Methodical Optimization of Mutual-Shielding Directional Gamma Detector

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Abstract—Mutual-Shielding Directional Gamma Detector excels at sensitivity and can achieve good angular accuracy and a large field of view. In this paper, we present, in detail, a method to optimize a mutual shielding directional detector array regarding the scintillators positioning for a given number and size of detection units. The optimization goals are improvement of accuracy and sensitivity.

The optimization uses two types of fast, non-Monte-Carlo simulations since the simulation needs to generate measurements from all directions for each array formation tested. Both these simulations are explained and demonstrated.

The presented method uses the ambiguity function to assess the accuracy and identify directions that may generate errors due to similar responses from other directions. Then, addressing these problematic directions can be fixed by changing the scintillators’ positions or adding a partial shield to change the response at one of the similar directions.

Keywords—Directional Gamma Detector, Detectors Array, Mutual Shielding.

I. INTRODUCTION

Typical gamma radiation detector measures the photon flux passing through its volume, estimating the gamma field intensity only and indicating whether a source is present via an alarm. The next step in radiation detection is to find the Direction Of Arrival (DOA) of the Gamma photons. This new operational data can help in many scenarios, such as locating concealed radioactive sources in homeland security, searching hotspots in a post-radiological event, or during Decontamination and Decommissioning (D&D).

We can count the coded mask aperture, Compton scatter, and collimation among the various principles used for Gamma directionality. The significant disadvantages of these methods are limited Field Of View (FOV), medium to low efficiency, and limited energy response. Alternatively, a compact array structure of detectors uses mutual shielding to generate significant difference measurements from different directions. This array enables high sensitivity, which can be increased since there is no limit to the sensor size. Although mutual shielding is highly effective for low-energy Gamma, it can be easily adjusted to higher energies by selecting larger detectors or adding more detector layers to increase the total cross-section length from every direction. Another significant advantage is that there is no inherent limit to the FOV, except the need to construct an intelligent structure with a unique response from every DOA required.

A. Previous works based on mutual-shielding

Several previous works suggested detectors based on the mutual-shielding principle. The initial studies in [1] - [4] used 3-7 scintillators in a close-packed structure to measure the different responses of a single source on a 2-D plane and estimate its angular direction.

In 2017 [5], our group introduced a concept of raising the central detector resembling a sun-dial (Fig. 1b). This structure adds a variation of the readings in different elevations due to the occlusion from the central scintillator. Using Monte-Carlo (MC) simulations of five or six cylindrical scintillators surrounding a raised central one, we achieved a mean angular error of 7°-9° or 4°-7° respectively for all elevations. In comparison, for a flat structure, with the central scintillator at the same height as the others, the worst mean angular errors at some elevations were 23° and 19°, respectively.

The work of McCann and Chen et al. [6] [7] presented a new 2x4 close-packed structure (Fig. 1c) using rectangular-cuboid CsI(Tl) scintillators to measure directionality from the whole 4π directions. The direction estimation method was simple: for each axis (x, y, and z), they calculated the total difference in count rates between the front four scintillators and the rear four scintillators and estimated the azimuth and elevation from this 3-dimensional vector. The count rates were measured for a specific energy photopeak. When simulating a one mCi ¹³⁷Cs point source at a 10 m distance, they calculated the angular Root Mean Square Error (RMSE). The results showed a 10°-30° error for a short measurement time (<20s), 6°-18° error for 30s measurements, and up to 8° error for 150s measurements, where the results variations were due to the angle of incident.

Rahn et al. [8] suggested putting a large number of small cubic scintillators to generate a large measurement vector, rich with DOA information. This detector aimed to identify and
localize deep space Gamma Ray Bursts (GRBs), with a spectrum dominant in the low Gamma energies. Their prototype Fig. 1c) used a random configuration of 90 cubic scintillators (9mm³) coupled to silicon photomultipliers (SiPMs) occupying 0.25 l volume. They also suggested a planned detector with 350 cubic scintillators occupying 1 l volume.

In continued work [9], our group improved the instrument’s accuracy and sensitivity compared to the random configuration. The optimization used a fast approximate simulation of slowly modified configurations, limited only in their volume and not by the number or position of the scintillators. Using a gradient descent of a loss function combining the sensitivity and accuracy, we improved the configuration from angular MSE of 3.73° to 2.84° and ~6% in the sensitivity.

![Fig. 1. Previous works of mutual-shielding directional detectors: (a) with azimuth only [1]; (b) added elevation capability for half a sphere (2π) using the ‘sun-dial’ array [5]; with whole 4π directionality using 2x4 cuboid scintillators array coupled to SiPMs [6]; (c) prototype of 90 small cubic scintillators randomly placed [8] for high accuracy.](image)

In this work, we introduce an analytical methodology to improve the spatial configuration of a mutual shielding array. The optimization is aimed toward both the accuracy and the sensitivity of the mutual shielding detector array under the constraint of keeping the same number and volume of scintillators. The accuracy is improved for the expected mean angular error as well as for the best and worst angle errors. To demonstrate the optimization method, we optimize our suggested seven scintillators ‘sun-dial’ directional detector as a test case throughout this paper. The aim is to develop a detector to locate ground contaminations (hotspots) for post-radiological events. The detector will be located on a robot at 1.5 m height; hence, it implies that the detector’s directions of interest are the bottom half sphere (2π).

II. OPTIMIZATION

We started by selecting the scintillator type and size, which will be constant throughout the optimization phase. We decided on six identical cylindrical NaI(Tl) scintillators, each with a 25 mm diameter and 50 mm height, while the central scintillator has the same diameter but double the height (100 mm), making the total scintillation volume of 0.2 l, which is comparable to a 2”x2” and 3”x3” cylindrical scintillators with volumes of 0.1 l and 0.35 l respectively.

A. simulation methods

To optimize the 7-scintillators array directional detector, we used simulations. The simulations must generate measurements from all DOAs for every array structure under evaluation. This requirement implies that the simulations cannot be slow to compute to try different structures, which means Monte Carlo (MC) physics simulations are unsuitable for array optimization.

The first type of simulation we used is called ‘zero energy’ simulation. Here, we simulate very low-energy gamma photons, almost entirely absorbed in the dense scintillator, similar to light photons. Given that, the simulation starts by drawing the 3-D structure of the dense materials in the detector, such as the scintillators, iron, or lead, and neglecting any light materials like plastics or aluminum. Each sensor is colored differently, and the detector is viewed from a specific viewpoint, representing the source position. By using perspective geometry, built in most plotting tools, it is easy to measure the area exposed to the source in a direct line of sight. This area is linearly linked to how many zero-energy photons will reach each sensor. Fig. 2a illustrates the simulation. When the seven scintillators are rotated to be viewed from the side with no elevation and 50° azimuth relative to detector #1 (dark blue), the two rear scintillators, #3 (yellow) and #4 (purple), are almost entirely occluded except for a small gap between the front scintillators; hence their reading will be close to zero, while about a quarter of detector #2 (orange) is visible. The bottom numbers at each detector in Fig. 2b represent the area measured in arbitrary units, while the percentage shows the expected readings at each detector relative to the total counts of the array.

![Fig. 2. Example of ‘Zero Energy’ simulation for the ‘sun-dial’ 7-cylindrical scintillators. (a) the view from 50° azimuth and 0° elevation (b) the results of the area measured (bottom number, arbitrary units) and as a percentage of the total area (middle number).](image)

This type of simulation is accurate for low energies and is very fast to compute. We simulated every one-degree over 360° azimuth with 15° elevation steps. On the other hand, the simulation accuracy degrades as the incident photon energies are higher, depending on the scintillator’s size and density.

To get an accurate spatial calibration table for higher energies, we use another simulation method we address as an ‘attenuation-only’ simulation. This simulation uses ray-tracing of multiple direct rays from a point source toward the array. For each ray, it calculates the cross-section length at each scintillator and the order in which the ray hits them. In an iterative loop from the first detector hit to the last, we calculate...
the absorption in each scintillator according to the Linear Energy Absorption Coefficient (LEAC) and the transfer percentage towards the next scintillator using the Linear Attenuation Coefficient (LAC).

Fig. 3. Example of attenuation-only simulation results for DOA of 50° azimuth and 0° elevation through 7-scintillators array. The results show the number of rays time, their probability of interaction (bottom number, arbitrary units), and the percentage of expected events per scintillator relative to the total array measurements (middle number).

It is very clear from the percentage out of the total counts and even more so when examining the absolute expected counts (bottom number in arbitrary units), where the front detectors (1, 5 and 6) show a reduction in the expected counts due to the lower probability of event in the detectors cross-section length. In contrast, the rear detectors (3 and 4) show an increase in the absolute measurement because fewer photons interacted with the front detectors, and the photon flux through the rear detectors is significantly higher.

B. Optimization methodology

The optimization process analyses the angular response using the ambiguity function. The ambiguity function $\rho$ is a two-dimensional function that evaluates the difference between two vectors, $\mathbf{a}(\theta_1)$ and $\mathbf{a}(\theta_2)$, measured from two directions $\theta_1$ and $\theta_2$. In our case, each vector is the seven photo-peak counts from the seven detectors.

$$\rho = \sum_{n=1}^{7} \left| \frac{\mathbf{a}(\theta_1) - \mathbf{a}(\theta_2)}{\sum \mathbf{a}(\theta_1) - \sum \mathbf{a}(\theta_2)} \right|$$  \hspace{1cm} (1)

An example of the ambiguity function generated from the zero-energy simulation is shown in Fig. 4. Here, the x and y axes span from 0°-360° for the azimuth only, while the elevation was kept level at 0° as seen on the right side of the figure. The minimum value of the ambiguity is zero and occurs at the diagonal since the difference between a vector and itself is zero. If we treat the ambiguity value as the height over $\theta_1$, $\theta_2$ plane, we get a valley along the diagonal, where its steepness corresponds to the accuracy attainable from the directional detector configuration. Hence, we can select a contour (a constant value of ambiguity) and measure the distance of the contour line from the diagonal, which will give a performance assessment. The ambiguity value corresponds to testing the angular error of a specific Signal-to-noise ratio (SNR), which translates to the number of counts measured. For example, in Fig. 4a of the ambiguity for the ‘sun-dial’ array, by selecting an ambiguity value of 0.1, we get an expected angular error of 14.1° at azimuth 60° and a minimum error of 9.5° in other azimuths.

The advantage of the method is that running the simulation once and without adding random noise in multiple runs produces a qualitative assessment of the expected error without linking it to a specific SNR value.

III. RESULTS

A. First optimization attempt: increasing scintillator distance

We started the array optimization from the proposed seven scintillators packed together in a ‘sun-dial’ shape with a minimal 5 mm distance between the scintillators caused by the aluminum case thickness of the cylindrical detectors. As described earlier, we selected an arbitrary ambiguity value of 0.1 and measured the distance from the diagonal as a qualitative test. When we increased the spacing between the detectors from 5 mm to 10 and 15 mm, the ambiguity function (Fig. 4) showed that for most DOAs, there is a reduction in the expected azimuth error from 9.5° to 7° and 5.6° respectively. However, every 60°, there is an increase in the expected error to 18.4° and 21.2°.

The improvement caused by distancing the detectors is probably due to a sharper occlusion change for a smaller DOA shift.

To understand the decrease in accuracy every 60°, we examine the response plot (Fig. 5). It shows that every 60°, when there are three detectors fully exposed to the source and three rear detectors, a symmetry causes the same response vector from two angles, e.g., 50° response is the same as 70° response, demonstrated in the views showed at Fig. 5a, and Fig. 5c. This symmetry happens again where 110° is the same as 130° and so on, as marked in the response plot on Fig. 5c.

When inspecting the response of any single detector in a close-packed ‘sun-dial’ array shows there are four states for the detector: (1) fully exposed over a 120° section, (2) fully occluded over a 120° section, and (3-4) the transitions between the states each taking about 60°. When the elevation is not zero, the detector is not fully occluded except for a specific angle behind the central extended detector, as seen in Fig. 5c.

The conclusion from the analysis of our first attempt is that in order to get better accuracy and fewer potential errors, we need to (a) break the symmetry seen from every side of a front detector, (b) generate more changes to the responses of each detector to differentiate the response vector from different DOAs.

B. Second optimization attempt

To break the symmetry, we moved the three odd-numbered detectors at a different distance and height than the three even-numbered detectors. The resulting array is labeled ‘triangles’ and can be seen in Fig. 6.

The increased distance of detectors 1,3, and 5 generates a large gap that creates a peaking gap for a rear detector (resembling collimation), such as the visibility of detector 6 (light blue) through the gap between the blue and grey detectors.
in Fig. 6b.

These uneven gaps generate more changes in the azimuthal response, highlighted in Fig. 6c, which enhance the DOA data and should enable a tighter DOA estimation.

The ambiguity plot of the ‘triangles’ array clearly shows the much steeper valley along the diagonal, implying better accuracy. However, a different phenomenon has manifested.

Three dips exist apart from the diagonal (the plot shows six; however, the upper triangle mirrors the lower one). These dips imply that the area (in zero-energy simulation) or the rays’ absorption (in attenuation-only simulation) at each detector is the same for two different views of the array. These similarities happen at specific azimuths: 28° vs. 332° (demonstrated Fig. 7b), 148° vs. 92° and 268° vs. 212°. The triangle shape and distances were found after several arrays were tried and showed promising results except for these dips.

A demonstration of the views of such two DOAs is shown in (b), where the area of each detector is the same in both views, although the views are different.

C. Third optimization attempt

We needed to address the resemblances generated at the three dips to benefit from the improved accuracy of the ‘triangles’ array. To do so, we added three lead slabs to generate differentiation between every two similar azimuths. We carefully placed each slab in front of the front detectors so that every unique angle found at the triangle’s dips shields a different detector to modify the response vector. The slabs and their shielding are demonstrated for a specific 2 DOA in Fig. 8b. The difference created by shielding even only one detector for each azimuth mitigates the problem of the dips, as shown in the ambiguity plot in Fig. 8a.
same angular density of rays makes it possible to compare the total absorption of all scintillators in each array as a measure of the sensitivity. When comparing the total absorption in

, it shows that as we increase the distance between scintillators (for ‘sun-dial’ arrays and then the ‘triangles’), the sensitivity improves, both for the minimal and the average sensitivity. The absolute sensitivity is higher for the 45° elevation due to the larger cross-section area. However, due to the two heights at the ‘triangles’ array, the sensitivity is slightly higher at zero elevation, which is also reflected in the more significant improvement from ‘sun-dial’ to ‘triangles’ at zero elevation.

As expected, adding the lead blockers (marked “T. & B.” in

) decreases the sensitivity relative to the plain ‘triangles’ array. The mean and minimal sensitivity are higher than the ‘sun-dial’ arrays. An exception is the case of 141 keV at 45° elevation, where the mean sensitivity is on par with the ‘sun-dial’ array with a 15 mm distance.

Fig. 10. Sensitivity comparison of the five arrays: (a) Total absorption in arbitrary units. (b) Total absorption relative to the close-packed ‘sun-dial’ array. The error bar limits mark the maximum and minimum values calculated for all DOAs.

IV. DISCUSSION

This work presents our methodical approach to improving the accuracy and sensitivity of a fixed-size directional detector array. The work was mainly done using two types of simulations: a quick ‘zero-energy’ simulation based on the built-in 3D image capabilities of the plotting tool, and the second we called ‘attenuation only’ simulation, based on ray tracing combined with LAC and LEAC parameters. Both of these simulations are much faster than a standard MC simulation, which is vital when examining many forms of detector arrays.

For the selected 25 mm diameter scintillators, it can be seen in Fig. 3. that for the 99mTc with 141 keV photopeak, the results of the ‘attenuation only’ simulation are very close to the zero-energy simulation, while for higher energy, such as the 137Cs 662 keV photopeak, the discrepancy is noticeable. This discrepancy indicates that different spatial calibration tables

D. Arrays accuracy comparison

As explained earlier, selecting a specific ambiguity threshold value and measuring the distance to the diagonal is equivalent to measuring the mean angular error for a specific SNR since the diagonal of the ambiguity plot represents a true DOA estimation. Although we cannot determine the SNR value precisely, it is a valid qualitative estimation of the expected error.

In Fig. 9, we plot a qualitative comparison based on the measured distance from true DOA at a constant ambiguity value. It is easily shown that the ‘triangles’ array (red) performs mostly well except for an area that can give a false DOA with huge errors. The ‘sun-dial’ array (blue) performance is consistent except every 60°, while the ‘triangles & blockers’ formation has the lowest mean error for almost all azimuths, with some larger errors every 120°, but still better than the ‘sun-dial’ expected errors. Since this array showed the best accuracy performance, we must examine the effect of the blockers on the array sensitivity.

E. Sensitivity analysis

Any array sensitivity depends on the energy photopeak measured; hence, we use the attenuation-only simulation to evaluate the sensitivity. The simulation sums the probability of each ray interacting with each scintillator and outputs the scintillator absorption as an arbitrary number, which depends on the density of rays generated by the simulation. Keeping the

Fig. 9. The arrays expected angular error at -15° elevation, generated using the constant ambiguity threshold.
will be needed for different energies.

The optimization method used the ambiguity function as a primary tool to estimate the expected angular error and to identify the problematic DOAs. These angles are identified by looking at local minima in the ambiguity map. We hypothesized that increasing the distance between the scintillators will increase the accuracy since a smaller change at the incident angle will have a more significant change in the occlusion for a larger distance. This hypothesis was proved by examining the ambiguity function as sowed in Fig. 9, where the distance to the diagonal represents the noise margin for correct DOA estimation for a constant ambiguity value.

We can use the normalized or un-normalized distance for the ambiguity function. However, we need to normalize the results in actual algorithms since we compare them to the spatial calibration table, measured with a specific count rate for a specific source activity. When normalizing the measurement vector, a basic matched filter algorithm does not consider the absolute number of events; thus, the Poisson distribution effect of having better accuracy at a higher count rate is not taken into account. As a further work, we will adjust and compare several algorithms to find the best one for a single source DOA with background estimation.

We are constructing a directional detector prototype based on the suggested optimized formation – the ‘triangles & blockers’ array. The development will include an embedded DAQ system to measure seven low-resolution energy spectrums since we do not need to identify isotopes, only measure several energy windows. These energy windows boundaries are determined so they would have approximately constant attenuation, for example, a division of five energy bands: under 80 keV, 80-200 keV, 200-400 keV, 400-700 keV, and above 700 keV. As part of the DAQ system design, we will analyze the absorption and attenuations in the NaI scintillators and decide on the required energy bands for the measurements and that will introduce minimal errors.

This paper presented a method to optimize a mutual shielding directional detector array regarding the positioning of the scintillators using the ambiguity function and the array simulated response. The method was demonstrated on a seven-scintillators array but can be applied to any other mutual shielding array for low and high energies.

REFERENCES


