# 論 文 の 内 容 の 要 旨

論文題目　Development of Wide Area and High Resolution Gamma-ray Imager Based on Compton Scattering Principle
（コンプトン散乱を用いた、広域高分解能ガンマ線画像計測装置の開発）

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Following the Fukushima Daiichi Nuclear Power Plant (FNPP) accident on March 11, 2011, substantial amounts of radionuclides were deposited primarily within a 20 km radius from the plant and rapidly extending up to 30 km to the northwest of the FNPP owning to winds at the time of the explosions. Because of the fallout and for public safety, a government-mandated exclusion zone or evacuated area was declared which resulted in at least 185,000 people displaced from their homes. In addition, radioactive contamination was detected in dairy products from affected areas. Methods to survey and clean-up the affected regions were implemented after the accident. However, even four years later, after the accident, most of the evacuation orders have not been lifted for the affected areas, because of the scale of the contamination along with the difficulty of the decontamination.

In addition to nuclear accidents, the capability of producing, the possession of, and the illicit trafficking of nuclear weapons or special nuclear materials(SNM) by hostile individuals, groups, and non-nuclear weapons countries, is considered to be an even more general nuclear threat to the world security and public safety at this time.

Whether for the clean-up in contaminated regions in, for example, Fukushima prefecture in Japan as a result of a nuclear power plant accident, or for the detection of the presence of those types of threat nuclear weapons and SNM, instruments that are capable of detecting, localizing, characterizing, monitoring the transport of, and estimating the intensity of radioactive sources in a large area with high efficiency and accuracy are helpful and subsequently highly demanded.

Detection of electromagnetic radiation in the form of gamma rays provides a path to reconstruct the origin of nuclear materials, regarding that the vast majority of possible threat radioisotopes emit gamma rays. Gamma rays are of high frequency and they have a long rang in air. Due to their high penetrating power, they are difficult to be detected. The detection and imaging of gamma rays depend upon an understanding of the methods in which the high-energy photons interact with matter. Gamma rays emitted from radioisotopes are usually within the energy band from tens of keV to a few MeV, in which, Compton camera is an ideally suited technique for detection and localization of the presence of nuclear sources.

This dissertation focusses on the design, development and characterization of a gamma-ray detection and imaging instrument that is capable of localizing radionuclides over a wide scale with high spatial resolution. We, for the first time, proposed a new airborne imaging modality through equipping a Compton camera on an Autonomous Unmanned Helicopter (AUH) that can hover and fly in a programmed route at an altitude of 10 ~ 150 m. The AUH is controlled autonomously according to a preset program when flying. A differential global positioning system (DGPS) is applied to provide the information of the AUH. Measured data are sent to the ground station in real time through wireless data communication modules. The system was designed to work in two modes, one is Compton camera mode(CCM) which discovers the origin of radioactive sources through Compton imaging using hovering flights, while the other one is Gamma camera mode(GCM) which maps the wide spread radiation via measured coincidence events using programmed flights.

The advantages of this new gamma-ray imager are apparently. They can easily assess activities of radioactive sources over large areas. Other than a non-directional detector which detects an increase in the detected photon rate operated in a raster pattern, the employment of Compton imaging enhances the detection accuracy of the system. This configuration is also capable of imaging the radiation distribution in high dose rate regions, for example, evacuated areas near the struck FNPP, in mountainous areas, paddy fields, and swampy grounds where are not easily accessible by people. Alternately, it would allow investigation of a scene without disturbing it, providing personnel safety from loose sources of radioactivity, and preserving evidence for eventual prosecution.

Compton camera is the heart of the wide area imager. Flying 10 ~ 150 m away from the ground to conduct airborne measurements, the number of counts collected in a limited time period is essential and directly determine the accuracy of reconstructed images. For this reason, $Ce:Gd_3(Al,Ga)_5O_{12}$ (GAGG) scintillation detectors with large sensitive areas(10 mm × 10 mm) are employed. The detectors are arranged in a two-planar configuration to allow for Compton imaging. The front plane consists of thinner active detectors to serve as a Compton scatter plane, while the back plane was constituted by thicker crystals to absorber the scattered photons. A new Dynamic time over threshold signal processing method was firstly and successfully applied to covert analog signals to digital signals for multi-channel spectra and coincidence measurement. Thanks for the application of this new method that is composed by simple circuits, a low power consumption and a stable circuit performance are realized.

A prototype system was firstly developed to demonstrate its capabilities for radiation detection, spectroscopy, and imaging over large areas. For the Compton camera in this prototype system, 32 GAGG crystals were coupled to 16 silicon photomultipliers and 16 avalanched photodiodes as the scatterer and absorber respectively. The 32-detector Compton camera was fully characterized within the laboratory and field environment. For point source imaging in CCM in the laboratory, an intrinsic efficiency of 1.68%± 0.04% and an angular resolution of 13.9°(FWHM) at 662 keV was achieved. In GCM, a spatial resolution of 10.7 cm (FWHM) was obtained when detecting area is 11.2 cm away from the detector. The overall power consumption was 1125 mW. The prototype system was brought to Fushima in April in 2014 for the first aerial test. The instrument proved reliable and performed very well under uncontrollable temperature, high humidity, AUH vibrations, and complicated terrains. The field measurement of the prototype wide area imager in Fukushima revealed regions of high intensity of cesium among a diffuse background through aerial-based coincidence count rate mapping, Compton imaging in hovering flights and ground measurements.

Encouraged by the results obtained in Fukushima by the prototype imager, a large volume Compton camera with 128 pixels, was devised and developed with the purpose to achieve higher efficiency and angular resolution. The fully characterization of this large volume Compton camera in the laboratory environment yields a system energy resolution of 6% (FWHM) at 662 keV, an angular resolution of 8.6°(FWHM) at 662 keV in CCM, an intrinsic efficiency of 1.30% ± 0.03%and a total power consumption of 1584 mW. With this angular resolution, the detector system is expected to achieve a spatial resolution of 1.6 m in field while it is working in CCM at an altitude of 10 m. Simulations by Geant4 proved an spatial resolution of 8.8 cm(FWHM) in GCM while the detecting area was 100 mm away. Field tests using the newly developed wide area gamma ray imager has also been conducted in Fukushima. The imager performed very well, e.g. with a similar count rate from each channel, the working temperature within the compensable range of the temperature compensation circuit, and promising images obtained under complicated terrains, high humidity, and strong AUH vibrations due to the wind. Challenges to field imaging were detailedly studied and recommendations for the next run were made based on the calibration flights.

Although the prototype wide area imager as well the benchmarked large volume system responses proved successful in wide area imaging in Fukushima, there remain several paths for optimization of the imager as well as technological challenges that need to be addressed prior to widespread deployment of a GAGG-based, Compton scattering principle applied gamma ray imager. For example, the employment of SiPMs lowered the requirement for electronics due to their high signal to noise ratio. However, for the same reason, the performance of the whole system was dependent on the temperature. Although temperature compensation circuits were applied, or even temperature compensation were employed during the data analysis process, the effect from the temperature cannot be hundred-percent eliminated and still remains one big problem that depress the performance of the imagers. In addition, the cubic centimeter GAGG scincillators allow a simplified instrument design, since they greatly decrease the amount of electronics required to operate the system. This subsequently reduces the number of electronics-induced problems that always happen during real-world operations. But a significant compromise with regard to performance is imposed by the employment of large voxels. The main issue with the large volume detectors is that the achievable angular resolution is limited for the Compton camera, since the interaction location resolution is determined by the size of the detector. This results in either a broad cross section distribution with long tails or in increase of sequences that cannot be reconstructed. Another example is about the geometry of the Compton camera in the system. The present geometry of the Compton camera in the imager is sufficient for field testing and demonstration purpose. However, to improve the efficiency and sensitivity for the real applications in real world, the Compton camera would need to be modified to effectively make use of each pixel. A reverse geometry for Compton camera was introduced, discussed, and could be a good candidate for the modification. With less pixels constituting a circle shaped scatterer and more pixels forming a ring shaped absorber, the absolute efficiency as well as the angular resolution would be improved when detecting the radioactive sources on the axis of the detector in far field.

Regardless of the current limitations of the imagers and AUH vibrations, the benchmarked response and proven capabilities of this new concept of wide area imaging as demonstrated with the prototype imager, the calibrated large volume system and through simulation is an important step for the development, fabrication, and application of wide area gamma ray imagers. The multi working modes of the systems were also proven and in either of them, the wide area imagers are able to provide detailed distribution map of radioactive sources in a wide scale. In real-world application, these two working modes are recommended to be combined. The system is firstly set to work in GCM to scan the contaminated places with high sensitivity, with the option of switching to CCM once a radiation field of interest has been detected. The systems can be rapidly improved for future measurements based upon the findings of this work.