Geant4 Simulation Study of Low-Z Material Identification Using Muon Tomography

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Abstract

Traditional X-ray scanning systems for cargo use ionising radiation which can be harmful to operators and the environment and requires shielding. Fully passive muon tomography is a promising alternative or a complementary approach to X-ray scanners. Muon tomography is a non-invasive technique that uses naturally occurring cosmic-ray muons and their scattering in various materials to create images of cargo in trucks or containers without applying ionising radiation. Muons are high-energy particles that are produced when primary cosmic rays collide with the Earth's atmosphere. These muons can penetrate through thick materials, such as concrete or metal, and are therefore useful for detecting hidden objects, including contraband. Muon tomography is expected to be used for detection of a wide range of materials, including metals, plastics, and organic materials like drugs or cigarettes, as well as weapons and explosives.

In this work we have used the GEANT4 toolkit to simulate the performance of muon tomography in identifying the contraband cigarettes hidden inside the legal low-Z materials in a truck trailer. We have used the Point of Closest Approach (PoCA) reconstruction algorithm to reconstruct the three-dimensional image of a loaded truck.

Introduction

This work is part of the ongoing SilentBorder project. Objectives of this project are to develop and construct a cosmic ray tomography (CRT) scanner for identification of hazardous and illegal goods hidden in trucks and sea containers. The developed sea container scanner system will be light-weight, compact and transportable. Be based on natural cosmic ray tomography technology that is inherently safe for people, generate full 3D images of the scanned volume, support automated customs procedures integrated to system, provides confirmation of container contents according to customs declarations.

Monte Carlo simulations of SilentBorder project includes studying the CRT detector performance, development of detailed models shipping containers and trucks and also creating models of complicated shapes of container loadings with custom goods. Then we modify custom loadings adding some amount of illegal goods. Most of previous works on muon tomography were concerning using this method for detection of special nuclear materials to prevent nuclear terrorism.

Muon generators

We have applied CRY and MUSIBO muon generators to sample cosmic-ray muons at the surface of the Earth. The CRY software package generates muons on a horizontal plane while MUSIBO, based on a well-known Gaisser's parameterisation of the muon spectrum and angular distribution, modified to account for muon decay and Earth surface curvature, generates muons on the surfaces of a box (rectangular parallelepiped) which is more appropriate for simulation of inclined muons.

MUSIBO is a parametric generator, where the flux and kinematics of muons are based on Geisser parametrization of the muon spectrum and angular distribution, particles sampled on surfaces of cube (parallelepiped) or flat surface. An advantage of such a sampling of muons on cube is the better coverage of highly inclined muons. As particular interest of SilentBorder project is scanning of sea containers and trucks the advantage of MUSIBO generator is obvious due to better sampling of inclined muons.

Geant4 model of sea container and cargo material composition

Besides modeling muon detectors, creating Geant4 models of shipping container and cargo loaded into shipping containers is an important part of the simulation chain. The shipping (sea) container is a standard-sized rectangular box used to transport goods by ship, train, or truck. As a source of data for cargo contents and average densities of cargo shipments one can use a PIERS (Port Import/Export Reporting Service) United States import data set. It can be used to understand containerized cargo traffic and cargo material composition. According to research [1] the mean cargo density is just under 0.2 g/cm^3. In order to evaluate sensitivity of CRT to realistic scenario's of cargo materials we create 3D models using Blender and FreeCAD tools. For testing Geant4 models of sea container and cargo materials we use simplified detector design - rectangular planes as ideal detectors. PoCA reconstruction algorithm is used to evaluate the quality of created Geant4 models.

Fig. 1 3D CAD model imported into Geant4 using CADMesh.

On Fig.1 an examples of CAD models which can be imported into Geant4 are presented. Fig.2 shows the Geant4 model of sea container with plane detectors. Fig. 3 and 4 shows PoCA reconstructed image of empty container in 3D and 2D projections.

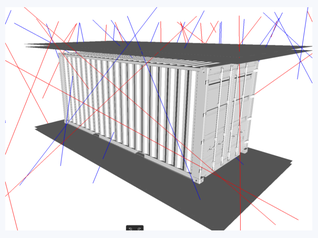

Fig. 2 Geant4 model of shipping container

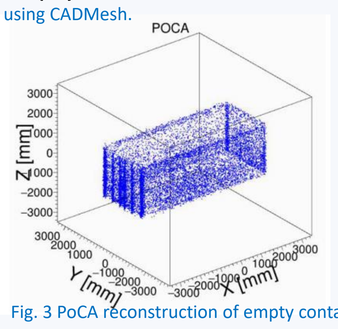

Fig. 3 PoCA reconstruction of empty conta

Simulating real scenario we created Geant4 model of container loading according based on established tips of loading cargo (see figure 5). On figure 6 boxes with clothes fixed on palettes. 20ft container can fit 11 Euro Pallets or 10 Standard Pallets. On figure 7 on each palette one randomly selected box of clothes (0.2 g/cm^3) is loaded with G4_BORON_OXIDE (1.812 g/cm^3)

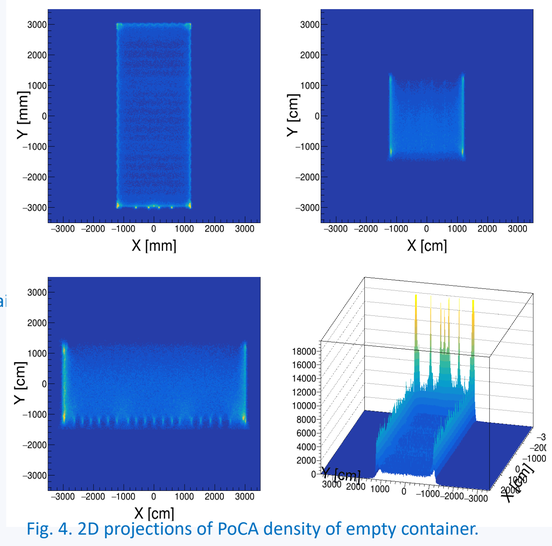

Fig. 4. 2D projections of PoCA density of empty container.

Fig. 5 Example of sea container loading with goods packed in cardboard boxes that are placed on pallets.

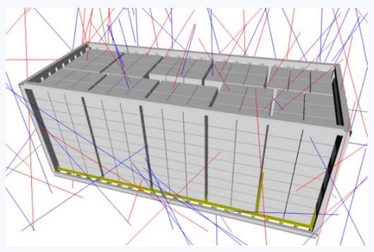

Fig. 6 Geant4 model of sea container loading with goods packed in cardboard boxes that are placed on pallets.

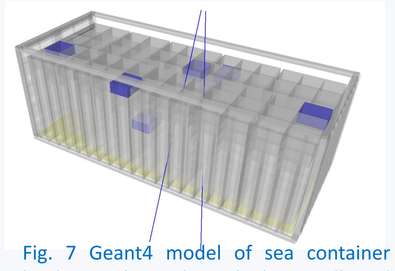

Fig. 7 Geant4 model of sea container loading with goods packed in cardboard boxes that are placed on pallets.

Figure 8 shows the reconstructed image of container loaded with clothes. Figure 9 shows the reconstructed image for the scenario with one box loaded with G4_BORON_OXIDE. On these images low-Z materials can be visualized and compared with one expected from custom manifest.

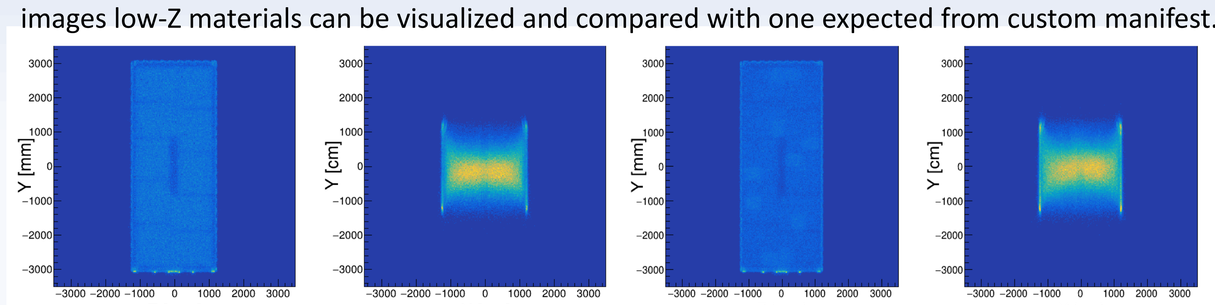

Fig. 8 Reconstructed image of container loaded with clothes.

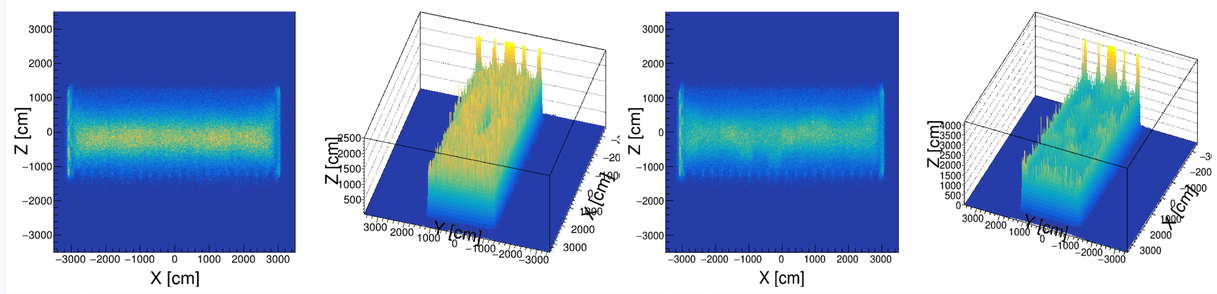

Fig. 9 Reconstructed image of container loaded with clothes and

To obtain a clearer image of illegal goods and a more accurate estimate of their density, the reconstructed image can be sliced to improve the signal-to-background ratio. On the resulting slices (Fig.10) one can well localize hidden G4_BORON_OXIDE.

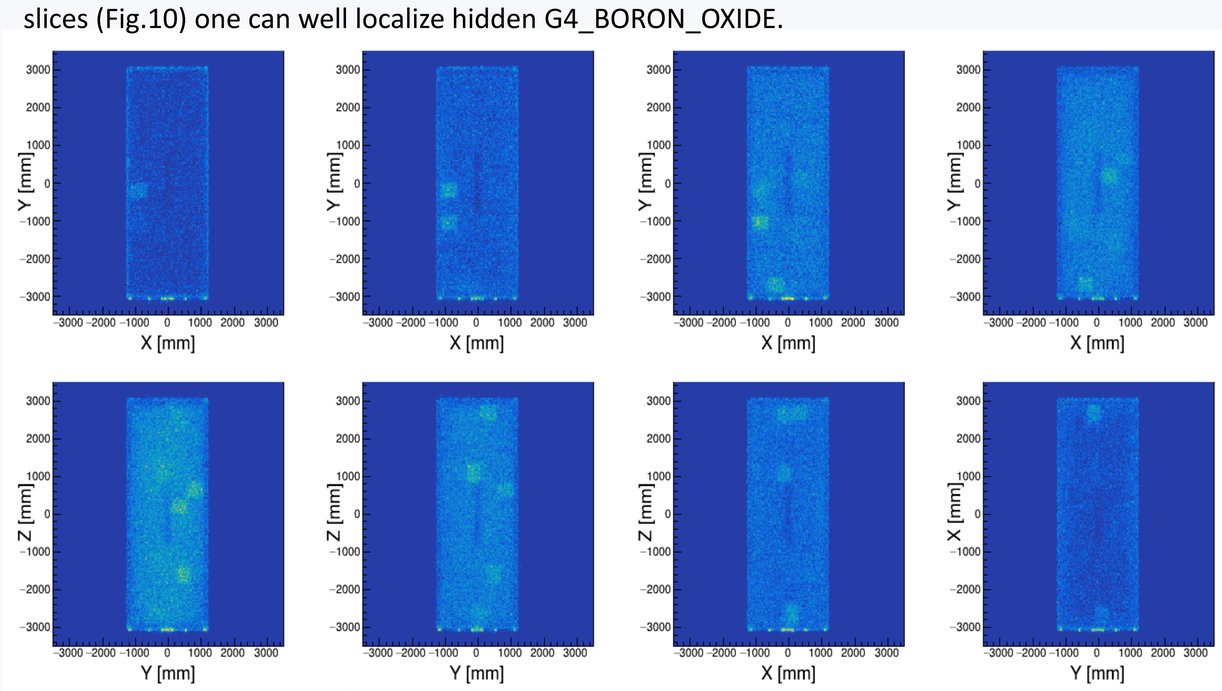

Fig. 10 Visualization of slices of 3D image of container loaded with boxes muon flux produced by CRY generator.

Simulation of truck and semi-trailer

Another real smuggling scenario taken from online resources describing cigarette smuggling hidden within wood pellets, plasterboards, or wooden boards. As an example, we looked at cigarettes (density 0.18 g/cm^3) hidden within wooden boards (density 0.8 g/cm^3) .

Fig. 11 Real cigarette smuggling to replace part of wooden boards

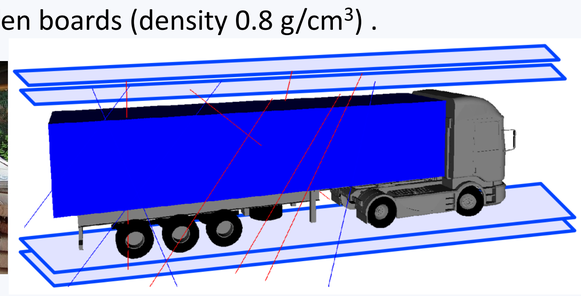

Fig. 12 Geant4 model of semi-trailer loaded with wooden boards

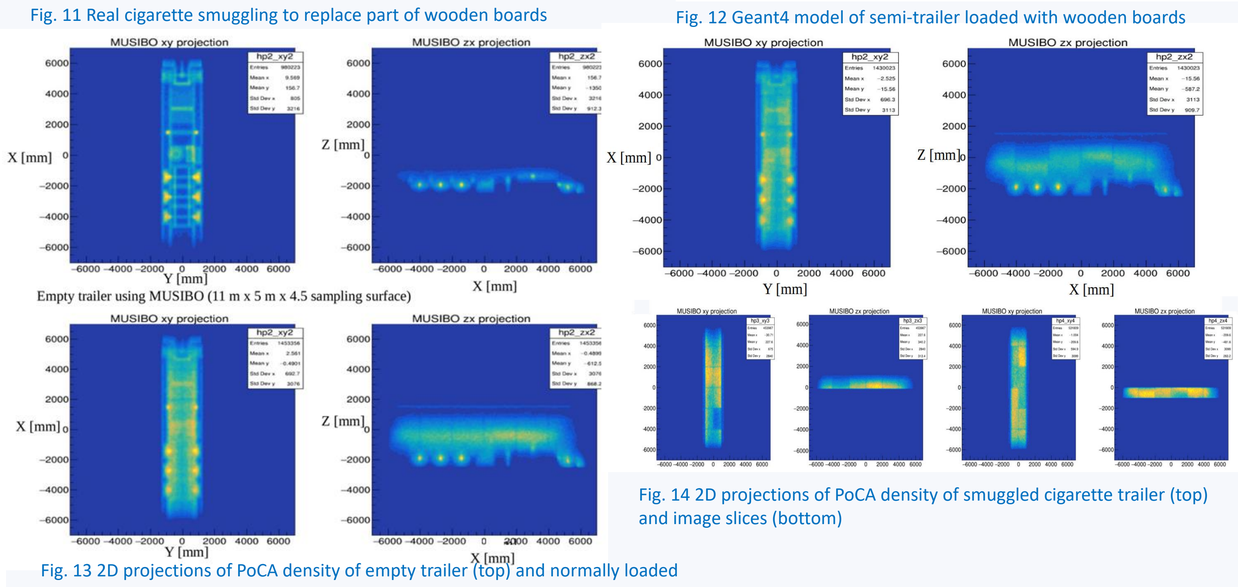

Fig. 13 2D projections of PoCA density of empty trailer (top) and normally loaded

Fig. 14 2D projections of PoCA density of smuggled cigarette trailer (top) and image slices (bottom)

As one an see of figures the cigarettes hidden within wooden boards are visualized and localised.

Conclusion

In this simulation study using GEANT4 we have used simplified detector design in form of ideal plane detectors and simple PoCA reconstruction algorithm to investigate the potential of muon tomography for detecting hidden materials in cargo. We conclude that muon tomography is capable of producing images of low-Z objects and can become a powerful tool for detecting verios types of contraband in a harmless way.

References

1. M.A. Descalle, D. Manatt, D. Slaughter, Analysis of Recent Manifests for Goods Imported Through US Ports, Lawrence Livermore National Laboratory Report UCRL-TR-225708, 2006.

Acknowledgments

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