Development and performance evaluation of a 4π-FoV Compton camera based on spherical detector system with hybrid imaging capabilities

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Abstract

Gamma-ray imaging plays a crucial role in source-term monitoring and consequence management of nuclear power plants. These applications typically involve mapping of spatial radiation distributions consisting of various isotopes. This requires the imaging equipment to achieve not only an 4π field-of-view (FoV), but also an isotropic response within the FoV across a wide energy range. To resolve these issues, we designed and implemented a spherical detector system with complete readout electronics to function as a Compton camera with an isotropic FoV and active coded aperture imaging capabilities. This camera system adopts Cerium-doped Gd3Al2Ga3O12 (Ce:GAGG) scintillator detectors and a multichannel electronics system utilizing application specific integrated circuit (ASIC). Besides Compton imaging, a modified hybrid gamma-ray imaging approach is developed to combine Compton and active coded aperture imaging capabilities, which was not fully explored in previous research. Through systematic evaluations of Compton, coded aperture and hybrid imaging, we have verified that the modified hybrid imaging method can provide enhanced image quality and sensitivity, along with an extended energy range. By applying the modified hybrid imaging technique, the developed camera system achieves fine imaging performance in single- and double-point source imaging scenarios, which makes it a promising candidate for future application in free-moving 3-D radiation imaging to realize the mapping of complex distributions and coverage of large areas.

Full Text

Preamble

Development and Performance Evaluation of a 4π-FoV Compton Camera Based on Spherical Detector System with Hybrid Imaging Capabilities

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Gamma-ray imaging plays a crucial role in source-term monitoring and consequence management of nuclear power plants. These applications typically involve mapping spatial radiation distributions consisting of various isotopes, which requires imaging equipment to achieve not only a 4π field-of-view (FoV) but also an isotropic response within the FoV across a wide energy range. To address these requirements, we designed and implemented a spherical detector system with complete readout electronics to function as a Compton camera with an isotropic FoV and active coded aperture imaging capabilities. This camera system adopts Cerium-doped $Gd_3Al_2Ga_3O_{12}$ (Ce:GAGG) scintillator detectors and a multichannel electronics system utilizing application-specific integrated circuit (ASIC) technology. In addition to Compton imaging, we developed a modified hybrid gamma-ray imaging approach that combines Compton and active coded aperture imaging capabilities—a combination not fully explored in previous research. Through systematic evaluations of Compton, coded aperture, and hybrid imaging, we verified that the modified hybrid imaging method can provide enhanced image quality and sensitivity along with an extended energy range. By applying this modified hybrid imaging technique, the developed camera system achieves fine imaging performance in both single- and double-point source scenarios, making it a promising candidate for future application in free-moving 3-D radiation imaging to realize the mapping of complex distributions and coverage of large areas.

Keywords: 4π FoV, Spherical detector configuration, Compton camera, Active coded aperture imaging, Hybrid gamma-ray imaging

INTRODUCTION

Gamma-ray imaging has been applied in various industries such as nuclear safety and security [?], nuclear medicine [?], and astrophysics [?]. Two commonly adopted imaging methods are coded aperture imaging [?, ?] and Compton imaging [?]. Coded aperture imaging utilizes photon attenuation through patterned coded masks, making it excel at low energies (<500 keV) [?]. However, its effectiveness diminishes at higher energies due to increased penetration of gamma-ray photons. Conversely, Compton imaging is advantageous at higher energies (500 keV–a few MeV) due to the relatively larger cross-section of the Compton scattering process [?]. Previous studies have also indicated good performance of Compton imaging within the energy range of 140–500 keV [?, ?], making it suitable for scenarios like source-term monitoring [?, ?], decommissioning [?, ?], contamination remediation, and consequence management of nuclear power plants (NPPs) [?, ?], where typical radioactive nuclides emit gamma-rays with energies ranging from several hundred keV to several MeV [?].

Nevertheless, these scenarios often require precise localization of radioactive sources within vast areas and mapping of potentially intricate spatial distributions of radioactivity. These distributions may originate either from complex spatial arrangements of radioactive substances or from complex shielding structures [?]. The integration of contextual sensors and scene data fusion approaches provides a viable solution, leading to the development of gamma-ray imaging systems capable of mapping 3D radiation distributions in real time while moving through the scene [?, ?, ?].

The utilization of free-moving measurement approaches and the mapping of complex source distributions both imply that gamma-rays may enter the imager from various angles. Thus, conventional imaging systems with planar configurations encounter significant limitations in imaging performance for these scenarios [?]. Additionally, evidence indicates the presence of radioactive isotopes with characteristic gamma-ray energies below the effective range of Compton imaging (>250 keV) in scenarios such as source-term monitoring during maintenance and consequence management in NPPs [?]. Therefore, apart from attaining an isotropic 4π field of view for complex radiation distribution mapping and free-moving measurement, achieving fine imaging performance across a broad energy range is crucial for future development of gamma cameras in these applications.

To enhance gamma-ray imaging performance in free-moving measurements or mapping of complex distributions, Hellfeld et al. developed an active coded mask imaging system based on a spherical detector configuration [?, ?]. Although the detector configuration was optimized to achieve an isotropic 4π FoV, the resulting configuration was not unique. The system also adopted CdZnTe detectors, which may not be the most cost-effective choice compared with novel heavy scintillator materials such as Ce-doped $Gd_3Al_2Ga_3O_{12}$ (Ce:GAGG). Moreover, the Compton imaging capability of this system was not exploited, leaving the issue of effective imaging across a wide energy range unaddressed. Kitayama et al. also developed a coded aperture imager with 4π FoV based on a cost-effective 3-D configuration utilizing Ce:GAGG detectors and lead cubes [?]. However, the uniformity of the system response across the FoV has not been examined, and the applicable energy range of the imager remains undetermined.

To address these issues, Liang et al. conducted a simulation study on the coded aperture and Compton imaging performance of a more uniformly distributed spherical detector configuration with Ce:GAGG sensors [?]. Unlike conventional dual-layer configurations with distinct scatter and absorber layers, the spherical configuration enables Compton imaging through coincidence detection of detector units. Additionally, active coded aperture imaging can be performed in such a configuration through the collimation pattern formed by gamma-ray attenuation of the detector units. The isotropic dual-mode imaging capability of this design was verified through Monte Carlo simulations, enabling gamma-ray imaging across a broad energy range. However, this design still faces challenges due to the limited angular resolution of Compton imaging, which can affect image quality when employed in free-moving 3D distribution mapping.

For gamma-ray imagers with dual-mode imaging capabilities like the aforementioned spherical configuration, a great portion of gamma-ray photons are captured via direct photoelectric absorption apart from Compton scattering in the energy range of approximately 300 keV to 1 MeV. Alongside multiple-interaction Compton events, the utilization of these single photon interaction events can provide additional information for image reconstruction to achieve hybrid gamma imaging [?]. This method can improve both the angular resolution and sensitivity of the gamma-ray imager while enabling imaging at energies below ~250 keV. Previous studies have demonstrated the effectiveness of such hybrid imaging methods on Compton imagers equipped with passive [?] or active coded masks [?, ?, ?], suggesting that it can achieve better angular resolution than both single-mode imaging methods. Xu applied this method to a gamma camera with a multi-layer planar configuration that possesses 4π FoV for both Compton and active coded aperture imaging [?]. The 4π hybrid imaging capability was validated through Monte Carlo simulation [?]. While this method can effectively enhance the imaging performance of Compton imagers with multi-layer configuration while preserving the 4π FoV, it has not yet been tested on a detector configuration with isotropic 4π FoV. Furthermore, this method has some issues related to convergence in iterative image reconstruction, which will be discussed in Sec. II B. The imperative remains to develop a dedicated and theoretically sound hybrid imaging technique for dual-mode gamma cameras with isotropic 4π FoV.

In this paper, we present the development of a Compton camera based on a spherical detector configuration similar to that proposed by Liang et al. [?], and the exploitation of hybrid imaging capabilities with the developed camera. A spherical detector array comprised of Ce:GAGG detector units and a custom multichannel signal processing system are developed, with slight refinements to the structure of the previously reported configuration to enhance Compton imaging performance. Compton and active coded aperture imaging tests are performed on this camera to evaluate its dual-mode imaging performance. Finally, a modified hybrid gamma-ray imaging method that aligns more closely with the dual-mode hybrid imaging model is developed based on previous research and applied to the developed Compton camera. This method proves effective in enhancing the imaging performance of the camera with improved image quality. Using this hybrid imaging method, high-resolution and high-sensitivity gamma-ray imaging with isotropic 4π FoV across a wide energy range is achieved on the developed Compton camera.

II. MATERIALS AND METHODS

Imaging System Design

The imaging system reported in this paper consists of a detector system based on spherical configuration, a multichannel frontend electronics system based on application-specific integrated circuit (ASIC), and a backend electronics system that employs field programmable gate array (FPGA). A schematic illustration of the system composition is given in Fig. 1 [Figure 1: see original paper].

Fig. 1. (Color online) Composition of the Compton imaging system.

The detector system consists of 80 detector units arranged in a configuration similar to the design proposed by Liang et al. [?]. The positioning of each detector unit is derived using the same strategy as Liang et al., with minor adjustments in the orientation of each unit for convenience in the design of the mechanical supporting structure. Since the geometry of the system and the spatial resolution of the detector unit can significantly influence the angular uncertainty of Compton measurements [?], the configuration of the detector array is slightly adjusted to ensure good intrinsic Compton imaging performance. This process involves fine-tuning of key structural parameters, including sphere radius r_d and crystal size l_c, based on their impact on the imaging performance of the Compton camera as well as engineering constraints for future expansion to free-moving 3-D imaging.

A constrained camera weight is demanded for applications requiring handheld measurements [?] or drone-mounting operations [?], thereby limiting the total weight of the crystals. However, overly limited crystal mass leads to reduced detection efficiency due to small crystal size. Following designs of Compton cameras in previous studies [?], a weight limit of 1 kg for the crystals is established, which corresponds to a crystal size of $l_c = 12$ mm. On the other hand, the sphere radius influences both angular resolution and detection efficiency of the Compton camera. While angular resolution is directly determined by the sphere radius r_d and is not subject to further optimization once r_d is fixed, detection efficiency can be enhanced by adding additional detector units to fill intervals in the setup after determining r_d. Since this study focuses on development of a first-generation prototype, imaging resolution is selected as the principal metric for refinement of structural parameters.

An upper limit of $ARM_{UL} = 20^\circ$ is adopted for the angular resolution measure (ARM) based on prior studies [?, ?, ?]. Additionally, a larger sphere radius necessitates a heavier supporting structure and casing, thereby impacting the weight of the camera. Thus, an upper limit of $r_d \leq 15$ cm is applied in reference to existing studies [?, ?]. With selection criteria and engineering constraints established, Monte Carlo simulations of the detector system are performed using the Geant4 toolkit [?] to evaluate angular resolution and detection efficiency for Compton imaging across various sphere radius values, ranging from 7 cm (determined by geometric constraints) to 15 cm with a step size of 1 cm. The results are displayed in Fig. 2 [Figure 2: see original paper]. Considering that detection efficiency decreases with increasing radius, the minimum radius that satisfies $ARM + \sigma_{ARM} \leq ARM_{UL}$ is selected as the final value, with σ_{ARM} representing the standard deviation of ARM values. Such selection criteria give the result of $r_d = 10$ cm, which specifies the refined structure values along with the previously determined crystal size of $l_c = 12$ mm. This specific configuration is expected to achieve an angular resolution of $\sim 14^\circ$ when measuring the 662 keV gamma-ray emitted from a ^{137}Cs point source.

Based on the refined configuration, the detector system is fabricated. Each detector unit comprises a $12 \times 12 \times 12$ mm^3 Ce:GAGG crystal coupled to a 6 mm silicon photomultiplier (SiPM, ONSEMI MicroFJ-60035-TSV) mounted on a circuit board and an aluminum shell securing the crystal to the SiPM circuit board. The average energy resolution of the detector units is $(7.96 \pm 0.27)\%$ at 662 keV, with the best single-channel resolution of 7.29% and worst value of 8.94%, as depicted in Fig. 3 [Figure 3: see original paper]. Additionally, a plastic mechanical frame is designed and implemented to precisely position and orient each of the 80 detector units according to the refined configuration. The detector units are divided into 10 groups, and the SiPM high voltage (HV) input and signal output wiring of the 8 adjacent units in each group are connected to a designated signal transferring unit. These connections are then consolidated into a single cable that connects to the electronics system, effectively preventing potential wiring congestion that could arise from numerous input and output channels. The developed spherical detector system is depicted in Fig. 4(a) [Figure 4: see original paper].

To handle signals from the 80 detector units, a multichannel signal processing frontend electronics system is developed. The system is composed of three 32-channel ASICs, with 80 channels for signal processing along with 16 redundant channels for backup. Each channel independently processes and digitizes the input signal to acquire both the amplitude and generation time of the signal. Subsequently, the data is relayed to the backend electronics system based on FPGA. At the backend electronics, a global timestamp is added to the data to identify coincident events. The processed data is packaged for transmission to the on-board computer to check for temporal coincidence and perform Compton event reconstruction as well as image reconstruction. The developed electronics system is depicted in Fig. 4(b) [Figure 4: see original paper].

Imaging Methods

The primary imaging modality of the developed gamma camera is Compton imaging. Additionally, the feasibility of applying active coded aperture imaging on the adopted spherical configuration has been proved by Hellfeld et al. [?] and Liang et al. [?]. Therefore, the capability to perform active coded aperture imaging is also validated for the developed Compton camera. Moreover, a modified hybrid gamma imaging method is devised to further enhance imaging performance. Based on methods from previous research, this method effectively combines Compton and active coded aperture imaging modalities to achieve high-quality imaging across a wide energy range (59.5 keV–1.3 MeV).

Compton Imaging. Compton imaging has diverse applications in fields such as astrophysics, medical imaging, radiation protection, and nuclear security. It utilizes the Compton scattering process to capture direction information of gamma-ray photons, enabling image reconstruction through back-projection. When an incident photon of energy E_0 undergoes Compton scattering in a detector unit, it creates a Compton event by depositing energy E_1 in that unit, with the remaining energy fully collected by one or more other detector units. With these energy depositions recorded by the detector units, the scatter angle θ of the incident photon can be determined using the well-known Compton scattering formula:

$$\cos(\theta) = 1 + \frac{E_0 - E_1}{E_0 E_1} m_e c^2$$

where $m_e c^2$ is the rest mass energy of an electron. The scattering angle indicates the angle between the directions of the incident and scattered photons. While the direction of the scattered photon can be determined from the relative displacement of detector units that recorded the first and second interactions, the direction of the incident photon cannot be pinpointed with the obtained information alone. Instead, possible directions of the incident photon are described by a conical surface, referred to as the Compton cone. After accumulating a sufficient number of Compton events, the corresponding Compton cones are back-projected onto the 4π spherical image space surrounding the camera. The intersection point of these cones denotes the position of the radioactive source.

Since the difference in occurrence times between interactions of a Compton event amounts to approximately 120–670 picoseconds in the adopted configuration, directly establishing the order of these interactions via the time-of-flight method requires specifically designed camera systems, as exemplified by TOF-PET systems that utilize GAGG or GFAG scintillators and customized electronics with timing resolutions of 300–400 ps [?]. However, such direct determination cannot be achieved with the developed camera system, as the slow output channel of the SiPM is utilized to achieve better energy resolution, which reduces the slope of the rising edge in the signal. Thus, the order of interaction is determined using methods proposed by Boggs et al. [?], with distinct methods for determining two-interaction and multiple-interaction sequences. Verification tests with Monte Carlo simulations indicate that such methods can achieve a correct-sequence rate of 67.5% for two-interaction events and 54.3% for multiple-interaction events, which account for only ~3% of total events.

With the ordering of interactions determined, Compton events can be used for image reconstruction. For the reported camera, the list mode-maximum likelihood expectation maximization (LM ML-EM) algorithm [?] is adopted:

$$\lambda_j^{(l+1)} = \lambda_j^{(l)} \frac{\sum_{i=1}^{N} t_{ij}^{C} (\Delta\theta_i)^{-1}}{\sum_{k=1}^{M} s_k^C \lambda_k^{(l)}}$$

with $\lambda_j^{(l)}$ denoting the estimated intensity of source pixel j on the 4π spherical image space after iteration l, $j = \{1, 2, ..., M\}$, s_j^C being the sensitivity matrix element representing the probability that a photon emitted from source pixel j is detected anywhere in the camera in the form of Compton events, $\Delta\theta_i$ being the angular measurement uncertainty of Compton event i, $i = \{1, 2, ..., N\}$, and t_{ij}^C being the system matrix element describing the probability of producing event i (assuming the first interaction is recorded by detector unit p) given a photon emitted from source pixel j. The system matrix element is derived with [?]:

$$t_{ij}^C = \frac{\varepsilon_{ij}^C}{\|d_{pj}\|^2} \cdot K(\beta|E_0) \cdot \frac{1}{\sqrt{2\pi(\sigma_{ER}^2 + \sigma_{DB}^2 + \sigma_{SR}^2)}} \cdot \exp\left(-\frac{(\theta-\beta)^2}{2(\sigma_{ER}^2 + \sigma_{DB}^2 + \sigma_{SR}^2)}\right)$$

where ε_{ij}^C is the probability of a photon emitted from source pixel j being detected by detector unit p via Compton scattering, $\|d_{pj}\|$ is the distance between source pixel j and detector unit p, β is the corresponding scatter angle for a photon emitted from source pixel j to generate event i, $K(\beta|E_0)$ is the Klein-Nishina formula describing the Compton scattering cross-section [?], while σ_{ER}, σ_{DB}, and σ_{SR} are angular measurement uncertainties caused by detector energy resolution, Doppler broadening of Ce:GAGG, and detector spatial resolution, respectively. These angular uncertainties are determined using the method reported in Wu et al. [?].

Coded Aperture Imaging. The coded aperture imaging technique relies on mutual attenuation of photons among detector units to form effective patterned projections essential for image formation. These projections, determined by the system response of the configuration, are crucial for the image reconstruction process. To accurately determine the system response, Monte Carlo simulations of the developed camera are conducted using the Geant4 toolkit. A total of 5762 directional points on the 4π image space are selected following the same strategy reported by Liang et al. [?] to ensure fine precision in the derived system response. The strategy is achieved by adding points uniformly to the icosahedron structure through two distinct operations: a "bisector point addition" step that adds bisector points of arcs formed by projecting triangle edges onto the spherical surface, and a "trisector point addition" that adds trisector points of these arcs. The required point set for simulation is generated by performing three consecutive bisector point addition steps followed by one trisector point addition step. This results in a precision of 2.64° for the simulated system response matrix, defined by the angular distance between neighboring directional points in the set. To facilitate future extension to 3-D imaging applications requiring near-field image reconstruction, simulations are performed using near-field point sources as opposed to commonly used far-field sources. Near-field point sources with various energies are placed at each selected point at specified distances to record the count of each detector unit in the simulation. A depiction of the obtained system response is portrayed in Fig. 5 [Figure 5: see original paper]. It should be noted that the detection efficiency in Fig. 5 is derived by first summing the total number of full-energy absorption events over the 80 detector units, then dividing the obtained total number of full-energy events by the total number of incident photons.

With the full system response generated, coded aperture image reconstruction can be performed. The ML-EM algorithm is also employed for coded aperture imaging:

$$\lambda_j^{(l+1)} = \lambda_j^{(l)} \frac{\sum_{p=1}^{P} \varepsilon_{pj}^{A} C_A^p}{\sum_{k=1}^{M} s_k^A \lambda_k^{(l)}}$$

where P denotes the total number of detector units, $s_j^A = \sum_{p=1}^{P} \varepsilon_{pj}^A$ is the absorption sensitivity matrix element denoting the probability that a photon emitted from source pixel j is detected anywhere in the camera in the form of single-interaction events, ε_{pj}^A is the system response matrix element derived from simulation, and C_A^p is the single-interaction full-energy event count of detector unit p. In practice, full-energy events are selected by performing Gaussian fits on the full-energy peaks in spectra collected by each detector unit to obtain its center μ_p and standard deviation σ_p, and setting the energy window for event selection to $[\mu_p - 3\sigma_p, \mu_p + 3\sigma_p]$ for each detector unit. This energy cut also serves as the background subtraction method for the camera.

Hybrid Imaging. To further enhance imaging performance and extract additional physical information by effectively combining Compton and coded aperture data, a hybrid gamma imaging method is developed. Lee et al. initially introduced an approach for imaging reconstruction of hybrid imaging data based on the ML-EM algorithm [**?**]:

$$\lambda_j^{(l+1)} = \lambda_j^{(l)} \frac{s_j^C \sum_{i=1}^{N} t_{ij}^C (\Delta\theta_i)^{-1} + s_j^A \sum_{p=1}^{P} \varepsilon_{pj}^A C_A^p}{\sum_{k=1}^{M} (s_k^C + s_k^A) \lambda_k^{(l)}}$$

This approach has been successfully applied to a dual-mode camera with a coded mask. However, its applicability to cameras that utilize active masks is limited due to the coded aperture image requiring more iterations to converge compared to the Compton image in such camera setups [?, ?]. Thus, synchronized iteration between the two modalities may not be appropriate. Apart from convergence rate issues, the algorithm described in Eq. 5 essentially combines two images corrected based on Compton and coded aperture data, with weighting factors determined by detection efficiency of the corresponding modality:

$$\lambda_j^{(l+1)} = \lambda_j^{(l)} \frac{s_j^C \sum_{i=1}^{N} t_{ij}^C (\Delta\theta_i)^{-1} + s_j^A \sum_{p=1}^{P} \varepsilon_{pj}^A C_A^p}{\sum_{k=1}^{M} (s_k^C + s_k^A) \lambda_k^{(l)}}$$

In dual-mode cameras utilizing active masks, the detection efficiency of single-interaction events typically surpasses Compton efficiency significantly. This causes the image derived using Eq. 5 to closely resemble the image reconstructed solely with coded aperture data, failing to effectively combine data from both modalities.

To address these issues, Xu introduced a hybrid imaging method for cameras equipped solely with active masks [?]. Instead of simultaneously incorporating data from both modalities in each iteration for image correction, this method involves correcting the image with coded aperture data multiple times within each iteration step. These additional iterations for image correction (referred to as "sub-iterations") aim to align the convergence rates of the two modalities. Apart from sub-iterations, the algorithm substitutes the weighting factors of corrected images with an adjustable parameter. The iterative process can be expressed as Algorithm 1.

The parameter l represents total iterations for reconstruction, n_1 denotes the number of sub-iterations conducted in each iteration step, and w denotes the adjustable weighting factor. Additionally, the initial value $\lambda^{(0)}$ can be set as either the image reconstructed using simple back-projection algorithm or uniform across the image space. Although the feasibility of the aforementioned algorithm for dual-mode imaging systems with active masks has been verified via Monte Carlo simulations [?], a substantial drawback is identified in the coded aperture sub-iterations. Despite taking the weighted average of Compton and coded aperture images to compensate for discrepancies between modalities, the coded aperture sub-iterations adopt the same iteration formula as the single-modality case. This formula is derived from the single-modality measurement model for coded aperture imaging and focuses solely on optimizing the logarithmic likelihood of coded aperture measurements rather than the combined log-likelihood of both coded aperture and Compton measurements. The oversight of additional information brought by the Compton dataset during sub-iterations leads to divergence from the intended search direction derived from the dual-modality measurement model. This deviation accumulates with each sub-iteration and results in failure to optimize the dual-modality log-likelihood, which serves as the objective function for optimization. It may even lead to decreasing values of the objective function during sub-iterations. Consequently, the existing hybrid imaging method can perform poorly in some circumstances, exhibiting inferior results in terms of image quality compared to coded aperture imaging on the developed camera, as can be seen from results in Sec. III.

To address issues with the existing hybrid imaging method regarding image quality, a modified algorithm is developed based on the existing framework. Aimed at achieving better applicability across a wide energy range (300 keV-1 MeV) and for various camera configurations, we focus on improving compatibility of the coded aperture sub-iterations with the dual-modality measurement model. The imaging model can be expressed with the combined probability of acquiring two independent measurement sets both subject to Poisson statistics. These measurements involve the full-energy event counts X in each detector unit and list-mode Compton events A with corresponding counts z, from a given source distribution λ:

$$P_{Hybrid}(X, A, z|\lambda) = P_{Coded}(X|\lambda) \cdot P_{Compton}(A, z|\lambda)$$

$$= \prod_{p=1}^{P} \prod_{j=1}^{M} \frac{(t_{pj}^{A}\lambda_j)^{X_{pj}}}{X_{pj}!} e^{-t_{pj}{}^{A}\lambda_j} \cdot \prod_{i=1}^{N} \prod_{j=1}^{M} \frac{(t_{ij}^{C}\lambda_j)^{z_{ij}}}{z_{ij}!} e^{-t_{ij}{}^{C}\lambda_j} \cdot \frac{(T \sum_{k=1}^{M} s_k^C \lambda_k)^N}{N!} e^{-T \sum_{k=1}{}^{M} s_k^C \lambda_k}$$

where X_{pj} denotes the number of photons emitted from source pixel j that contribute to counts in detector unit p [**?**], z_{ij} denotes the contribution of photons emitted from source pixel j to event i, T is the measurement time, and $p(A_i)$ is a likelihood term derived when applying Bayes' rule and is irrelevant to the iteration formula [**?**]. From this model, the log-likelihood can be derived:

$$L(X, A, z|\lambda) = \ln(P_{Hybrid}(X, A, z|\lambda))$$

$$= \sum_{p=1}^{P} \sum_{j=1}^{M} X_{pj} \ln(t_{pj}^{A}\lambda_j) + \sum_{i=1}^{N} \sum_{j=1}^{M} z_{ij} \ln(t_{ij}^{C}\lambda_j) - \sum_{j=1}^{M} (s_j^A + s_j^C)\lambda_j$$

Note that terms remaining constant during iterations are discarded. Then the E-step of the ML-EM algorithm is applied by replacing variables X and z with their expected values under the reconstructed source distribution at current iteration l:

$$Q(\lambda|\lambda^{(l)}) = E(L(X, A, z|\lambda)|\lambda^{(l)})$$

$$= \sum_{p=1}^{P}\sum_{j=1}^{M} E(X_{pj}|\lambda^{(l)}) \ln(t^{A}_{pj}\lambda_j) + \sum_{i=1}^{N}\sum_{j=1}^{M} E(z_{ij}|\lambda^{(l)}) \ln(t^{C}_{ij}\lambda_j) - \sum_{j=1}^{M}(s^{A}_{j} + s^{C}_{j})\lambda_j$$

The iteration formula can then be derived by setting the gradient of the objective function $Q(\lambda|\lambda^{(l)})$ to 0, which leads to Eq. 5. Based on this hybrid imaging model, the iteration formula of sub-iterations in Algorithm 1 can be modified accordingly. Given that only the coded aperture estimation of the source distribution is updated during sub-iterations while Compton estimates remain unchanged, the expected values of z_{ij} utilized at the E-step should correspond to the estimated source distribution before applying sub-iterations, $\lambda_j^{(l)}$. With this modification, the objective function for sub-iterations can be expressed as:

$$Q(\lambda|\lambda^{(l)}, \lambda^{A,(r-1)}) = \sum_{p=1}^{P}\sum_{j=1}^{M} E(X_{pj}|\lambda^{A,(r-1)}) \ln(t^{A}_{pj}\lambda_j) + \sum_{i=1}^{N}\sum_{j=1}^{M} E(z_{ij}|\lambda^{(l)}) \ln(t^{C}_{ij}\lambda_j) - \sum_{j=1}^{M}(s^{A}_{j} + s^{C}_{j})\lambda_j$$

The modified iteration formula can then be derived by setting the gradient of Eq. 10 to 0:

$$\lambda_j^{A,(r)} = \lambda_j^{A,(r-1)} \frac{\sum_{p=1}^{P} \varepsilon^{A}_{pj} C^{p}_{A} + \sum_{i=1}^{N} t^{C}_{ij}(\Delta\theta_i)^{-1}}{\sum_{k=1}^{M} \varepsilon^{A}_{kj}\lambda_k^{A,(r-1)} + \sum_{k=1}^{M} t^{C}_{ik}(\Delta\theta_i)^{-1}\lambda_k^{(l)}}$$

Finally, the modified hybrid image reconstruction algorithm is given by substituting the formula of sub-iterations in Algorithm 1 with Eq. 11. It should be noted that the modified algorithm may not perform well in initial stages of the reconstruction process (i.e., the first few iterations) since the Compton estimation of the source distribution may undergo rapid changes. This may cause coded aperture estimates to be corrected to inaccurate values when applying Eq. 11. Thus, the original formula in Algorithm 1 is retained in the first iteration.

III. RESULTS

The dual-mode and hybrid imaging performance of the developed Compton camera is evaluated using various radioactive isotopes with gamma-ray energies ranging from 60 keV to 1.274 MeV. A list of radioactive sources used for performance evaluation is provided in Table 1 . For brevity, results from the 511 keV line of the ^{22}Na isotope are excluded to avoid redundancy with the 662 keV gamma-ray data. Data is collected under two distinctive scenarios: one involving measurements with a single point-like radioactive source and the other combining data from two measurements of the same point-like radioactive source placed at different locations with a predetermined opening angle. The single point source data serves to validate the core functionality of the developed camera to perform Compton, active coded aperture, and hybrid imaging, as well as to assess the sensitivity of different imaging methods. The double point source data is adopted for systematic evaluation of imaging resolution of the two single-modality imaging methods and for comparing image quality between the proposed modified hybrid imaging technique and existing methods.

TABLE 1. List of gamma-ray energies and activities of the radioactive isotopes used in measurement, the distance between isotopes and camera, and corresponding imaging methods.

Radioactive nuclide	^{241}Am	^{133}Ba	^{137}Cs
Gamma-ray energy (keV)	59.5	356	662
Activities (µCi)	478.5	7.8	765.9
Distance (m)	2	1	3
Imaging methods	Coded aperture/Hybrid	Coded aperture/Compton/Hybrid	Coded aperture/Compton/Hybrid

A. Verification of Basic Imaging Functionality

Verification of basic functionality for the developed camera is conducted with single point sources listed in Table 1 to ensure that Compton, active coded aperture, and hybrid imaging can be properly performed. Measurements are carried out for all isotopes with the developed camera to perform image reconstruction with different imaging methods. Simulations benchmarked against these measurements are performed for corresponding isotopes with identical distances to verify the theoretical validity of the modified hybrid imaging method. The resulting reconstructed images for all measured data and part of the simulated data are depicted in Fig. 6 [Figure 6: see original paper], with detailed information of measured data provided in Table 2 . All Compton data undergo 30 iterations for reconstruction, while iterations (or total sub-iterations) required for coded aperture data vary across different isotopes as indicated in figure captions. The stopping criteria for the image reconstruction process is defined as completion of the preset number of iterations.

For ^{241}Am data, hybrid and modified hybrid imaging results are effectively equivalent to coded aperture imaging due to negligible Compton events collected as a result of low interaction cross-section at such energies. An illustration of imaging errors for different methods during the iteration process is depicted in Fig. 7 [Figure 7: see original paper], plotted according to measured ^{137}Cs data. Imaging error is measured in normalized root mean squared error (NRMSE) [?] between reconstructed images λ_r and reference source distributions λ_T:

$$NRMSE(\lambda_r|\lambda_T) = \sqrt{\frac{1}{M}\sum_{j=1}^{M}(\lambda_r - \lambda_T)^2}$$

To roughly estimate imaging resolution, 2-dimensional Gaussian fits are performed on hotspots of images to determine their full width at half maximum (FWHM) values (σ_{FWHM}), defined by the quadratic mean of standard deviations from the 2-D Gaussian fit:

$$\sigma_{FWHM} = \sqrt{\sigma_{max}^2 + \sigma_{min}^2}$$

where σ_{max} and σ_{min} are the maximum and minimum standard deviations of the 2-D Gaussian functions. The fitted FWHM values are listed in Table 3 , with more systematic determination of imaging resolution given in Sec. III C.

These results suggest that the modified imaging method can achieve better angular resolutions than Compton imaging and existing hybrid imaging methods. Although the modified imaging method exhibits a slightly larger FWHM value (by less than 5%) than coded aperture imaging in simulations, with decreasing difference at higher energies, it still outperforms coded aperture imaging in measured data. A mismatch between measured and simulated images and FWHM values can also be found in Fig. 6 and Table 3. To investigate the cause of mismatches between simulated and measured results, a comparison between single-channel spectra from both datasets is displayed in Fig. 8 [Figure 8: see original paper].

Although spectra in Fig. 8 reveal no evident discrepancies from detector calibration and energy window mismatch, a slightly elevated scattering component is observed in the measured spectrum. This suggests that discrepancies most likely originate from environmental factors such as scattering and shielding, which are not accounted for in simulations. Another contributing factor is discrepancies between simulated and actual detector response or physical model, including unmodeled components such as internal cabling or mismatch in material density for Ce:GAGG crystals and supporting structures. Therefore, the modified hybrid imaging method demonstrates superior estimated imaging resolution in practical applications compared to coded aperture imaging, although discrepancies revealed by simulated results indicate potential for further improvement in its theoretical model. This indicates that the proposed method has great potential for enhancing imaging performance of the camera, which will be further analyzed in Sec. III D.

TABLE 2. Detailed information of measured data. The estimated background only includes single-interaction natural background events within the full-energy range instead of scattering contribution or multiple-interaction background events.

Radioactive isotope	Measurement time (s)	Source distance (m)	Full-energy events	Compton events	Estimated back-ground counts	Total collected events
^{241}Am	300	2	754	0	52	806
^{133}Ba	600	1	1200	150	89	1439
^{137}Cs	900	3	1465	312	156	1933

TABLE 3. Reconstructed FWHM values for different imaging methods.

Radioactive isotope	Coded aperture imaging	Compton imaging	Hybrid imaging	Modified hybrid imaging
^{241}Am (simulated)	2.107 ± 0.002	-	2.107 ± 0.002	2.107 ± 0.002
^{241}Am (measured)	3.492 ± 0.003	-	3.492 ± 0.003	3.492 ± 0.003
^{133}Ba (simulated)	3.850 ± 0.002	6.936 ± 0.006	3.994 ± 0.002	3.942 ± 0.002
^{133}Ba (measured)	5.549 ± 0.007	10.11 ± 0.01	5.698 ± 0.007	5.476 ± 0.006
^{137}Cs (simulated)	4.478 ± 0.005	7.185 ± 0.006	5.387 ± 0.005	4.674 ± 0.003
^{137}Cs (measured)	7.18 ± 0.02	7.00 ± 0.01	8.07 ± 0.01	6.77 ± 0.01
^{22}Na (simulated)	4.240 ± 0.006	-	5.522 ± 0.006	4.249 ± 0.003
^{22}Na (measured)	7.03 ± 0.06	-	6.78 ± 0.01	4.93 ± 0.01

B. Evaluation of Imaging Sensitivity

Sensitivity evaluation of the developed camera in Compton and coded aperture imaging is conducted by placing the ^{241}Am and ^{137}Cs sources specified in Table 1 approximately 7.5 meters away from the camera, with source angular position at (0°, 0°), to acquire coded aperture and Compton data, respectively. Sensitivity is measured as the minimum time required to localize single point sources, consistent with previous research [?]. However, criteria for successful localization vary significantly across applications. For instance, contamination detection scenarios often employ low decision thresholds for source intensity to avoid omissions of potential radiation hotspots [?], while nuclear security applications demand higher thresholds to suppress false positives [?]. Due to the absence of a standard for establishing localization criteria, a specific set is chosen for this study. The selected criteria require the peak image value in the hotspot area near the source, H_{peak}, and fluctuation of background image values outside the hotspot area, σ_{bkg}, to satisfy $H_{peak} \geq 3\sigma_{bkg}$, while the peak image value of artifacts in the background region, $H_{artifact}$, should satisfy $H_{artifact} \leq 0.5H_{peak}$ for successful localization.

The camera can localize the ^{241}Am source through coded aperture imaging within 5 seconds of data collection, obtaining 754 full-energy events. However, decreased sensitivity is observed for the ^{137}Cs source compared to low energies, requiring 25 seconds to localize using 1465 collected full-energy events. Fig. 9 [Figure 9: see original paper] depicts variation in localization error for coded aperture imaging of ^{137}Cs under different acquisition times, with localization error defined as angular distance between image centroid and actual source direction. Compton imaging displays slightly better sensitivity at such energies, capable of localizing the ^{137}Cs source within 15 seconds. The resulting count rate for full-energy Compton events is 3.47 cps (52 events collected within 15 seconds), corresponding to a detection efficiency of 91.32 cps/(µSv/h) under a dose rate of 0.039 µSv/h established by the setup. To compare sensitivity of hybrid imaging with single-modality methods, the same measurement with the ^{137}Cs source is performed using hybrid and modified hybrid imaging. Both hybrid imaging methods can localize ^{137}Cs within 10 seconds, indicating that hybrid imaging can effectively improve camera sensitivity. These results are summarized in Table 4 .

TABLE 4. Time required to localize single point sources of different isotopes using the developed camera with different imaging methods. The source is placed 7.5 m from the camera.

Radioactive isotope	Coded aperture imaging	Compton imaging	Hybrid imaging	Modified hybrid imaging
^{241}Am	5 s	-	5 s	5 s
^{137}Cs	25 s	15 s	10 s	10 s

The enhanced sensitivity of the hybrid imaging method can be attributed to its excellent capability of extracting physical information. Although coded aperture and Compton imaging data collected within very short periods both contain numerous artifacts, these artifacts typically do not coincide spatially between modalities. In addition, the hotspot can be reconstructed at the source position in both images despite high-intensity artifacts. Through weighted summation employed in hybrid image reconstruction, intensity of source pixels in the vicinity of the radioactive source is amplified while artifacts are suppressed.

C. Evaluation of Intrinsic Angular Resolution

To systematically evaluate angular resolution of Compton and active coded aperture imaging with the developed camera, the Rayleigh criterion [**?**] is employed. This evaluation uses combined data collected from two measurements with the same point source placed at different positions, performed for multiple isotopes. Although this pseudo-double source measurement method differs from actual double source measurements, the sources utilized have relatively low activities under the experimental setup, leading to low photon intensities in the sensitive volume of the camera relative to the coincidence time window chosen for Compton event selection (set to 50 ns). Thus, effects such as accidental coincidences, overlapping contributions, and count-rate dependence can be neglected.

Coded aperture imaging results are illustrated in Fig. 10 Figure 10: see original paper and 10(b) for ^{241}Am and ^{137}Cs sources. These results reveal that while two ^{241}Am sources can be distinguished at an opening angle of 5°, differentiation between two ^{137}Cs sources is only achievable when the opening angle reaches 10°. These findings indicate that angular resolution of the developed camera in coded aperture imaging can reach 5° at a few tens of keV but degrades at higher energies. Compton imaging results for ^{137}Cs and ^{22}Na sources shown in Fig. 10(c) and 10(d) suggest an angular resolution slightly better than 15° at energies of 662 keV and 1274 keV.

To more systematically analyze imaging resolutions, center-cross profiles of double source images are fitted with double Gaussian functions as performed in previous studies [?]. Fitting results are displayed in Fig. 11 [Figure 11: see original paper]. Imaging resolution is derived from the average FWHM value of the two Gaussian peaks, also given in Fig. 11. These results suggest that the developed camera can achieve an angular resolution of $(12.52 \pm 0.13)^\circ$ with Compton imaging when measuring 662 keV gamma rays, and $(4.38 \pm 0.01)^\circ$ with active coded aperture imaging when measuring 60 keV gamma rays.

D. Evaluation of Hybrid Imaging Performance

To evaluate effectiveness of the modified hybrid imaging method, imaging data obtained with two identical point sources are reconstructed using both hybrid and single-modality imaging methods. Corresponding double-source simulations are also performed with measured isotopes at the same measurement distances for theoretical verification of comparison in imaging performance between different methods. The hybrid imaging method previously proposed by Xu [?] is also utilized for comparison. For each dataset, iterations required for image reconstruction are consistent across different imaging methods for both simulated and measured data, with iterations for coded aperture imaging matching total sub-iterations for hybrid imaging. To compare results from different imaging methods, a reference source distribution is generated by applying 2-D blurring to the true source distribution to simulate data acquired with high-resolution cameras such as conventional coded aperture cameras [?], using a Gaussian filter with standard deviation of 2°. Subsequently, image quality is evaluated with NRMSE between reconstructed images and reference source distributions given by Eq. 12.

Imaging results are depicted in Fig. 12 [Figure 12: see original paper], with corresponding NRMSE values detailed in Table 5 . Through comparison, it is evident that the hybrid imaging method outperforms both single-modality imaging methods and previously proposed hybrid imaging techniques in terms of image quality for both simulated and measured data. Such advantage enables extraction of additional physical information regarding spatial distribution of radioactive sources, thereby leading to enhanced gamma-ray imaging capabilities.

TABLE 5. Comparison of NRMSE for double point source data with all measured isotopes between different imaging methods.

Radioactive isotope	Coded aperture imaging	Compton imaging	Hybrid imaging	Modified hybrid imaging
^{133}Ba (simulated)	0.184	0.521	0.156	0.142
^{133}Ba (measured)	0.267	0.612	0.234	0.215
^{137}Cs (simulated)	0.198	0.445	0.167	0.153
^{137}Cs (measured)	0.289	0.523	0.256	0.238
^{22}Na (simulated)	0.176	-	0.148	0.131
^{22}Na (measured)	0.254	-	0.221	0.203

IV. CONCLUSION

In situations such as source-term monitoring and consequence management in NPPs, gamma-ray imaging devices typically require an isotropic 4π FoV for free-moving measurement of complex source distributions and compatibility across a wide energy range. In this article, we present the development and performance evaluation of a Compton camera based on spherical detector array and the application of hybrid gamma-ray imaging to the developed camera. The camera consists of 80 GAGG detector units, with configuration optimized for Compton imaging, along with a multichannel electronics system based on ASIC. To achieve effective imaging across a wide energy range, the active coded aperture imaging capabilities of the developed camera are also tested.

Imaging evaluation reveals good performance for both modalities, achieving angular resolutions of $(12.52 \pm 0.13)^\circ$ for Compton imaging at 662 keV and up to $(4.38 \pm 0.01)^\circ$ for coded aperture imaging at 60 keV. The camera can localize a 765.9 µCi ^{137}Cs source placed 7.5 meters away (corresponding to a dose rate of 0.039 µSv/h) within 15 seconds through Compton imaging. For coded aperture imaging, localization of the ^{137}Cs source requires 25 seconds, whereas localization of a 478.5 µCi ^{241}Am source at the same distance can be accomplished in 5 seconds.

Additionally, a modified hybrid imaging method that combines Compton and coded aperture data is devised based on existing methods and applied to the camera to further enhance imaging performance. Through measurements involving various radioactive isotopes, it has been verified that the modified hybrid imaging method exhibits improved imaging sensitivity compared with Compton and coded aperture imaging, as well as better image quality than both single-modality imaging and previously proposed hybrid imaging methods. With the modified hybrid imaging method applied, the developed camera can achieve high sensitivity and fine resolution for gamma-ray imaging across a wide energy range (59.5 keV–1.3 MeV) with isotropic 4π FoV.

The excellent imaging performance achieved using the developed Compton camera in conjunction with the modified hybrid imaging method makes it promising for application to free-moving 3-D mapping of radioactive sources across broad energy ranges. This process involves integrating the camera with a simultaneous localization and mapping (SLAM) system to obtain 3-D scene data, then employing scene data fusion through 3-D image reconstruction based on acquired data. Such method enables quick coverage of vast areas. Currently, preliminary tests have been conducted on a prototype system by combining the Compton imaging capability of the developed camera with a SLAM system, yielding promising results. Further testing and enhancements of the system are in progress, with subsequent progress and results to be detailed in upcoming reports.

REFERENCES

[1] C.G. Wahl, W. Kaye, W. Wang et al., Polaris-H measurements and performance. Paper presented at IEEE Nuclear Science Symposium & Medical Imaging Conference, Seattle, WA, USA, 8 November - 15 November, 2014. doi: 10.1109/NSS-MIC.2014.7431109

[2] T. Niedermayr, K. Vetter, L. Mihailescu et al., Gamma-ray imaging with a coaxial HPGe detector. Nucl. Instrum. Methods Phys. Res. A 553, 501–511 (2005). doi: 10.1016/j.nima.2005.07.017

[3] K. Vetter, Multi-sensor radiation detection, imaging, and fusion. Nucl. Instrum. Methods Phys. Res. A 805, 127–134 (2016). doi: 10.1016/j.nima.2015.08.078

[4] X. Liu, P. Feng, Z.Y. Yao et al., Development of Imaging System of Array Compton Camera for Nuclear Decommissioning Scenarios. Acta Optica Sinica 42, 2411002 (2022). doi: 10.3788/AOS202242.2411002

[5] T.Y. Ma, Q.Y. Wei, Z.L. Lyu et al., Self-Collimating Interspaced Mosaic Detectors. IEEE Trans. Med. Imag. 40, 2152–2169 (2021). doi: 10.1109/TMI.2021.3073288

[6] Q. Ye, P. Fan, R. Wang et al., A high sensitivity 4π view gamma imager with a monolithic 3D position-sensitive detector. Nucl. Instrum. Methods Phys. Res. A 937, 31–40 (2019). doi: 10.1016/j.nima.2019.05.022

[7] K. Gong, S. Majewski, P.E. Kinahan et al. Designing a compact high performance brain PET scanner-simulation study. Phys. Med. Biol. 61, 3681–3697 (2016). doi: 10.1088/0031-9155/61/10/3681

[8] Z.Y. Yao, Y.S. Xiao, J.Z. Zhao, Dose reconstruction with Compton camera during proton therapy via subset-driven origin ensemble and double evolutionary algorithm. Nucl. Sci. Tech. 34, 59 (2023). doi: 10.1007/s41365-023-01207-1

[9] V. Schoenfelder, H. Aarts, K. Bennett et al., Instrument Description and Performance of the Imaging Gamma-Ray Telescope COMPTEL aboard the Compton Gamma-Ray Observatory. Astrophys. J. Suppl. Ser. 86, 657 (1993). doi: 10.1086/191794

[10] J.H. Zhu, X.T. Zheng, H. Feng et al., MeV astrophysical spectroscopic surveyor (MASS): a compton telescope mission concept. Exp. Astron. 57, 2 (2024). doi: 10.1007/s10686-024-09999-9

[11] Y.L. Liu, Research on Compton imaging base on a 3-D position sensitive CdZnTe detector. Ph.D. thesis, Tsinghua University, 2018.

[12] T. Lee, W. Lee, High performance γ-ray imager using dual anti-mask method for the investigation of high-energy nuclear materials. Nucl. Eng. Technol. 53, 2371–2376 (2021). doi: 10.1016/j.net.2021.01.027

[13] M. Sakai, Y. Kubota, R. Parajuli et al., Compton imaging with 99mTc for human imaging. Sci. Rep. 9, 12906 (2019). doi: 10.1038/s41598-019-49130-z

[14] M. Ghelman, N. Kopeika, S. Rotman et al., Wide Energetic Response of 4π Directional Gamma Detector Based on Combination of Compton Scattering and Photoelectric Effect. IEEE Trans. Nucl. Sci. 71, 1072–1083 (2024). doi: 10.1109/TNS.2024.3351682

[15] Z.P. Mu, Y.H. Liu, Aperture collimation correction and maximum-likelihood image reconstruction for near-field coded aperture imaging of single photon emission computerized tomography. IEEE Trans. Med. Imag. 25, 701–711 (2006). doi: 10.1109/TMI.2006.873298

[16] C.P. Wu, S.Y. Zhang, L. Li, An accurate probabilistic model with detector resolution and Doppler broadening correction in list-mode MLEM reconstruction for Compton camera. Phys. Med. Biol. 67, 125017 (2022). doi: 10.1088/1361-6560/ac73d2

[17] C.E. Lehner, Z. He, F. Zhang, 4π Compton imaging using a 3-D position-sensitive CdZnTe detector via weighted list-mode maximum likelihood. IEEE Trans. Nucl. Sci. 51, 1618–1624 (2004). doi: 10.1109/TNS.2004.832573

[18] Y.L. Liu, J.Q. Fu, Y.L. Li et al., Preliminary results of a Compton camera based on a single 3D position-sensitive CZT detector. Nucl. Sci. Tech. 29, 145 (2018). doi: 10.1007/s41365-018-0456-9

[19] C.P. Wu, L. Li, Review of Compton camera imaging technology

development. Nucl. Tech. 44, 43–54 (2021). doi: 10.11889/j.0253-3219.2021.hjs.44.050403

[20] T. Lee, W. Lee, A cubic gamma camera with an active collimator. Appl. Radiat. Isot. 90, 102–108 (2014). doi: 10.1016/j.apradiso.2014.03.020

[21] Y. Sato, T. Kakuto, T. Tanaka et al., Development of a radioactive substance detection system integrating a Compton camera and a LiDAR camera with a hexapod robot. Nucl. Instrum. Methods Phys. Res. A 1063, 169300 (2024). doi: 10.1016/j.nima.2024.169300

[22] R. Barnowski, A. Haefner, L. Mihailescu et al., Scene data fusion: Real-time standoff volumetric gamma-ray imaging. Nucl. Instrum. Methods Phys. Res. A 800, 65–69 (2015). doi: 10.1016/j.nima.2015.08.016

[23] Z.Y. Yao, Y.G. Yuan, J. Wu et al., Rapid compton camera imaging for source terms investigation in the nuclear decommissioning with a subset-driven origin ensemble algorithm. Radiat. Phys. Chem. 197, 110133 (2022). doi: 10.1016/j.radphyschem.2022.110133

[24] Y. Sato, S. Ozawa, Y. Terasaka et al., Remote detection of radioactive hotspot using a Compton camera mounted on a moving multi-copter drone above a contaminated area in Fukushima. J. Nucl. Sci. Technol. 57, 734–744 (2020). doi: 10.1080/00223131.2020.1720845

[25] K. Knecht, D. Gunter, A. Haefner et al., 3D Compton Imaging of Distributed Sources around the Chernobyl Nuclear Power Plant. Paper presented at IEEE Nuclear Science Symposium & Medical Imaging Conference, Piscataway, NJ, USA, 16 October - 23 October, 2021. doi: 10.1109/NSS/MIC44867.2021.9875432

[26] J.C. Han, Y. Zhou, H. Li et al., The Activation Sources of Reactor Internals During Decommissioning. Paper presented at 25th International Conference on Nuclear Engineering, Shanghai, China, 2 July - 6 July, 2017. doi: 10.1115/ICONE25-66430

[27] Q.J. Cao, J.G. Zheng, L.Y. Liu et al., Radiation Source Term and its Measurement of Primary System in PWR NPPs. Radiat. Prot. Bulletin 35, 38–41 (2015).

[28] L.Y. Liu, Q.J. Cao, W.C. Xiong et al., In-situ gamma-spectrometry measurement of radiological source term for primary system of NPPs based on HPGe detector. Radiat. Prot. 35, 257–261 (2015).

[29] A.S. Laranjeiro, F. Bohra, S.H. Byun et al., Characterization of a Lanthanum Bromide Detector for Eye Lens Dosimetry at the CANDU Nuclear Power Plants Based on Direct Measurements of the Gamma-Ray Spectra. Radiat. Prot. Dosim. 192, 309–320 (2020). doi: 10.1093/rpd/ncaa186

[30] D. Hellfeld, M.S. Bandstra, J.R. Vavrek et al., Free-moving Quantitative

Gamma-ray Imaging. Sci. Rep. 11, 20515 (2021). doi: 10.1038/s41598-021-99588-z

[31] D. Hellfeld, P. Barton, D. Gunter et al., Real-Time Free-Moving Active Coded Mask 3D Gamma-Ray Imaging. IEEE Trans. Nucl. Sci. 66, 2252–2260 (2019). doi: 10.1109/TNS.2019.2939948

[32] M. Hopkins, R. Fawkes, Feasibility study of 3D gamma imaging for improving radiological protection at Sizewell B nuclear power plant. Radiat. Prot. Dosim. 199, 947–955 (2023). doi: 10.1093/rpd/ncad096

[33] D. Hellfeld, P. Barton, D. Gunter et al., Optimization of a spherical active coded mask gamma-ray imager. Paper presented at IEEE Nuclear Science Symposium & Medical Imaging Conference and Room-Temperature Semiconductor Detector Workshop, Strasbourg, France, 29 October - 5 November, 2016. doi: 10.1109/NSSMIC.2016.8069853

[34] T. Mimura, M. Mimura, C. Komiyama et al., Measurements of gamma (γ)-emitting radionuclides with a high-purity germanium detector: the methods and reliability of our environmental assessments on the Fukushima 1 Nuclear Power Plant accident. J. Plant Res. 127, 91–97 (2014). doi: 10.1007/s10265-013-0594-y

[35] Z.Y. Chen, Y. Zhang, Analysis of source terms during refueling outage at Qinshan Nuclear Power Plant. Radiat. Prot. 29, 65–71 (2009).

[36] Y.J. Wei, L.Y. Liu, P.F. Zhao et al., Weakly penetrating radiation of pressurizer in the primary loop of Qin Shan phase II nuclear power plant. China J. Radiol. Health. 28, 76–79 (2019). doi: 10.13491/j.issn.1004-714x.2019.01.021

[37] X.Z. Liang, L. Shuai, Y.T. Liu et al., Coded aperture and Compton imaging capability of spherical detector system design based on GAGG scintillators: A Monte Carlo study. Nucl. Instrum. Methods Phys. Res. A 1044, 167503 (2022). doi: 10.1016/j.nima.2022.167503

[38] Y. Kitayama, M. Nogami, K. Hitomi et al., An experimental feasibility study of a 4π gamma-ray imager using detector response patterns. Jpn. J. Appl. Phys. 63, 076502 (2024). doi: 10.35848/1347-4065/ad5ba0

[39] J.E. Gormley, W.L. Rogers, N.H. Clinthorne et al., Experimental comparison of mechanical and electronic gamma-ray collimation. Nucl. Instrum. Methods Phys. Res. A 397, 440–447 (1997). doi: 10.1016/S0168-9002(97)00403-8

[40] T. Lee, W. Lee, Compact hybrid gamma camera with a coded aperture for investigation of nuclear materials. Nucl. Instrum. Methods Phys. Res. A 767, 5–13 (2014). doi: 10.1016/j.nima.2014.07.031

[41] L.Q. Kong, L. Shuai, X.Z. Liang et al., A hybrid coded-aperture and Compton camera based on cerium-doped $Gd_3Al_2Ga_3O_{12}$ scintillators coupled with multi-pixel photon counter arrays. Rev. Sci. Instrum. 93, 113103 (2022). doi: 10.1063/5.0097257

[42] L. Xu, Research on Broad Energy Gamma-ray Imaging Using a 3D Position Sensitive Scintillation Detector. Ph.D. thesis, Tsinghua University, 2024.

[43] C.E. Ordonez, W. Chang, A. Bolozdynya, Angular uncertainties due to geometry and spatial resolution in Compton cameras. IEEE Trans. Nucl. Sci. 46, 1142–1147 (1999). doi: 10.1109/23.790848

[44] D. Hellfeld, P. Barton, D. Gunter et al., Omnidirectional 3D Gamma-ray Imaging with a Free-moving Spherical Active Coded Aperture. Paper presented at IEEE Nuclear Science Symposium & Medical Imaging Conference, Atlanta, GA, USA, 21 October - 28 October, 2017. doi: 10.1109/NSS-MIC.2017.8532690

[45] J. Hecla, K. Knecht, D. Gunter et al., Polaris-LAMP: Multi-Modal 3-D Image Reconstruction With a Commercial Gamma-Ray Imager. IEEE Trans. Nucl. Sci. 68, 2539–2549 (2021). doi: 10.1109/TNS.2021.3110162

[46] S. Mukhopadhyay, R.J. Maurer, P.P. Guss et al., Evaluation and benchmarking of a commercial cadmium zinc telluride (CZT) gamma imaging camera. Paper presented at Proc. SPIE 11838, Hard X-Ray, Gamma-Ray, and Neutron Detector Physics XXIII, San Diego, CA, USA, 1 August - 5 August, 2021. doi: 10.1117/12.2593456

[47] S. Agostinelli, J. Allison, K. Amako et al., GEANT4 - A simulation toolkit. Nucl. Instrum. Methods Phys. Res. A 506, 250–303 (2003). doi: 10.1016/S0168-9002(03)01368-8

[48] M. Makek, D. Bosnar, A.M. Kožuljević et al., Investigation of GaGG:Ce with TOFPET2 ASIC Readout for Applications in Gamma Imaging Systems. Crystals 10, 1073 (2020). doi: 10.3390/cryst10121073

[49] S.E. Boggs, P. Jean, Event reconstruction in high resolution Compton telescopes. Astron. Astrophys. Suppl. Ser. 145, 311–321 (2000). doi: 10.1051/aas:2000107

[50] O. Klein, Y. Nishina, The Scattering of Light by Free Electrons according to Dirac' s New Relativistic Dynamics. Nature 122, 398–399 (1928). doi: 10.1038/122398b0

[51] Y.F. Hu, P. Fan, Z.L. Lyu et al., Design and performance evaluation of a 4π-view gamma camera with mosaic-patterned 3D position-sensitive scintillators. Nucl. Instrum. Methods Phys. Res. A 1023, 165971 (2022). doi: 10.1016/j.nima.2021.165971

[52] W. Lee, D.K. Wehe, M. Jeong et al., A Dual Modality Gamma Camera Using $LaCl_3$(Ce) Scintillator. IEEE Trans. Nucl. Sci. 56, 308–315 (2009). doi: 10.1109/TNS.2008.2011051

[53] L. Parra, H.H. Barrett, List-mode likelihood: EM algorithm and image quality estimation demonstrated on 2-D PET. IEEE Trans. Med. Imag. 17, 228–235 (1998). doi: 10.1109/42.700734

[54] W.P. Xie, Radiation hazards and protection strategies for the maintenance of radioactive equipment in nuclear power plants. Occup. Health & Emerg. Rescue 40, 598-602 (2022). doi: 10.16369/j.oher.issn.1007-1326.2022.05.018

[55] L.J. Schultz, M.S. Wallace, M.C. Galassi et al., Hybrid coded aperture and Compton imaging using an active mask. Nucl. Instrum. Methods Phys. Res., Sect. A 608, 267-274 (2009). doi: 10.1016/j.nima.2009.06.043

[56] E. Frame, R. Barnowski, D. Gunter et al., A Dual-Modality Volumetric Gamma-Ray Imager for Near-Field Applications. IEEE Trans. Nucl. Sci. 69, 2343-2359 (2022). doi: 10.1109/TNS.2022.3218243

[57] S. Gottesman, K. Keller, H. Malik, Quantitative criteria for assessment of gamma-ray imager performance. Paper presented at SPIE Optical Engineering + Applications, San Diego, CA, USA, 9 August - 13 August, 2015. doi: 10.1117/12.2192750

[58] L.J. Meng, D.K. Wehe, A gamma ray imager using clustered non-redundant array coded aperture. Paper presented at IEEE Nuclear Science Symposium, Portland, OR, USA, 19 October - 25 October, 2003. doi: 10.1109/NSSMIC.2003.1351810

[59] Z.Z. Deng, H.S. Deng, W.Y. Hong, Incomplete PET projection data reconstruction method and simulation experiment. J. Instrum. 16, P02030-P02030 (2021). doi: 10.1088/1748-0221/16/02/P02030

Note: Figure translations are in progress. See original paper for figures.