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Localization and spectral isolation of special nuclear material using stochastic image reconstruction

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A B S T R A C T

In this work we present a technique for isolating the gamma-ray and neutron energy spectra from multiple radioactive sources localized in an image. Image reconstruction algorithms for radiation scatter cameras typically focus on improving image quality. However, with scatter cameras being developed for non-proliferation applications, there is a need for not only source localization but also source identification. This work outlines a modified stochastic origin ensembles algorithm that provides localized spectra for all pixels in the image. We demonstrated the technique by performing three experiments with a dual-particle imager that measured various gamma-ray and neutron sources simultaneously. We showed that we could isolate the peaks from ^{22}Na and ^{137}Cs and that the energy resolution is maintained in the isolated spectra. To evaluate the spectral isolation of neutrons, a ^{252}Cf source and a PuBe source were measured simultaneously and the reconstruction showed that the isolated PuBe spectrum had a higher average energy and a greater fraction of neutrons at higher energies than the ^{252}Cf. Finally, spectrum isolation was used for an experiment with weapons grade plutonium, ^{252}Cf, and AmBe. The resulting neutron and gamma-ray spectra showed the expected characteristics that could then be used to identify the sources.

1. Introduction

Radiation imaging is an effective tool for localizing sources of radioactive material by reconstructing source distributions. A specific type of imaging system, radiation scatter cameras, have long been the subject of study for applications including astronomy, emergency response, and non-proliferation [1–7]. Scatter cameras are an attractive tool due to their large field-of-view and ability to characterize source location and energy. However, image reconstruction using simple backprojection produces images with low resolution and low signal-to-noise ratios due to a large range of possible origins for each detected event.

To improve image resolution and signal-to-noise, statistical techniques have been successfully applied to image reconstruction. One of the most widely used methods is list-mode maximum-likelihood expectation-maximization (MLEM), which estimates the source distribution by using a response matrix created from observed events [8–11]. List-mode MLEM constructs an image through a number of iterations where the estimate at each iteration increases the value of the likelihood function. While list-mode MLEM provides a large improvement in image quality from simple backprojection, images can suffer from the algorithm over-fitting noise due to incomplete information in the system matrix. A stopping condition is also required as over-iteration is well known to cause degradation in image quality [12].

The stochastic origin ensembles (SOE) method has been proposed by Andreyev et al. [13] as an alternative image reconstruction method to list-mode MLEM that addresses the aforementioned issues. SOE is an iterative method that is based on Markov-chain Monte Carlo through use of the Metropolis-Hastings algorithm [14]. The SOE algorithm was originally applied to tomography and later Compton cameras with literature showing that SOE can produce comparable image quality to list-mode and bin-mode MLEM image reconstructions [13,15,16]. In prior work we have also demonstrated the image reconstruction capabilities of SOE for experiments using a dual-particle imaging system to measure ^{252}Cf and mixed-oxide nuclear fuel – which was designated as Category-III special nuclear material (SNM) [16].

Because past application of the SOE algorithm was for medical imaging, radioactive tracers with known emitted energy spectra were used. However, for imaging applications involving SNM, the emitted energy spectra are of great interest as they can be used to identify and discriminate between weapons-usable and non weapons-usable radio-

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active materials. Aggregate energy spectra for gamma-rays and neutrons are easily reconstructed by the dual-particle imager (DPI) but more advanced analysis is required to isolate the spectra for each source present. In this paper we have modified the SOE algorithm to include a reconstructed energy spectrum for the emitted gamma-rays and neutrons from each pixel in the image. The spectra from pixels corresponding to sources in an image can then be used for source characterization.

Spectral isolation also has the advantage of suppressing environmental background. When the spectrum is isolated from a fraction of the image, in which a source is located, the ratio of source-to-background will be larger. The ratio is improved because in that region, the source strength outweighs the background more than in other regions of the image not containing the source. Including image regions without the source will only add more background, lowering the source-to-background ratio.

This paper presents results from three experiments that demonstrate the ability of the modified SOE algorithm to isolate energy spectra from multiple sources measured simultaneously. An experiment with ^{22}Na and ^{137}Cs was used to measure isolated gamma-ray spectra for two sources. A second experiment using ^{252}Cf and PuBe showed spectrum isolation for a spontaneous fission neutron source and a ^{9}Be(α,n) neutron source. Finally, an experiment with weapons-grade plutonium (WGPu) metal, ^{252}Cf, and AmBe was performed to show that SOE can discriminate WGPu from the other two sources, which also emit both gamma-ray and neutrons.

2. Methods

In this section of the paper we will briefly describe the DPI, which was the measurement system used to acquire data, and the experimental parameters used in acquisition. We will also describe the modifications made to the SOE algorithm to reconstruct both images and spectra for each pixel in the image.

2.1. The dual-particle imager

The DPI is a combined Compton and neutron scatter camera. It has a two-plane design in which the front plane is composed of organic liquid scintillators and the back plane is a checkerboard pattern containing liquid scintillators and NaI(Tl) scintillators. The pulse shape discrimination capability of the liquid scintillators, through digital charge integration, allows them to function as scatter plane detectors for both gamma-rays and neutrons [17]. The physics principles and design of the system have been detailed in [5] and [18]. The system is pictured in Fig. 1.

In this work, the SOE algorithm uses the reconstructed angle, which defines a cone of possible source locations, and the reconstructed energy for each event recorded by the system. In the context of this work, the terms event and count will be used to refer to a correlated detection in two detectors that can be used to reconstruct both the angle and energy of the incident particle. For gamma-rays, a correlation between a front-plane liquid scintillator and back-plane NaI(Tl) scintillator is required to be recorded as an event. For a neutron to be recorded as an event, a correlation is required between a front-plane liquid scintillator and a back-plane liquid scintillator.

2.2. Spectral isolation using a modified SOE algorithm

The SOE algorithm was used for image reconstruction with the DPI in [16]. However, because the algorithm has been modified in several important ways, a full description of the algorithm is provided in this paper. The steps outlined are performed separately for gamma-rays and neutrons.

1) For each event, a single possible source position is sampled on the intersection of the cone, representing possible source locations, and a sphere surrounding the system. This sampled location is referred to as an origin. For two experiments in this work, a long-distance imaging approximation is used, which locates the apex of each cone at the center of the sphere. In this scenario, the distances from the actual cone apexes to the sphere center are assumed to be sufficiently small compared to the distance that the actual source or sources are located from the system. We define the center of the sphere to correspond to the middle of the gap between both detection planes of the DPI. Because uncertainties exist in the measured quantities, not all cones will overlap with the location of the actual source.

   To compensate, the angle for each cone is sampled from a probability density function (PDF) defined as a normal distribution,

$$\mathrm{PDF} = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(x-\theta)^2}{2\sigma^2}} \tag{1}$$

with the calculated angle, θ, as the mean. In a separate analysis, we found that spatial uncertainty, caused by the unknown interaction location within each detector cell, dominated the overall uncertainty. Other factors in the overall uncertainty include the energy and time resolution of detected particles. Sampling each calculated cone angle from a normal distribution with a FWHM of 10° (σ=4.25°) for both gamma-ray and neutron events was found to be a sufficient approximation for image reconstruction.

An origin is then sampled on the cone-sphere intersection that is

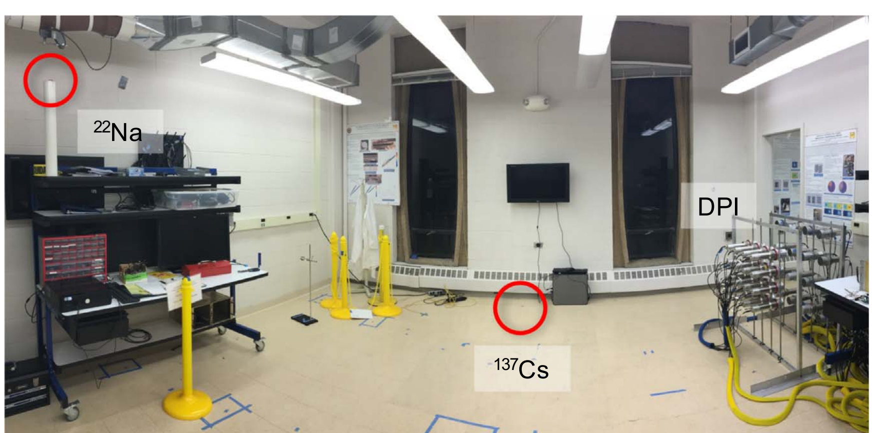

Fig. 1. This photo shows the experimental setup for a measurement of ^{22}Na and ^{137}Cs. The sources positions are highlighted by red circles. The ^{22}Na was located at an angular coordinate of (116°, 72°), 543 cm from the DPI and the ^{137}Cs was located at (57°, 104°) at a distance of 306 cm. The DPI is seen at the right of the photo. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)