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SPECTRUM ISOLATION IN MULTI-SOURCE IMAGE RECONSTRUCTION USING A DUAL-PARTICLE IMAGER

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ABSTRACT

A dual-particle imager (DPI) has been developed at the University of Michigan that is capable of detecting photons and neutrons. It is possible for the DPI to reasonably estimate the spatial distribution and photon and neutron energy spectra of present radioactive sources by using the principles of Compton scattering and neutron elastic scattering. However, basic reconstruction methods, such as simple backprojection, typically yield noisy images and only report the aggregate neutron and photon energy spectra over the entire field of view. When multiple sources are present, it is desirable to determine the energy spectra for several regions of interest within the field of view such that each "hot spot" on the image can be associated with a specific photon and neutron energy spectrum. A maximum-likelihood expectation-maximization (MLEM) approach was used to reconstruct the spatial distribution and simultaneously unfold the energy spectra for each spatial pixel. The system matrix utilized by the MLEM algorithm was computed using the Monte Carlo transport code MCNPX-PoliMi. The response of the DPI to an emitted neutron spectrum (ranging from 0-10 MeV) and an emitted photon spectrum (ranging from 0-5 MeV) was simulated at 5° increments over a 2π field of view. The simulated responses were used to construct a bin-mode system matrix that accounted for energy in both observation and source dimensions. This paper describes how this method can be used to isolate the energy spectra for each individual source in a multi-source field. Image reconstruction and spectrum isolation results will be shown for a multi-source measurement of ^{252}Cf and ^{60}Co.

1. INTRODUCTION

The ability to locate and characterize radioactive materials of interest is applicable in fields such as nuclear safeguards, nonproliferation, and treaty verification. The dual-particle imaging system (DPI) being developed at the University of Michigan is capable of imaging and providing energy information for both photons and neutrons [1]. The DPI utilizes the principles of Compton scattering and neutron elastic scattering and is comprised of EJ-309 liquid scintillators (to induce photon and neutron scattering) and NaI inorganic scintillators (to induce photoelectric absorption). The DPI has demonstrated the ability to correctly locate special nuclear material (SNM) as well as differentiate spontaneous fission from (α,n) sources [2].

Previous work involving the DPI has primarily focused on the use of simple backprojection (SBP) image reconstruction techniques and aggregate energy spectrum reconstruction for the full field of view. In this work, a maximum-likelihood expectation-maximization (MLEM) technique is explored to simultaneously deconvolve spatial and energy information. This technique uses pre-computed photon and neutron system response matrices along with bin-mode MLEM [3]. A similar technique has been demonstrated using list-mode MLEM for gamma-ray imaging and source identification [4].

The use of this MLEM technique enables the DPI to accurately estimate photon and neutron energy spectrum for each source in a multi-source field of view (FOV). The ability to isolate the energy spectra facilitates further analysis of each located source. Such capabilities are relevant to applications in which several unique sources may be present, such as hold-up measurements, cargo screening, and warhead verification.

2. METHODS

2.1 Reconstruction Techniques

Previous work involving the DPI has focused on the use of SBP image reconstruction. This technique typically yields a noisy image and can suffer from poor signal-to-noise ratio (SNR). Because SBP requires knowledge of the incident particle energy, it is also possible to reconstruct the photon and neutron energy spectra for the measured FOV. However, due to the nature of SBP image reconstruction, it is not possible to accurately isolate the energy spectra for particular regions of interest on the image. Additionally, the reconstructed energy spectra will be degraded due to convolution with the detector response.

MLEM can be used to simultaneously reconstruct the spatial and energy distributions of a measured field of radioactive sources. By performing these reconstructions simultaneously, it is possible to accurately estimate the energy spectra at every spatial pixel within the FOV. The MLEM reconstruction technique also has the benefit of deconvolving the detector response from the measured spectra.

MLEM is an iterative, statistical inverse method that uses a system response matrix, A, to estimate the true spatial and energy distributions, x, that yielded that measured data, n. The system response matrix is an $S \times D$ matrix where each element, $a_{d,s}$, contains the probability that a particle emitted from source bin, s, will be observed in detection bin, d. It follows that x is $S \times 1$ and n is $D \times 1$.The exact binning structure of the system response matrix is not fixed and can be chosen as necessary to solve a particular problem.

In general, an observation bin may correspond to any quantity measured by the DPI, such as detector pair (interaction location), incident energy, or incident angle. These bins can also be nested within one another. For example, bins $a_{d,s}$ through $a_{d+10,s}$ might contain 10 energy bins for a specific detector pair while bins $a_{d+11,1s}$ through $a_{d+20,s}$ contain 10 identical energy bins for another detector pair.

A source bin corresponds to a source specific parameter, such as energy or location. In pure image reconstruction, each s represents a source location within the field of view. However, for the spectrum isolation technique, each s represents an emitted energy bin for a specific spatial bin. In this way, it is possible to view an estimation of the emitted spectrum at a specific pixel (or region of pixels). Additionally, an image can be reconstructed by collapsing the energy bins at each pixel. Similarly, an image can be created for a specific energy range by summing only the appropriate energy bins at each pixel.

The computation performed at each iteration of the MLEM algorithm is shown in Eq. (1):

$$\hat{x}_s^{(k+1)} = \hat{x}_s^{(k)} \left\{ \frac{1}{\sum_{d=1}^{D} a_{d,s}} \sum_{d=1}^{D} \left\{ \frac{n_d}{\sum_{s'=1}^{S} a_{d,s'} \hat{x}_{s'}^{(k)}} a_{d,s} \right\} \right\}, s = 1, \dots, S, \quad (1)$$

where $\hat{x}$ is the estimate of the true distribution after k iterations.

2.2 System Response Matrix Computation

The system response matrix is computed by simulating the response from a source distribution at specific locations around the system. The simulations are run using the Monte Carlo transport code MCNPX-PoliMi [5]. The system response matrix used in this study was created using 5° spatial bins in both the polar and azimuthal directions. The polar angle bins ranged from 5° to 175° while the azimuthal angle bins ranged from 0° to 180°; these bins result in 1,295 unique source locations that comprise a 2π hemisphere in front of the DPI. A 5-meter standoff from the system center was used for each location. Neutrons and photons were simulated independently at each source location. For neutrons, the source was distributed between 0 and 10 MeV. For photons, the source was distributed between 0 and 5 MeV. For both particles, the energy distributions were distributed continuously, which allows for the energy bin sizes along the source dimension to be tailored to particular applications.

The neutron system response matrix used in this study was created using 500 keV energy bins (ranging between 0 and 10 MeV) along the source dimension. The detection dimension was binned using 256 detector pairs, 500 keV energy bins (ranging between 0 and 15 MeV), and 10° incident angle bins (ranging between 0 and 90°). This binning structure results in a 69,120×25,900 system response matrix for neutrons. It should be noted that the energy range in the detection dimension extends higher than the energy range in the source dimension to account for uncertainties in the detected energy; a similar method is used for photons.

The photon system response matrix was created using 100 keV energy bins (ranging between 0 and 5 MeV) along the source dimension. The detection dimension was binned using 192 detector pairs, 100 keV energy bins (ranging between 0 and 6 MeV), and 10° incident angle bins (ranging between 0 and 180°). This binning structure results in a 207,360×64,750 system response matrix for photons.

2.3 Data Acquisition

The DPI was used to simultaneously measure a 3.3×10^4 fissions-per-second ^{252}Cf source and a 63 μCi ^{60}Co source. The measurement set up is shown in Fig. 1. The ^{252}Cf source was located 175 cm away at (114°, 93°) and the ^{60}Co source was located 390 cm away at (58°, 84°). For reference, the system is aligned such that a source located directly in front of the DPI would be identified at (90°, 90°). The measurement was carried out for 350 minutes and a total of 1.15×10^4 neutrons and 1.44×10^6 photons were detected by the system.

All waveforms were collected using 12-bit, 250-MHz CAEN V1720 digitizers. A 20-keVee threshold was applied to all channels and the charge-integration, pulse-shape-discrimination technique was used to distinguish between photons and neutrons in the liquid scintillators.

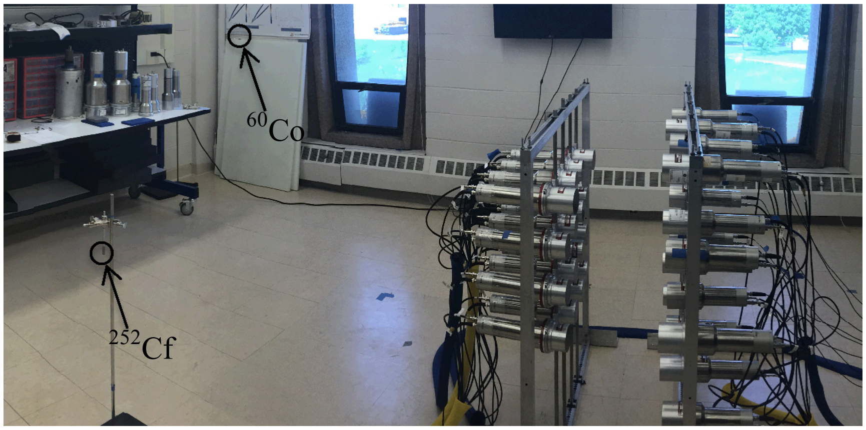

Fig. 1. Photograph of the experimental set up. The ^{252}Cf source is located 175 cm away at (114°, 93°). The ^{60}Co source is located 390 cm away at (58°, 84°).

3. Results and Discussion

Figure 2 shows the reconstructed images for both neutrons and photons. Fig. 3 shows the reconstructed energy spectra for both source locations. 8 iterations of MLEM were used to reconstruct the neutron data and 5 iterations were used to reconstruct the photon data. In the neutron image, a hotspot is correctly centered at (115°, 95°), which corresponds with the location of the ^{252}Cf source. In the photon image, a hotspot is very clearly visible at (55°, 85°), which corresponds with the location of the ^{60}Co source. While not immediately obvious, a second "hotspot" is also visible in the photon image at the location of the ^{252}Cf source. This ^{252}Cf photon hotspot is at a lower intensity than the ^{60}Co hotspot, but is still discernable above the background intensity level.

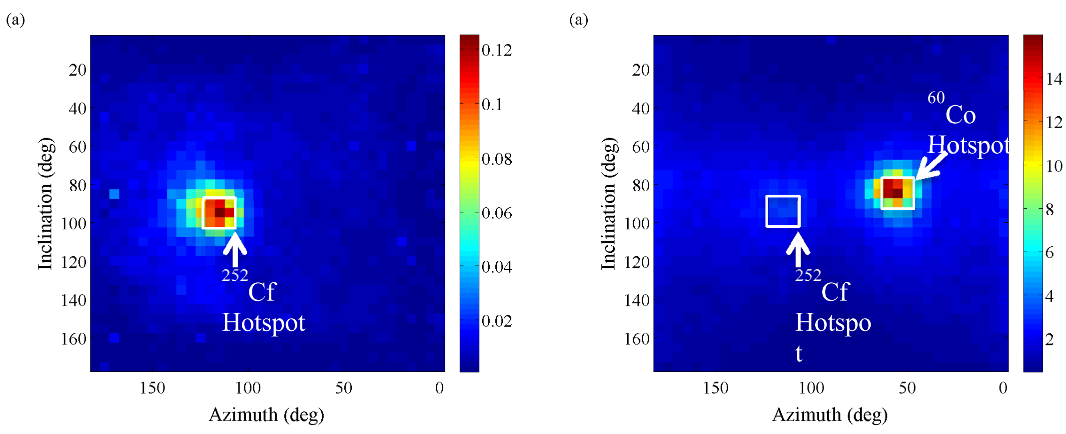

Fig. 2. MLEM reconstructed images for neutrons (a) and photons (b). The ^{252}Cf source can be clearly located in the neutron image, while the ^{60}Co source can clearly be located in the photon image. The ^{252}Cf is also seen in the photon image at a lower intensity than the ^{60}Co.

Figure 3 shows the photon and neutron energy spectra isolated from each source location. The spectra are a summation of the 3×3 pixel regions centered at (115°, 95°) and (55°, 85°). An outline of the three true hotspots is shown in Fig. 2. The neutron spectrum for the ^{252}Cf region is representative of the expected spontaneous fission Watt spectrum. While ^{60}Co does not emit any neutrons, the isolated neutron spectrum for the ^{60}Co region does show a low intensity spectrum with a shape similar to that of the ^{252}Cf region. This spectrum is approximately 5% of the intensity relative to the ^{252}Cf region. This erroneous spectrum is an artifact of the reconstruction and may be able to be reduced by optimizing the number of iterations used or by using regularization during the reconstruction.

The photon spectrum for the ^{60}Co region shows a high intensity region between 1.1 and 1.4 MeV, which corresponds well with the expected gamma-ray energies of 1.17 and 1.33 MeV. While both peaks appear as a single, broader, peak, it is possible that increasing the resolution of the system matrix would allow for the peaks to be resolved individually. The photon spectrum for the ^{252}Cf region is representative of the photon spectrum emitted by the spontaneous fission Watt spectrum. There does appear to be artifacting between the two photon spectra; the ^{60}Co region is representative of the Watt spectrum below 1 MeV, and the ^{252}Cf region shows a small increase in energy around the ^{60}Co energies.

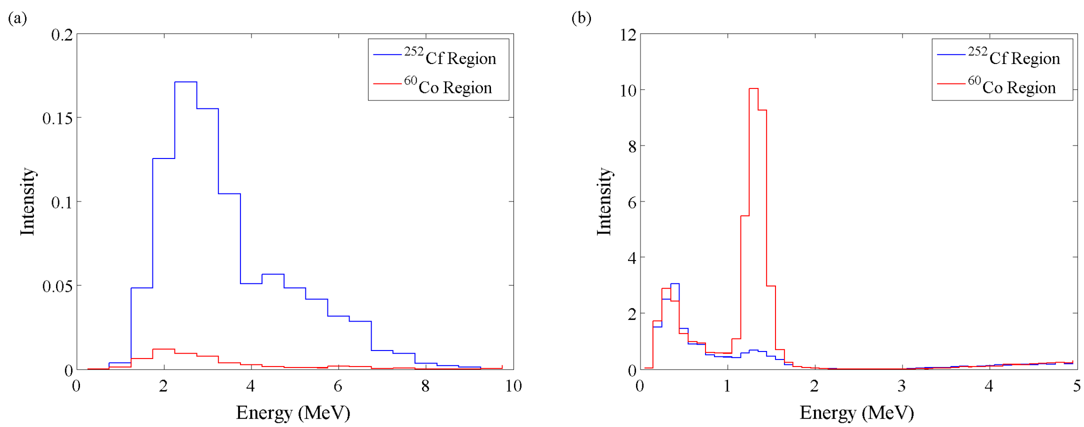

Fig. 3. Isolated neutron (a) and photon (b) energy spectra for both the ^{252}Cf region and the ^{60}Co region.

By using energy spectrum information seen in Fig. 3, it is possible to verify the presence of a photon hotspot in the ^{252}Cf region. Figure 4 shows the photon image for an energy window of 200 to 900 keV. This region was selected such that the ^{60}Co energies were excluded from the reconstruction. While the energy windowed image is not as well resolved as the images for the full energy range, it is now clear that a photon hotspot is present in the ^{252}Cf region.

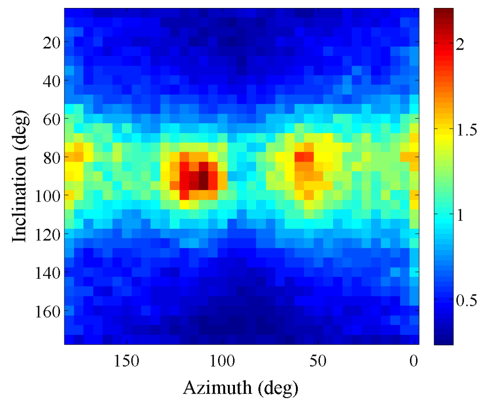

Fig. 4. Photon image for an energy window ranging between 200 and 900 keV.

4. SUMMARY AND CONCLUSIONS

An MLEM technique was investigated for simultaneously reconstructing the spatial and energy distributions using data from the DPI. By including energy information in the source dimension of the system response matrix, it was possible to estimate the energy distribution at each spatial location in the image. This technique was tested by simultaneously measuring a ^{252}Cf spontaneous fission source and a ^{60}Co gamma-ray source. Using this technique, the DPI was able to successfully locate both sources and estimate the emitted neutron and photon spectra reasonably well. The ^{252}Cf was correctly identified as emitting both neutrons and photons, while the ^{60}Co was identified as emitting gamma rays in the region of 1.1 to 1.4 MeV. These results demonstrate the value of being able to perform image and energy spectrum reconstruction for both photons and neutrons. The results also suggest that the DPI is a useful tool for applications in which locating and identifying multiple sources is important; such applications include hold-up measurements, cargo screening, and warhead verification.

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