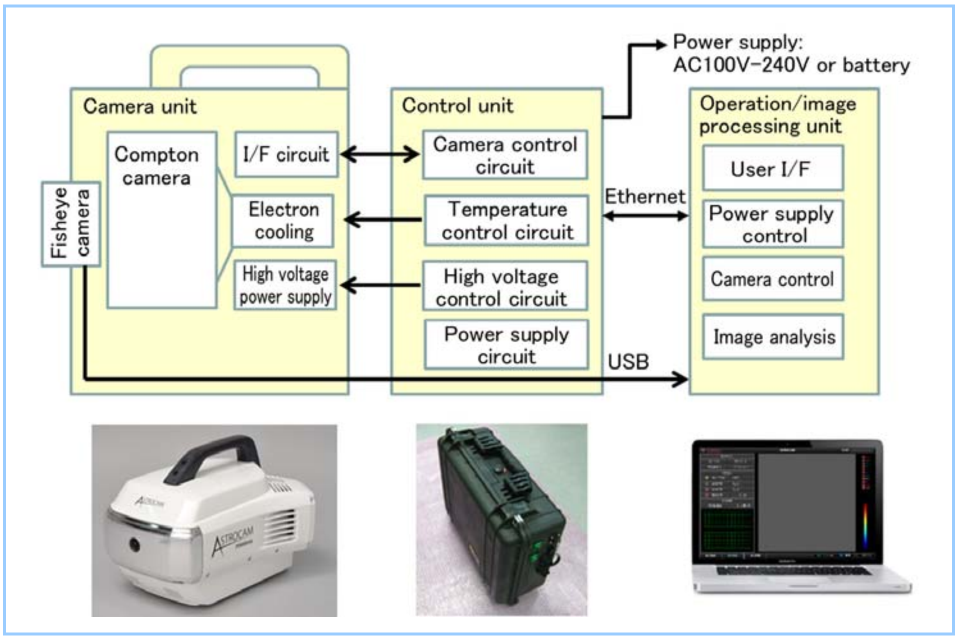

Figure 5 System configuration of ASTROCAM 7000HS

Table 2 Basic specifications of ASTROCAM 7000HS

Model No.	ASTROCAM 7000HS
Outer dimensions	L445×W340×H235 (mm) (Camera unit, excluding projections)
View angle	180 degrees (super wide angle) Detecting efficiency varies depending on the angle
Nuclide	12 types, can be selected by user
Energy resolution	2.2% (FWHM) at 662keV
Angle resolution	5.4 degrees (FWHM) at 662keV ARM (Angular Resolution Measure) evaluation value
Weight	Approx. 8-13kg (Camera unit) Depends on the number of sensor layers that constitute the camera
Power supply	AC100V-240V/battery
Temperature	Operating temperature: 0 to +40°C, storage temperature: 0 to +50°C
Operating temperature	35-80%, to be free from condensation
Accessories	Camera control box, notebook PC, measurement software

(1) Camera unit

The camera unit consists of Si/CdTe Compton camera, a high voltage power supply to the camera, an interface circuit, an electronic cooler, visible light fisheye camera, etc. The camera unit is 445 mm in depth, 340 mm in width and 235 mm in height, and the weight is 8 to 13 kg. The unit was downsized and the weight was reduced so that the product can be carried by one individual, assuming its use for the removal of contamination.

The Compton camera structurally takes over the camera mounted on the ASTRO-H satellite. The number of sensor layers in the camera, however, is less than that of the camera intended for the satellite, and the camera has 12 layers in total, 8 layers of Si semiconductor for the scattering layer and 4 layers of CdTe semiconductor for the absorbing layer. The configuration was decided by performing a simulation and analysis to determine the layer configuration appropriate for contamination removal. The sensitivity of the camera can be adjusted according to the application and the sensitivity can be increased to about 16 times the current specification if the number of sensor layers is increased to the maximum.

A fisheye camera is installed in front of the camera, and the direction of incoming radioactive rays is identified by superimposing the optical image of the fisheye camera over the gamma ray image.

(2) Control unit

The control unit houses a camera control circuit, a temperature control circuit, a high voltage control circuit, a power supply circuit, etc. The control unit receives commands from the operation/image processing unit and transmits voltage supply control commands and measurement control signals to the camera unit. The control unit features a safety design and constantly monitors temperature/humidity abnormalities and communication between the operation unit and the image processing unit, as well as a function to prevent failures by shifting the camera to safe mode upon error detection.

(3) Operation/image processing unit

All measurements can be controlled on the user interface screen of a PC. Therefore, remote operation is possible if the remote operation function of a PC is used, reducing the exposure of measurers to radiation.

The user interface screen is shown in **Figure 6**. Operations on the screen are very simple, and the measurer simply needs to turn on the voltage supply to the camera and start measurement using the "operation buttons" on the screen. When the measurement is started, the ring of gamma rays detected by the Compton camera is overwritten on the optical image at the center of the screen imaged by the fisheye camera in nearly real time, and the hot spot is emphasized gradually. The camera status, energy spectrum and change in the number of detections over time can be checked on the screen.

The nuclide selection button is on the top right of the screen and the nuclide for image display can be switched in real time during measurement. The user can register up to 12 types of arbitrary nuclides in the database. The selection function is one of the special features that characterize image processing by the ASTROCAM 7000HS. Gamma rays generated from radioactive substances, such as ^{137}Cs featuring 662keV, have energies specific to each nuclide. The image processing unit processes the data for visualization only when the measured energy matches the energy information specific for each nuclide in the database. Secondary gamma rays scattered by or absorbed in the ground, buildings, etc., are excluded by this processing method, and only the gamma rays coming directly from radioactive substances are processed, realizing accurate analysis of radioactive substance locations.

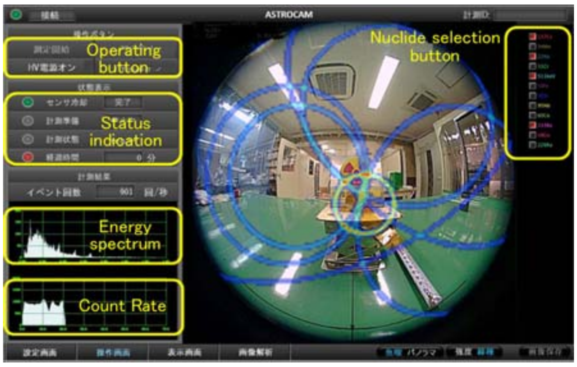

Figure 6 User interface screen

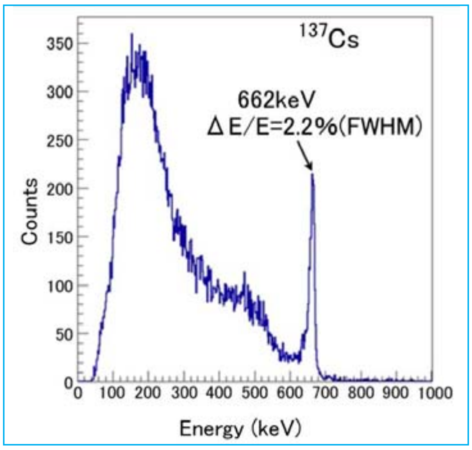

Figure 7 Energy spectrum of ^{137}Cs

4.2 Basic performance

The energy resolution and angle resolution of the camera are essential for the generation of clear gamma images. The energy resolution of the ASTROCAM 7000HS is 2.2% in respect to 662 keV gamma rays at FWHM (Full Width at Half Maximum) (**Figure 7**). The angle resolution is 5.4 degrees (FWHM) in ARM (Angular Resolution Measure) evaluation value, and a 10 m distance from the camera corresponds to 1 m.

5. Results of validation test performed on ASTROCAM 7000HS

5.1 Simultaneous measurement of multiple radiation source

Three types of radioactive substances were used for measurement, aiming to prove that different types of nuclides can be distinguished when multiple radioactive substances are measured simultaneously. The radioactive substances that we used were barium 133 (^{133}Ba), natrium 22 (^{22}Na) and ^{137}Cs. The image obtained in a 10-minute measurement is shown in **Figure 8**. The locations of the three types of radioactive substances were clearly distinguished on one screen. We also confirmed visualization by a test using europium 154 and cobalt 60, which is a target nuclide for the decommissioning of nuclear reactors at nuclear power plants.

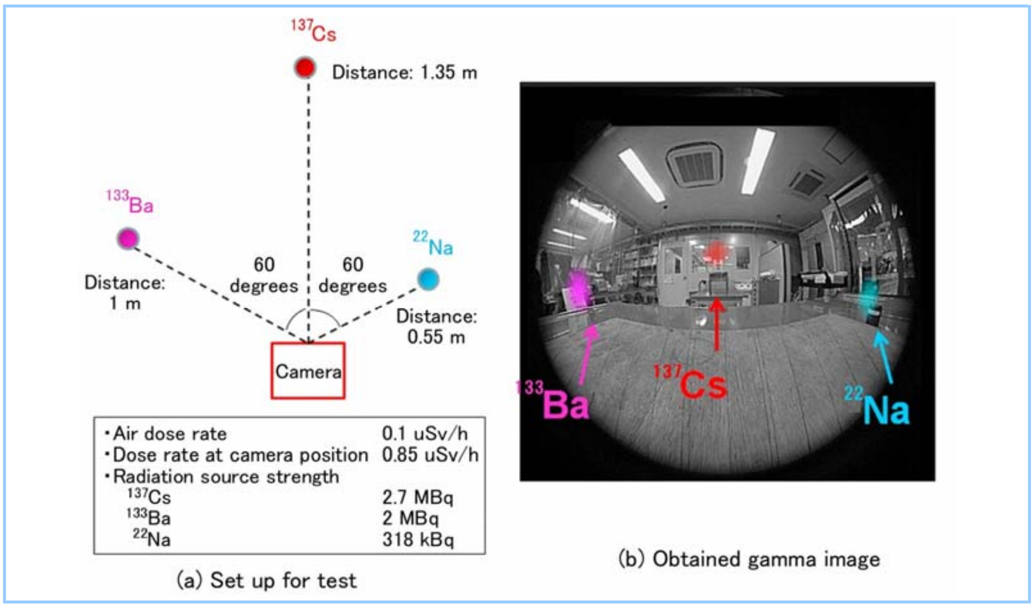

Figure 8 Results of simultaneous measurement of three types of radioactive substances

5.2 Evaluation of sensitivity

To evaluate the sensitivity on the side with lower radiation source strength, we performed measurement by setting radioactive substances at a position where the air dose rate at the camera position was equivalent to the air dose. For the measurement conditions, ^{137}Cs with an air dose of 0.09 microsieverts/hour (μSv/h) and a strength of 1MBq was set at a distance of 3.2 m from the camera. We confirmed in an eight-hour measurement that the locations of radioactive sources can be identified under the same conditions as for air dose, which means that visualization is possible even if the difference in dose rates is so small that the existence of radioactive substances cannot be detected by a survey meter.

5.3 Influence of obstacles

To prove that the locations of radioactive substances can be identified even if there is an obstacle such as a pipe or a metallic tank between the radioactive substances and the camera, we performed a measurement using a 24-mm stainless steel plate as an obstacle. The measurement result indicated that the existence of an obstacle does not largely affect the size of gamma images, which means the influence of gamma rays scattered by the obstacle is minimized and the locations of radioactive substances hidden by the obstacle can be identified clearly. The ratio of detected gamma ray events between a measurement with an obstacle and a measurement without an obstacle was 100:15, which is nearly the same as 100:12, which was obtained by a calculation based on damping due to the simplified obstacle.

5.4 3D gamma image

For the creation of 3D gamma images, we performed measurements from two directions to prove that information on distance between the camera and radioactive substances can be measured when the same radioactive substances are measured from multiple locations. It was confirmed that the distance was measured accurately, as **Figure 9** shows, because of the disparity (difference in views between cameras A and B), which was realized by the superior angle resolution of the ASTROCAM 7000HS[3, 7].

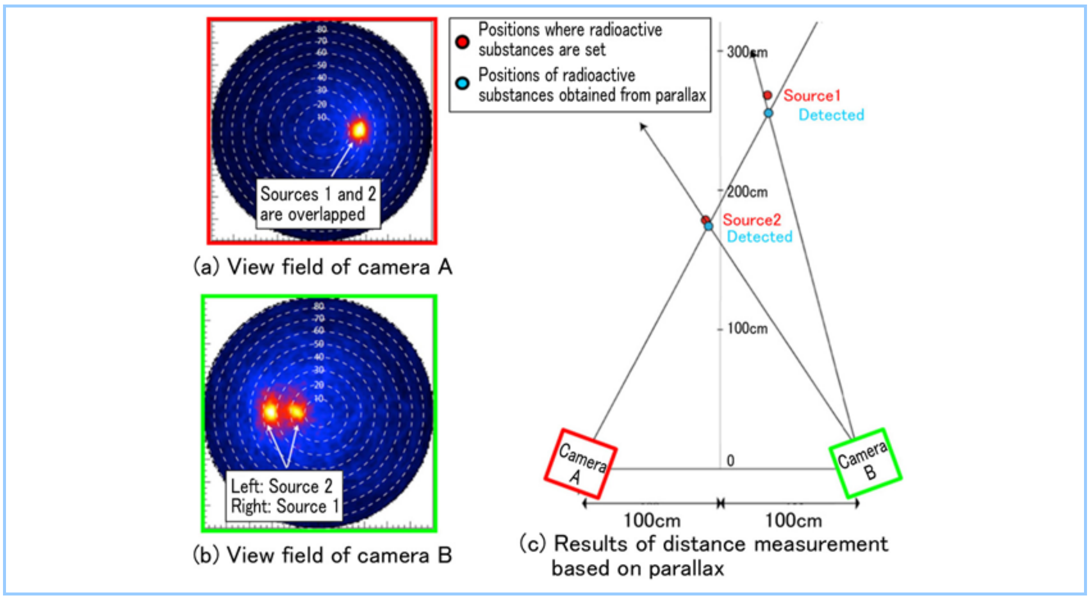

Figure 9 Measurement results of distance from radioactive substances based on parallax

5.5 On-site test

To prove that actual hot spots can be visualized, on-site tests were performed in the area where living is restricted in Fukushima Prefecture in June 2013 (**Figure 10** (a)). The ^{137}Cs gamma image obtained by a 30-minutre measurement under a 1.5 μSv/h air dose is shown in Figure 10 (b). The red areas in the image are the areas where gamma rays were strong according to the measurement. The dose rate of the measured area was checked by a survey meter, and it was confirmed that the red areas in the gamma image coincide with a 20 μSv/h hot spot located 1 m from the camera and a 30 μSv/h hot spot located 10 m from the camera. At another test site, locations before and after contamination removal were distinguished by a 30-minute measurement under the same air dose rate of 1.5 μSv/h (Figure 10 (c)).

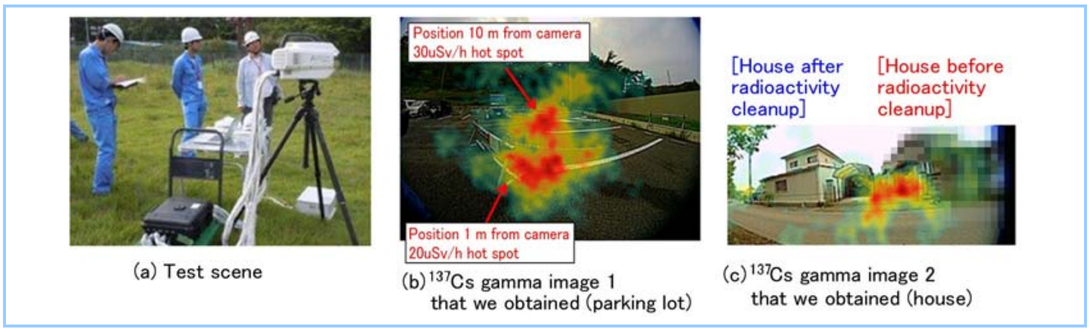

Figure 10 Results of measurement in the area where living is restricted in Fukushima Prefecture

6. Conclusion

As a result of the accident at the Fukushima Daiichi Nuclear Power Plant, gamma ray visualization cameras have been released by a number of companies in recent years. MHI released the "ASTROCAM 7000HS," a radioactive substance visualization camera, and has been performing verification and validation of the system. Through the on-site test performed in the area where living is restricted in Fukushima Prefecture, we succeeded in visualizing the hot spot and distinguishing between places before and after contamination removal, and confirmed that the product is moving toward commercialization. We hope that the product will support operations for contamination removal and contribute to the reconstruction of Fukushima Prefecture.

The future development will be as follows:

- Technological development: Application to reactor decommissioning operations and control at nuclear power plants through the creation of 3D gamma images and a network of multiple cameras, as well as an increase in the upper limit energy value of gamma rays that can be measured
- Business development: Measurement service business using the ASTROCAM 7000HS

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JST Development of Systems and Technology for Advanced Measurement and Analysis
"Development of Next-generation Ultra-wide Angle Compton Camera"
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