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Rotating scatter mask optimization for gamma source direction identification

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ABSTRACT

Rotating scattering masks have shown promise as an inexpensive, lightweight method with a large field-of-view for identifying the direction of a gamma emitting source or sources. However, further examination of the current rotating scattering mask design shows that changing the geometry may improve the identification by reducing or eliminating degenerate solutions and lower required count times. These changes should produce more linearly independent characteristics for the mask, resulting in a decrease in the mis-identification probability. Three approaches are introduced to generate alternative mask geometries. The eigenvector method uses a spring–mass system to create a geometry basis. The binary approach uses ones and zeros to represent the geometry with many possible combinations allowing for additional design flexibility. Finally, a Hadamard matrix is modified to examine a decoupled geometric solution. Four criteria are proposed for evaluating these methodologies. An analysis of the resulting detector response matrices demonstrates that these methodologies produced masks with superior identification characteristics than the original design. The eigenvector approach produces the least linearly dependent results, but exhibits a decrease in average efficiency. The binary results are more linearly dependent than the eigenvector approach, but this design achieves a higher average efficiency than original. The Hadamard-based method produced a lower maximum, but a higher average linear dependence than the original design. Further possible design enhancements are discussed.

1. Introduction

Identifying a gamma source's direction is important in a variety of applications such as portal monitoring, treaty compliance verification, and locating orphan sources. Three general categories exist for gamma source direction identification; count-based systems, collimator and coded aperture systems, and Compton cameras. In count-based systems, a source's direction is determined by the relative change in the count number as the detector changes positions. This method can be inefficient and increase the user's exposure as they search for the source. Collimator and coded aperture systems use intervening material or a mask to create a unique detection pattern, which can be used to identify the source's direction. However, the intervening material reduces the detector's field-of-view (FOV) [1], which increases the time required to survey surrounding areas. For higher gamma energy levels, the system's weight and portability can become problematic as shown by the 32,000 lb SuperMISTI system [2] and 2700 lb Large-Area Imager [3]. These systems are mounted on mobile platforms in order to image the area of interest. Complicate Compton Cameras can offer up to a 4π FOV [4] and can distinguish between background and source radiation [1,5]. However, these systems require multiple detectors to measure coincident Compton events and usually ignore full-energy-peak (FEP) information.

A novel approach, similar in concept to the coded aperture system, exists that eliminates many of the alternative's limitations. This system utilizes a Low-Z mask placed over a single position-insensitive detector [6]. The system records energy spectra as a function of the geometrically varying mask, which is accomplished through a set, constant mask rotation. The measured position dependent spectra, referred to as detector response curves (DRCs), depend on the source position and can be used to identify the source direction. FitzGerald's mask geometry [6] generates some DRCs that are nearly identical, which can lead to mis-identification of the source direction. This work seeks to reduce the DRCs' linear dependence by optimizing the mask's geometry.

The rotating scatter mask (RSM) concept offers many benefits over other gamma source position identification detectors. Specifically, it "provides a nearly 4π field-of-view, operates for a broad range of gamma energies, and has a relatively simple design [7]". This system uses a

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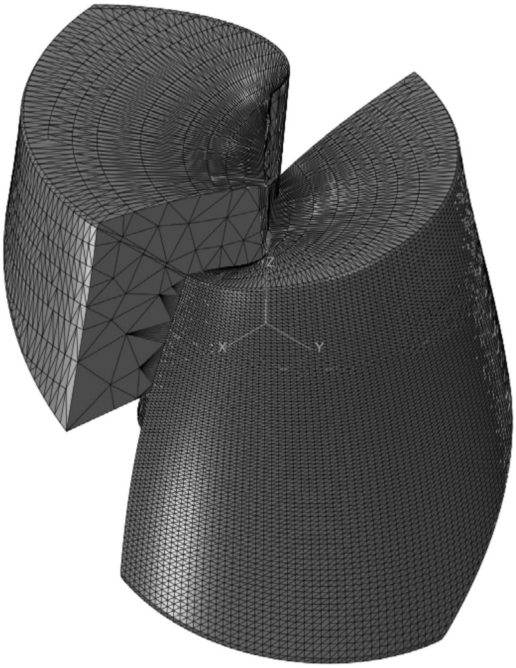

Fig. 1. Isometric view of the unstructured mesh used to model the FitzGerald RSM in MCNP.

spherical reference system, where θ is the azimuthal and ϕ the polar angle. The mask works by attenuating and scattering the incoming particles in order to produce unique detector response curves [7]. To obtain the measurements for the position identification, the mask starts at an initial θ and ϕ position. It then rotates in θ around the detector with the signal recorded at each discrete θ position. The measured DRC is generated by summing the counts over a desired energy range for each θ position in one complete mask rotation. Comparing this curve with each possible DRC, which are known through experimentation or simulation using a mean square error, least squares, or maximum likelihood estimate approach identifies the source direction.

FitzGerald introduced the RSM shown in Fig. 1 that has a 14 in diameter and surrounds a 3 × 3 in cylindrical NaI scintillating detector [6]. His original MCNP model contained 31 elements or one element every 11.6°. In order to increase the accuracy of the geometric representations, the model's angular resolution was later increased to every degree.

FitzGerald's design methodology assumes that the detector response is related to the mask geometry. Without this assumption, intentional mask design degenerates into random trial and error. In addition, he proposed three desirable characteristics for the RSM system. First, for any given initial source position, there is a unique response curve generated as the mask rotates 360°. This condition is necessary as a non-unique response would make at least two initial source position DRCs indistinguishable and a unique identification impossible. The second characteristic requires the mask's average thickness over a 360° rotation to be a constant value for all ϕs. This criteria prevents higher or lower average responses for different ϕ positions. This requirement is not necessary to ensure the uniqueness of the DRC; however, DRCs with widely varying average thicknesses may have a lower average count, which makes them more susceptible to measurement noise and increases the time required to obtain an accurate measured response. The final characteristic is for the solid angle from the detector centroid to be equal for all cells. This constraint provides the same spatial resolution in both azimuthal and polar directions. Not explicitly mentioned by FitzGerald is an assumption that the geometry should be continuous, thereby allowing the DRCs to be discretized as desired.

The remainder of this paper is organized as follows. Section 2 provides an overview of the RSM experimental setup, design assumptions and limitations, design criteria, and the design methodologies used to generate improved RSM designs. Section 3 describes the performance of each of the alternative designs and compares that performance to the FitzGerald baseline. Finally, Section 4 discusses possible future improvements on the methodologies presented here and key results from the improved RSM designs.

2. RSM design

Logan et al. [8] showed statistical agreement between experimental and simulated DRCs using GEANT4 [9] and agreement of simulated DRCs [7] using GEANT4 and MCNP [10]. Thus, this work will use MCNP to simulate the experimental DRCs needed to evaluate each RSM design's performance. Instead of using only the full energy peak (FEP), the DRC for this work is formed by summing all counts above 200 keV to increase the source direction identification's efficiency. The 200 keV limit was chosen as Logan et al. noted discrepancies for counts below this value due to scatter in the environmental elements not considered in the model [7].

Originally, both the analysis of FitzGerald's RSM and the new designs were to be discretized into 10° increments in θ and 5° in ϕ. However, due to requirements for the Hadamard method, (which is discussed in Section 2.3.4) the proposed designs are broken into 32 discrete angles in θ resulting in $\Delta\theta = 11.25°$ and $\Delta\phi = 5.625°$ for 30 angles in ϕ.

The RSM design is to be optimized for a ^{137}Cs point source located 34 in from the center of the detector, mimicking Logan et al.'s setup [7]. To simulate the relative source rotation in MCNP, the mask is stationary, while the source is rotated in spherical coordinates every increment for θ from 0 to 348.75° and for each ϕ from 5.625° to 168.75°. The modeled NaI detector includes a 1/8 in 2024 Aluminum alloy sleeve on which the acrylic RSM is placed. The maximum width of the RSM depends on the methodology, but the maximum mask thickness is a constant 7.87 in (20 cm). A sphere of air surrounds the source and detector, and all other environmental factors were ignored. To increase the solution convergence rate, particles were emitted within a 27.26° half angle cone extending from the source to the detector's center. This variance reduction technique assumes that the effect of the few particles that scatter in the air outside of the cone, though the mask, and into the detector will have negligible contributions to the simulated DRCs. In addition, a 0.095 in air gap between the mask and aluminum sleeve constrains the mask geometry from impinging on the sleeve and provides a space for grease to be applied between the moving parts. Finally, due to manufacturing constraints, each mask angle must have a non-zero thickness.

2.1. Design assumptions and limitations

It is assumed that the detector-mask-source geometry is related to the DRC and that geometry can be reconstructed using the DRC. Qualitative studies of this correlation showed that, in general, this assumption is valid with two qualifications. First, a discontinuous geometry results in a continuous DRC due to correlations with neighboring rotations. Second, while the RSM may offer an increase in the total counts, it comes with a limit on the spatial resolution. To understand this statement in detail, consider a rectangular prism cell with a given thickness extending from the centroid of the detector (outside of the aluminum sleeve) in a given direction. Since the cells do not have impenetrable walls, particles from one source position enter cells pointed at other positions. In fact, this phenomena is one of the desirable characteristics of FitzGerald's design as an increase in scattered particles can increase the total number of counts seen by the detector thereby increasing the efficiency. However, if the cells are too small compared to the detector footprint, then neighboring cells may see a response comparable to the cell located between the detector and source.