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Communication

GEANT4 Simulation of a Muon Tomography Station Using Novel and Simple Reconstruction Algorithm for Homeland Security Application

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Abstract: Muon tomography leverages cosmic muons' exceptional penetration capabilities to reconstruct detailed tomographic images via multiple Coulomb scattering interactions, making it invaluable for detecting High-Z materials critical to homeland security. This study introduces the Slope Intercept (SI) algorithm, a novel approach for rapid and precise tomographic image reconstruction. Implemented using Geant4 simulations in a standard-sized container tomography station, SI demonstrates superior performance in speed and simplicity compared to traditional methods. While the imaging results of SI and the Point of Closest Approach (POCA) algorithm are nearly identical, the SI algorithm is simpler to implement, requires shorter CPU time, and exhibits a smaller margin of error. Its computational efficiency and simplicity make it a robust alternative to the POCA algorithm. These findings highlight SI's suitability for applications demanding robust imaging and efficient data processing, which are crucial for advancing security measures and scientific research.

Keywords: particle tracking detectors; simulation methods; Geant4; point of closest approach; slope and intercept

1. Introduction

The illicit trafficking of nuclear and radioactive materials poses a significant threat to global security, particularly at border crossings and ports. Traditional security measures, such as X-ray systems, have limitations in detecting shielded or dense materials, necessitating the development of more advanced detection techniques. Muon tomography, a technique based on the interaction of cosmic muons with matter, has emerged as a promising solution for homeland security applications [1,2].

Cosmic muons are high-energy charged particles produced by the interaction of cosmic rays with the Earth's atmosphere. Due to their penetrating nature and relatively long lifetime, cosmic muons can traverse dense materials, making them ideal probes for imaging applications [3,4]. When cosmic muons interact with materials, they undergo multiple Coulomb scattering, resulting in changes in their trajectory and scattering angles.

Muon tomography utilizes the information obtained from detecting these cosmic muons to reconstruct tomographic images of inspected objects. By measuring the trajectories and scattering angles of muons as they pass through the inspected volume, it is possible to infer the internal structure and composition of the materials within. This non-invasive imaging technique has gained traction in various fields, including nuclear waste imaging and homeland security [5,6].

While muon tomography holds promise for security applications, existing reconstruction algorithms have limitations in terms of complexity and computational efficiency. The Point of Closest Approach (POCA) and Expectation Maximization-Maximum Likelihood (EM-ML) algorithms, although effective, may be computationally intensive and impractical for real-time image processing, particularly in the context of homeland security [7].

To address this research gap, we propose a novel reconstruction algorithm, termed the Slope Intersection (SI) algorithm. This algorithm simplifies the reconstruction process by calculating the scattering points of materials using hit-position information obtained from detector planes. By leveraging

a simple geometrical approach, the SI algorithm offers fast and efficient reconstruction of tomographic images, making it well-suited for real-time applications in homeland security.

2. Challenges in Muon Tomography Station

The general concept of muon tomography for container scanning is illustrated in Figure 1. A muon tomography station typically consists of a set of detector planes placed above and below the sample volume to provide information regarding the hit position and angle of the incoming and outgoing muon tracks, which are used as the basis for reconstruction.

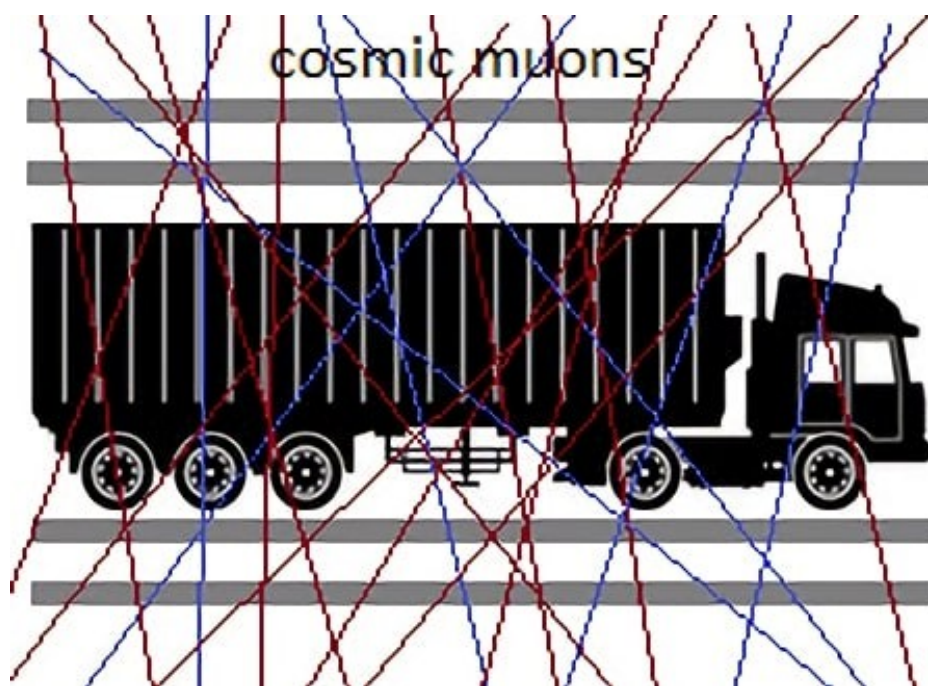


Figure 1. Demonstration of muon scattering tomography station for homeland security.

It is possible to reconstruct the muon track and obtain the scattering angle with information from the upper and lower detectors. The deviation angle distribution is approximately a zero-mean Gaussian, in which the variance is related to the radiation length of the material that the muon passes through [8,9].

Clearly, there are some problems associated with muon tomography. Firstly, muons do not travel in a straight line through the sample volume. Secondly, natural muons have limited flux and come from directions with wide angular distribution around the zenith. Finally, the multiple Coulomb scattering angle is stochastic and is approximated as a zero-mean Gaussian, but there are long tails in the actual distribution.

To achieve good precision in the reconstruction of the tomographic image, a high-quality tracking muon detector is required. On the other hand, imaging algorithms of good quality with relatively short computing time are also needed. Therefore, along with designing a high-quality detector system, utilizing effective imaging algorithms has a significant impact on the performance of muon tomography systems.

3. Challenges in Muon Tomography Station

The general concept of muon tomography for container scanning is illustrated in Figure 2. A muon tomography station typically consists of a set of detector planes placed above and below the sample volume to provide information regarding the hit position and angle of the incoming and outgoing muon tracks, which are used as the basis for reconstruction.

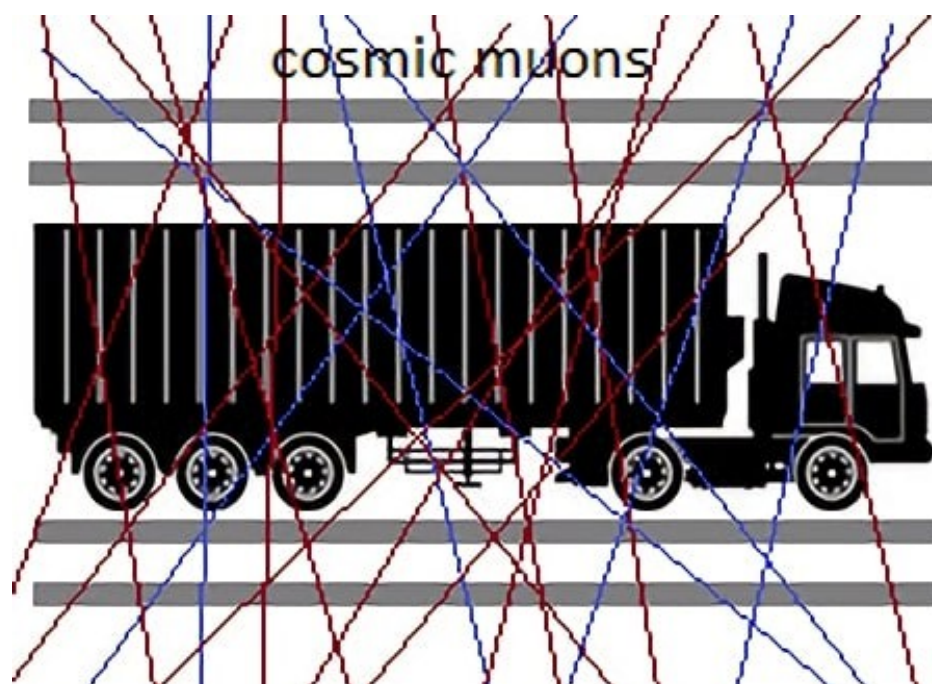


Figure 2. Demonstration of muon scattering tomography station for homeland security.

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4. Reconstruction Algorithm

A simple reconstruction algorithm, which can be comparable with the POCA method, is proposed. In this method, the space coordinates of the target materials are calculated using the hit-position information measured by the detector planes in the muon tomography station. The intersection point of the incoming and outgoing tracks in the xz and yz projection planes is considered as the scattering point of the target material. In addition to being simple and easy to use, this method also allows obtaining a three-dimensional image of the materials. Considering the passive nature and high energy of the muons, we can think of the traces of the muons passing through the detector planes as straight lines because the scattering angles from the detector planes and air molecules are very small compared to the target materials.

For a muon tomography system, we need at least four detector planes so that we can identify the trace of the muon and approximate the muon trace as a straight line. As seen in Figure 3, cosmic muons pass through the top two detector planes, scatter from the atoms of the possible hazardous material placed between the top and bottom detectors, and then pass through the bottom two detector

planes. The interaction points of muons at the detectors or hit-positions are (x_i, z_i) and (y_i, z_i) where $i = 1, 2, 3, 4$.

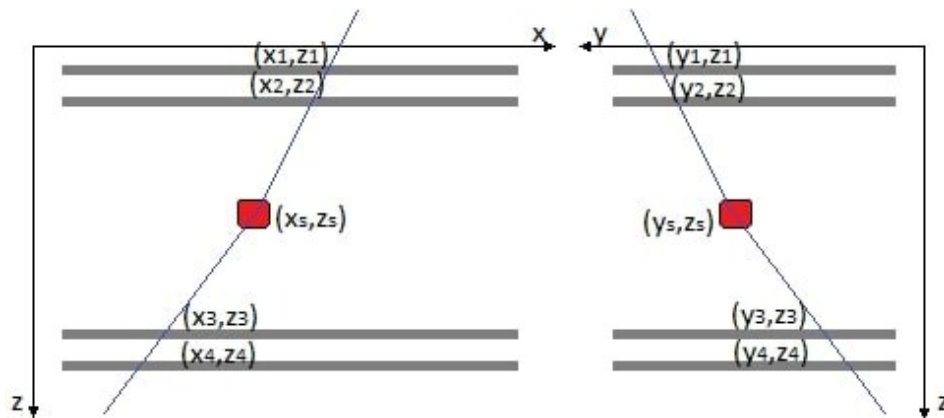


Figure 3. Demonstration of muon scattering tomography station for homeland security.

Figure 3 XZ and YZ projections of hit-position detection planes for muon tomography station
The equations representing scattering point (x_s, y_s, z_s) are:

$$x_s = \frac{P_{1x} + P_{2x}}{2} \quad (1)$$

$$y_s = \frac{P_{1y} + P_{2y}}{2} \quad (2)$$

$$z_s = \frac{P_{1z} + P_{2z}}{2} \quad (3)$$

where P_{1x} , P_{2x} , P_{1y} , P_{2y} , P_{1z} and P_{2z} are given by:

$$P_{1x} = \frac{d_{xy} - b_{xy}}{a_{xy} - c_{xy}} \quad (4)$$

$$P_{1y} = \frac{a_{xy}d_{xy} - c_{xy}b_{xy}}{a_{xy} - c_{xy}} \quad (5)$$

$$P_{1z} = \frac{d_{xz} - b_{xz}}{a_{xz} - c_{xz}} \quad (6)$$

$$P_{2x} = \frac{a_{xz}d_{xz} - c_{xz}b_{xz}}{a_{xz} - c_{xz}} \quad (7)$$

$$P_{2y} = \frac{a_{yz}d_{yz} - c_{yz}b_{yz}}{a_{yz} - c_{yz}} \quad (8)$$

$$P_{2z} = \frac{d_{yz} - b_{yz}}{a_{yz} - c_{yz}} \quad (9)$$

In the equations, a and c represent the slopes, and b and d represent the intercepts of the incoming and outgoing tracks, respectively, with subscripts xy , xz and yz denoting the sections of the inspected volume. The calculation of the scattering point involves determining the intersection of the tracks in the xy , xz and yz planes.

5. Simulation Setup

The typical geometry of the muon tomography station for simulation study is shown in Figure 4. The muon tomography station includes tracking detectors at the top and bottom. Each tracker consists

of two 10mm thick plastic scintillator detector plates with 20cm separation. The upper and lower tracking detectors have an area of $6m \times 3m$ with 3m spacing.

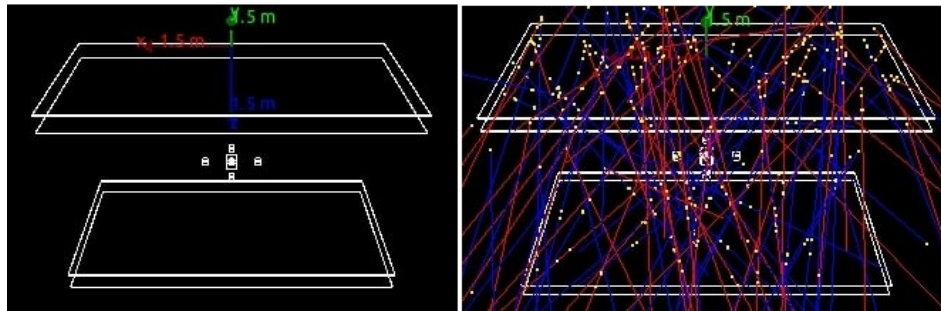


Figure 4. Muon tomography station demonstration with 0.2 seconds of cosmic ray exposure.

We placed five material blocks representing different Z values; low-Z: Aluminium (Al), medium-Z: Iron (Fe) and high-Z: Lead (Pb), Uranium (U) with typical sizes of $10cm \times 10cm \times 10cm$ in the middle of the muon tomography station for a simple target scenario that simulates the real situation with Geant4 simulation package (Geant4-11.1.3) [10,11]. Monte Carlo cosmic ray generator (CRY) package was used for the simulation [12,13]. Muons are generated above the horizontal plane with an angular distribution and energy spectrum corresponding to cosmic ray muons at sea level. The generator was interfaced with Geant4 for simulating the geometry of the muon tomography station, including interactions of the muons with targets, including multiple scattering. The natural flux of cosmic ray muons is approximately $10000m^{-2}min^{-1}str^{-1}$ [14]. Therefore, 1.8×10^6 events were generated, which is equivalent to about 10 minutes of exposure time in real conditions.

We implemented uncertainties for the hit-positions due to the fact that there are measuring errors in the actual application. Hit-positions are smeared with a Gaussian of width equal to the detector position resolution as:

$$\sigma = \frac{p}{\sqrt{12}} \quad (10)$$

where p is the WLS fiber separation.

6. Results

Comparison of the reconstructed image of M shaped lead letters with pitch lengths of 0 mm, 5 mm, 10 mm, and 20 mm is shown in Figure 5. It is clear from the figure that a smaller pitch length provides better resolution. However, a smaller pitch length requires more fiber and SiPM. Therefore, we chose a 10 mm pitch length for our application in which plastic scintillator with WLS fiber-embedded tracker detectors are used. Similar detector systems for muon tomography applications are reported in [15].

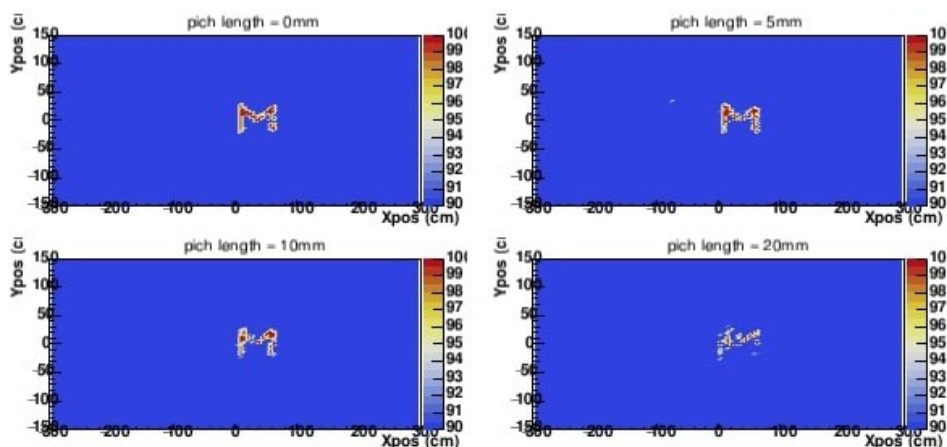


Figure 5. Comparison of reconstructed M letter with different pitch lengths

Figure 6 displays the reconstruction results of a scenario involving five target boxes using the SI and POCA algorithms with a 10 mm uncertainty after a 10-minute exposure to cosmic muons. The colorbar represents the number of muons, normalized to one. In both the POCA and SI reconstruction algorithms, the images undergo a filtering process where a threshold higher than the standard deviation of the energy difference observed between the upper and lower trackers is applied. This filtering ensures that only significant features, corresponding to regions with substantial muon interaction, are retained in the final reconstructed images. This step enhances the contrast and clarity of the reconstructed objects, facilitating more accurate analysis and interpretation of the tomographic results. Both the SI and POCA algorithms produce nearly identical results under identical conditions. In Figure 7, centrally positioned within the muon tomography station, lead letters shaped like "MUON" are reconstructed, showcasing the SI algorithm's capability in imaging.

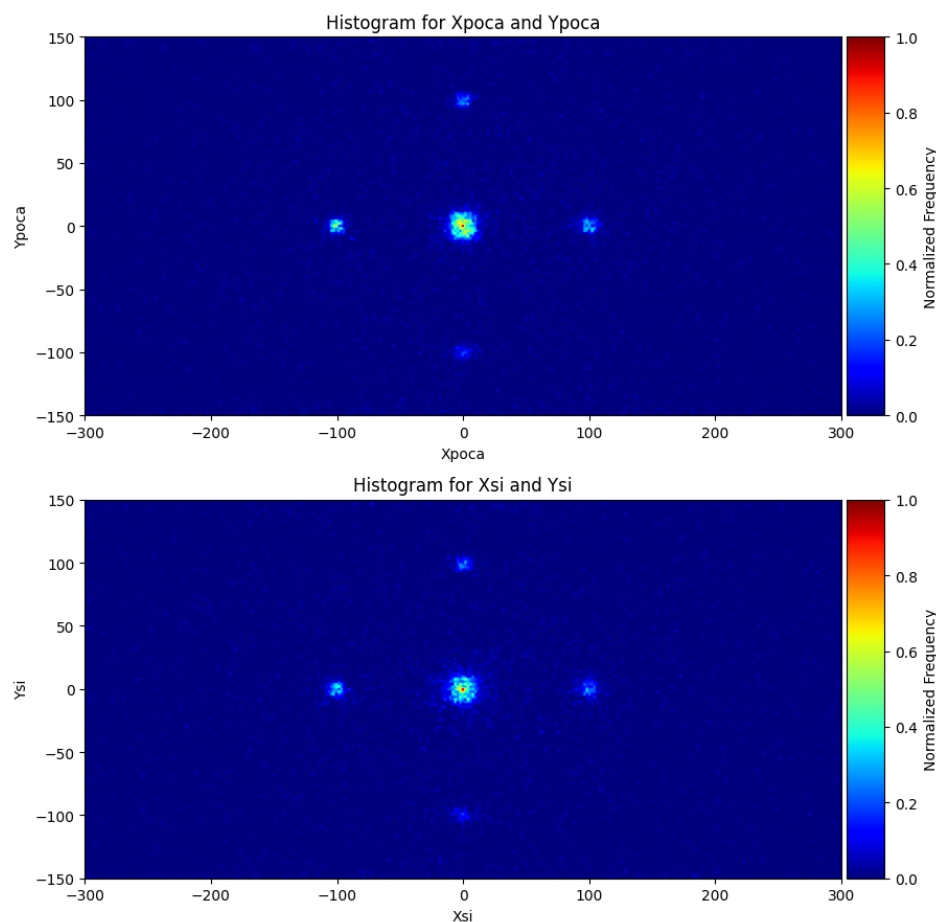


Figure 6. 2D reconstruction of five-block scenario using SI and POCA method

Figure 8 illustrates a comparison of CPU time between the SI and POCA algorithms. It is evident that the SI method not only generates clear images but also requires shorter computational time compared to the POCA algorithm.

To visually compare the SI and POCA algorithms in muon tomography, a plastic scintillator measuring one meter by one meter was positioned at the center of the system (Figure 9). By examining the residuals between the measured and calculated hit positions (Figure 10), it becomes evident that the margin of error is smaller when using the SI algorithm compared to the POCA algorithm.

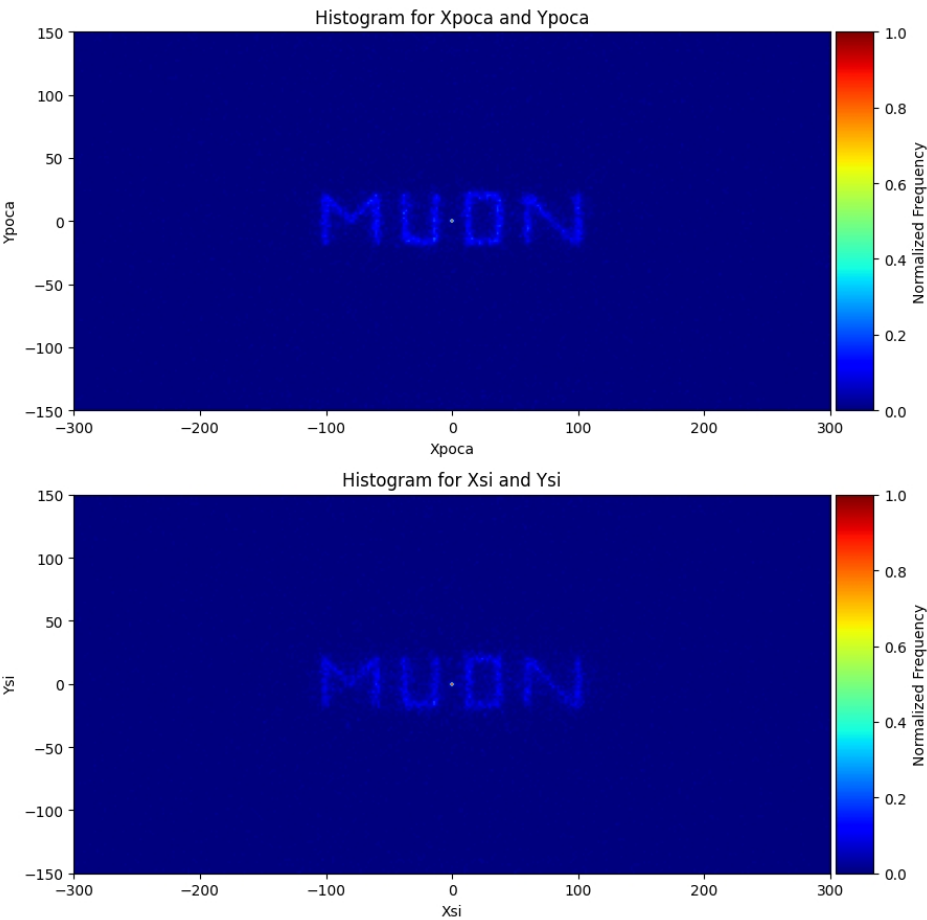


Figure 7. Comparison of SI and POCA reconstruction methods in the same conditions

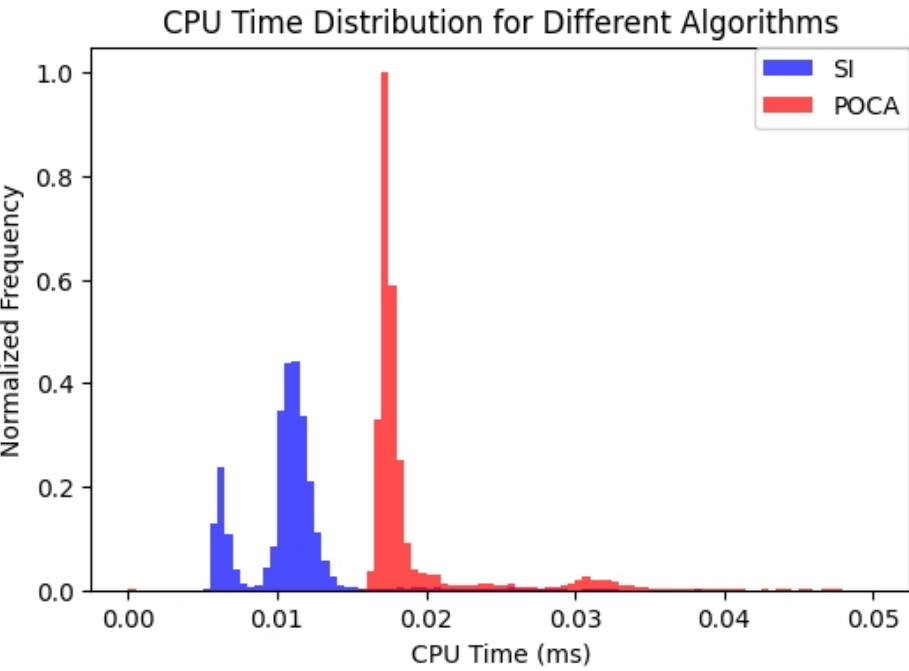


Figure 8. Comparison of CPU time for SI and POCA algorithms in the same conditions

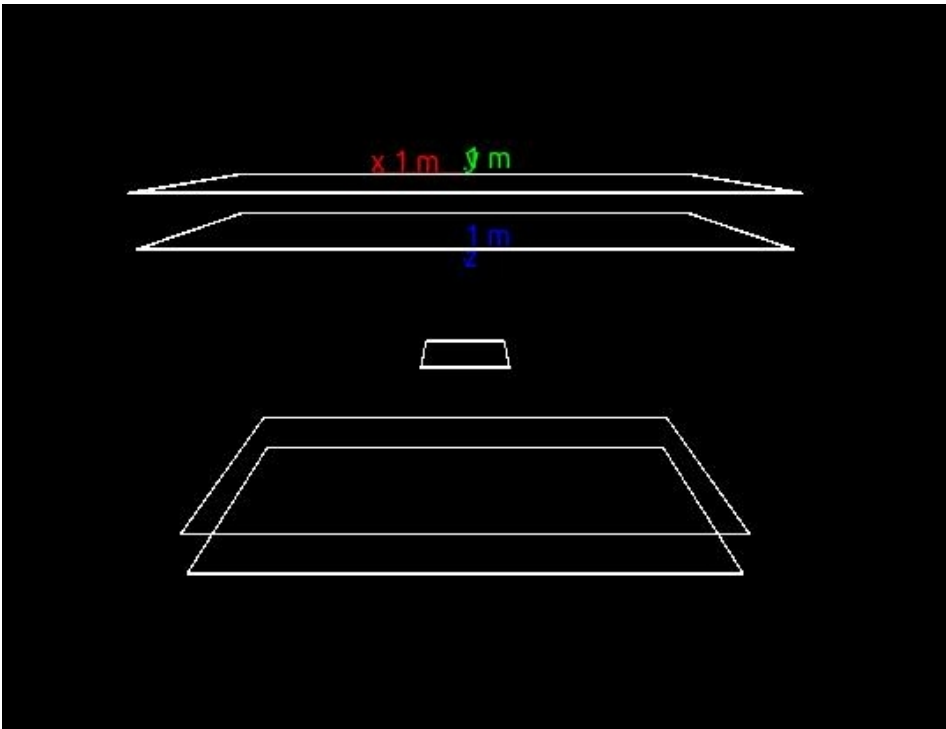


Figure 9. Placement of a one-meter by one-meter plastic scintillator at the center of the muon tomography system for comparing the SI and POCA algorithms

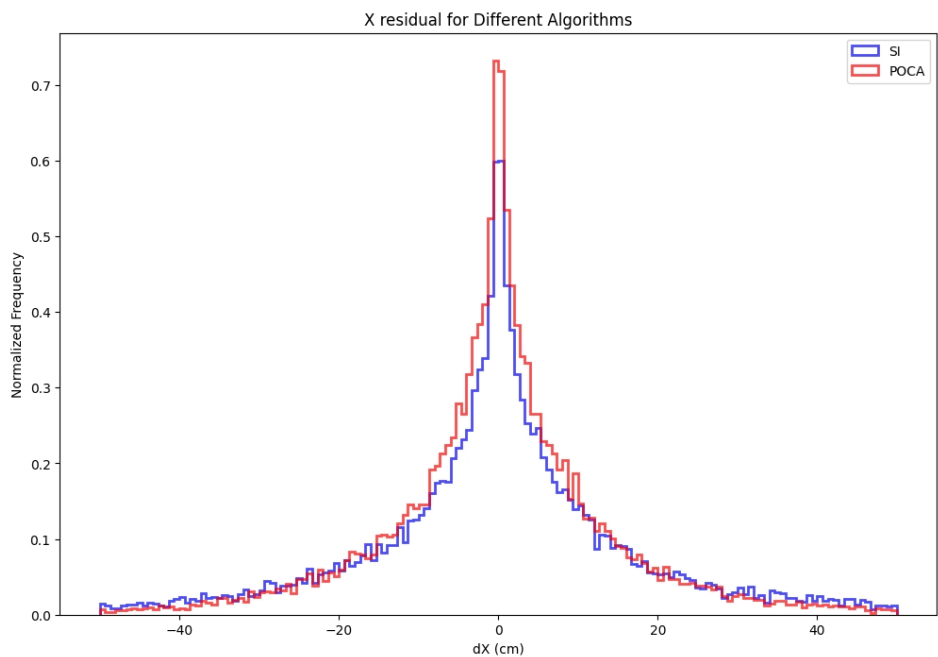


Figure 10. Residuals between measured and calculated hit positions, illustrating smaller margin of error with the SI algorithm compared to the POCA algorithm in muon tomography

We defined the Signal-to-Noise Ratio (SNR) as a measure of performance based on the residual distribution relative to the true hit positions. SNR evaluates how well the algorithms perform by comparing the residuals of calculated hit positions with the true positions. As depicted in Figure 11, the SI algorithm shows superior performance compared to the POCA algorithm, with higher SNR values indicating smaller residuals and thus better accuracy in hit position estimation. The SNR values

reflect the performance of each algorithm in estimating hit positions, with higher SNR indicating better accuracy and lower residuals.

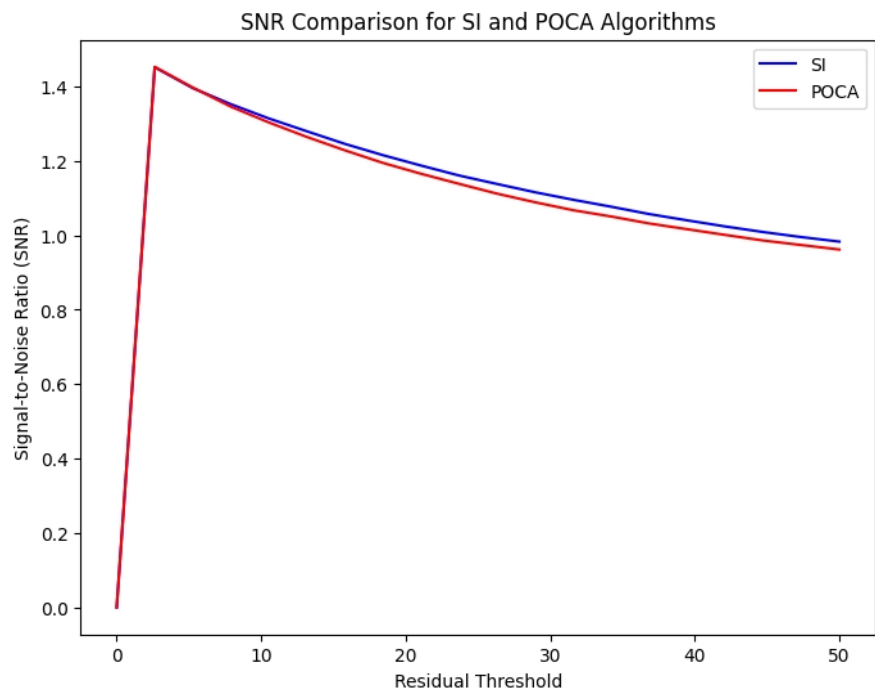


Figure 11. Comparison of Signal-to-Noise Ratio (SNR) for SI and POCA algorithms

Additionally, we conducted an analysis using the receiver operating characteristic (ROC) for the scattering angle. The scattering angles were calculated using the reconstructed scattering points, and we set a threshold of 10 milliradians. The ROC analysis helps to understand the discrimination capability of the algorithms. As shown in Figure 12, the area under the curve (AUC) values for SI and POCA are 0.99 and 0.96, respectively. This indicates that the SI algorithm has a superior ability to correctly classify the scattering events compared to the POCA algorithm.

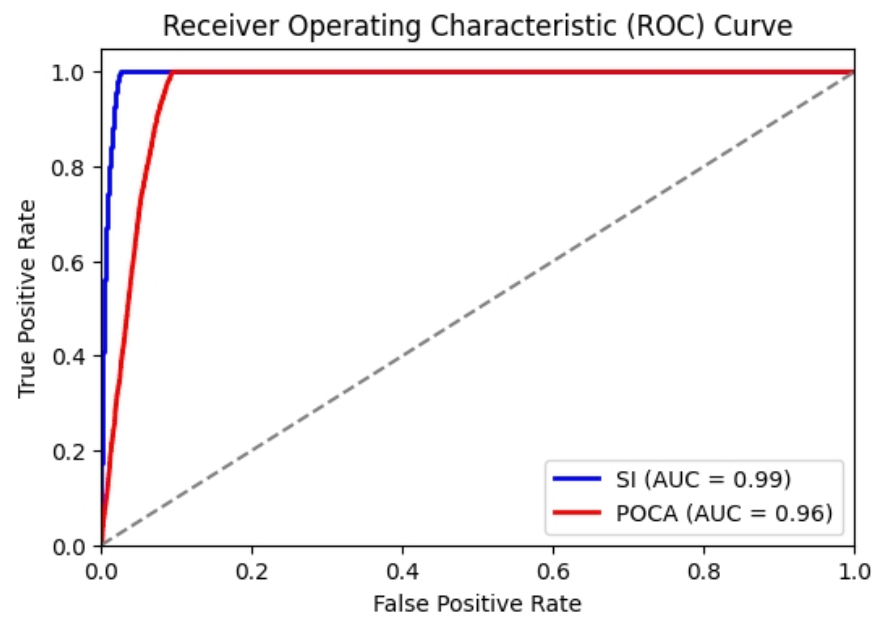


Figure 12. Receiver Operating Characteristic (ROC) Curve for scattering angle, with a threshold set at 10 milliradians

7. Discussion

Reconstructed images in Figures 5 (five-block scenario) and 6 (MUON-shaped lead letters) show nearly identical results for the SI and POCA algorithms. Figure 7 compares CPU time, demonstrating that the SI algorithm operates more efficiently under identical conditions. To assess positional accuracy, we placed a 1x1 m² scintillator plate at the center of the muon tomography station, comparing measured hit positions with reconstructed positions. Figure 8 illustrates the comparison of X residuals distribution, revealing that the SI algorithm produces smaller residuals, indicating more accurate hit position calculations. We also analyzed the Signal-to-Noise Ratio (SNR), which measures the clarity of a signal relative to background noise. The SI algorithm exhibits a higher SNR, highlighting its ability to distinguish signals more effectively than the POCA algorithm. Finally, ROC analysis using a 10 milliradian scattering angle threshold shows an AUC of 0.99 for the SI algorithm and 0.96 for POCA, underscoring the SI algorithm's superior performance in accurately identifying true hit positions.

In conclusion, these findings demonstrate that the SI algorithm offers comparable imaging quality, lower CPU time, smaller residuals in hit position calculations, higher SNR, and superior performance in ROC analysis compared to the POCA algorithm in muon tomography. These advantages position the SI algorithm as a promising choice for enhancing the accuracy and efficiency of muon tomography applications.

8. Conclusions

The comparative analysis between the Slope Intercept (SI) and Point of Closest Approach (POCA) algorithms in muon tomography reveals compelling advantages of SI across several critical metrics. SI consistently outperforms POCA in key aspects. Firstly, SI enables superior visualization of inspected volumes, resulting in clearer and more accurate image reconstructions crucial for effective material identification and characterization. Additionally, SI demonstrates enhanced computational efficiency with reduced CPU time compared to POCA, facilitating faster data processing and analysis.

Moreover, SI shows fewer residuals, indicating closer agreement between measured and estimated impact positions. This reduction in disparity enhances the sensitivity of SI-based reconstructions, ensuring more reliable imaging results. SI also excels in metrics such as Signal-to-Noise Ratio (SNR) and Area Under the Curve (AUC) in Receiver Operating Characteristic (ROC) analyses, signifying its superior capability for precise material identification and localization.

Overall, these findings highlight SI's suitability for applications requiring robust imaging and efficient data processing, which are crucial for advancing security measures and scientific research. While further research is necessary to optimize SI's accuracy and practical implementation, its promising performance indicates significant potential for real-time imaging of materials in inspected volumes. SI represents a valuable advancement in muon tomography algorithms, offering a straightforward yet effective solution to enhance imaging capabilities across security, industrial, and scientific applications.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

POCA	Point of Closest Approach
SI	Slope Intercept
EM-ML	Expectation Maximization-Maximum Likelihood
SNR	Signal-to-Noise Ratio
ROC	River Operating Characteristic
AUC	Area Under the Curve

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