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Geant4 simulation study of low-Z material detection using muon tomography

Anzori Sh. Georgadze[a,b,*] **and Vitaly A. Kudryavtsev**[c]

[a]*Institute of Physics, University of Tartu,*
  W. Ostwaldi 1, 50411 Tartu, Estonia

[b]*Institute for Nuclear Research of the National Academy of Sciences of Ukraine,*
  Prospekt Nauky 47, 03680 Kyiv, Ukraine

[c]*Department of Physics and Astronomy, University of Sheffield,*
  Hounsfield Road, Sheffield S3 7RH, U.K.

  E-mail: anzori.heorhadze@ut.ee

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 hidden inside the legal cargo. We have used the Point of Closest Approach (PoCA) reconstruction algorithm to reconstruct the three-dimensional image of a loaded truck.

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*Corresponding author.

Contents

1 Introduction

The rapid growth in international commerce has presented a significant challenge for cargo security, and one of the primary issues is the limited capacity to inspect and verify the contents of containers. Only a small percentage of containers are typically scanned or inspected thoroughly at ports and border crossings which leaves open the possibility of security breaches and smuggling activities. Traditional methods of cargo inspection, such as X-ray scanning and manual inspections, are often time-consuming and may not provide a comprehensive view of the contents of containers or cargo. Cosmic-ray tomography is an innovative method for cargo security and inspection that has the potential to address the challenges posed by the rapid growth in international commerce.

Muons are subatomic particles that are naturally produced when cosmic rays interact with the Earth's atmosphere. They have the unique property of being highly penetrating, which means they can pass through thick materials like concrete and metal. This property makes them suitable for cargo inspection, as they can be used to create detailed images of the interior of containers or cargo without the need for physical intrusion. Muons interact with matter primarily through the electromagnetic force which makes muons to deflect from their original trajectory (Coulomb scattering) and causes the reduction in muon energy (mainly via ionisation and excitation energy loss mechanism). Cosmic-ray muons are part of the natural background radiation environment that humans are exposed to continuously and hence, will not harm or alter the objects being investigated, making them ideal for non-invasive inspection and imaging. Cosmic-ray muons have energies at sea level about 3–4 GeV and are able to penetrate much deeper into the materials compared to X-rays. Cosmic-ray tomography (CRT) [1–3] is considered to be a new inspection technology, complementary to the X-ray imaging which is most widely used to scan cargo at borders. It is expected that CRT will help to increase the number and fraction of scanned cargoes. Besides detection of high atomic number materials, namely Special Nuclear Materials there was research on possibility to detect low-Z materials [4–6].

This paper investigates the possibility of applying cosmic-ray tomography for scanning shipping containers and lorries for contraband hidden inside legal cargo within acceptable measuring time. We have used GEANT4 toolkit [7] for simulating realistic scenarios of hidden illegal low atomic number (low-Z) materials inside other low-Z materials.

2 The SilentBorder project

The SilentBorder project [8] funded by the European Union through the Horizon 2020 scheme, is developing a new high-technology CRT scanner that enables safe and fast screening, detection and identification of hazardous and illegal goods, contraband, and persons hiding in containers and trucks. The SilentBorder project is focusing on the imaging of shipping containers and trucks to search for the low-Z contraband hidden inside the legal cargo. According to research [9] the mean cargo density is expected to be about or below $0.2 \, g/cm^3$, which means that most of the commerce goods traffic consist of low-Z materials that contain mainly C, H, O and N. Illegal materials like drugs or explosives also consist of the same elements which make the task of their detection challenging when they are hidden among the legal goods, because the Coulomb scattering of muons for these materials is small, resulting in a small deviation of the muon trajectory from a straight line. The future CRT system will be light, compact and transportable. It should be capable of generating three-dimensional (3D) images of the scanned volume, supporting automated customs procedures integrated into the system, and providing confirmation of container/truck contents according to customs declarations.

2.1 The SilentBorder project detector concept

The detector concept of the SilentBorder project is based on the use plastic scintillator with SiPM read out. The detailed geometry of detector modules consisting of orthogonal double layer scintillator trackers (figure 1(a)) has been constructed in Geant4 toolkit [7] for simulation of optical photon transport as well as acquiring muon momentum and energy deposited by muons. The Monte Carlo simulation of the CRT allow to optimize the scintillating fiber (SciFi) trackers combined in detector modules and to optimize distance between tracking detectors to obtain best track reconstruction accuracy.

3 Monte Carlo simulations of the cosmic-ray tomography system

3.1 GEANT4 simulation study

The ability of muon tomography to distinguish hidden illegal materials was studied by GEANT4 [7], simulating the passage of a muon through a shipping container or truck and analyzing the resulting tomographic images. A model of the CRT setup consisting of two sets of trackers, each having two position sensitive detectors has been built in GEANT4 platform. The detectors have been modeled as plane detectors made of plastic scintillator having a 100 % detection efficiency. A geometry of a Cosmic Ray Tomography (CRT) Station is shown in (figure 1(b)). The CRT station consist of tracking modules at the top, the bottom, and on the sides. Plane detectors with dimensions $8 \times 4 \times 0.001 \, m^3$ for scanning shipping container and with dimensions $12 \times 4 \times 0.001 \, m^2$ for scanning truck have been added to the model. In the GEANT4 simulation, we use the standard physics list for high-energy transport named "FTFP_BERT", which contains all cross sections of muon interactions with matter, including ionisation, bremsstrahlung, pair production, photonuclear interaction and multiple Coulomb scattering.
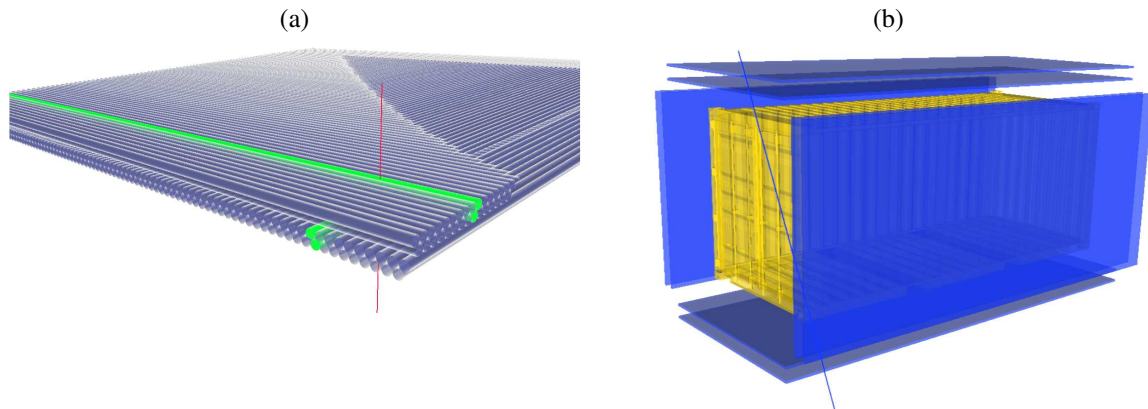
Figure 1. Layout of the plastic scintillator tracker in GEANT4 (a), schematic view of cosmic ray tomography station (b).

All hits in the sensitive detector volume have been stored for further analysis. The uncertainty in the hit position due to the detector resolution has been taken into account by adding a random value to hit point as its mean and the standard deviation equal to the spatial resolution of 0.1 mm.

3.2 Cosmic-ray muon generation

To generate muons we used a well known cosmic-ray shower generator (CRY) [10], EcoMug generator [11] and a muon generator MUSIBO [12], previously used in a number of applications and particle physics projects including work on muon tomography and adapted for the SilentBorder project. All generators have been interfaced with the GEANT4 toolkit. CRY uses the library where fluxes and kinematic variables of muons, neutrons, protons, electrons, gammas, pions and kaons are tabulated. The generator takes into account geomagnetic effects, depending on time of the year and geographical location. Particles are sampled on a flat surface. EcoMug allows the generation of CR muons according to user-defined parametrizations of their differential flux. Muons can be sampled on a flat, cylindrical or hemispherical surface. MUSIBO is based on a well-known Gaisser's parameterization [13] of the muon spectrum and angular distribution, modified to account for muon decay and Earth's surface curvature. Muons are sampled on the surface of a box (rectangular parallelepiped), which is efficient for modelling inclined muons. This is an advantage for the SilentBorder project due to a more complete coverage of muon sampling surfaces around shipping containers and lorries. Comparison between energy spectra and zenith angle distributions from the three generators are shown on figures 2(a) and (b), respectively.

3.3 Tomographic reconstruction

A simple Point-of-Closest-Approach (PoCA) method [14] was used to reconstruct 3D images from simulated data. This method makes the simplified assumption that the muon scattering occurs in a single point and allows for a quick test of developed GEANT4 geometries of a real scenarios of cargo. The PoCA is a geometrical algorithm which determines the minimum distance between the two skew lines in a three dimensional space and selects the central point on the line that corresponds to this minimum distance. PoCA algorithm returns a set of PoCA points and scattering angles at each point. All hits in all detector planes before and after muon transport through the cargo have been used
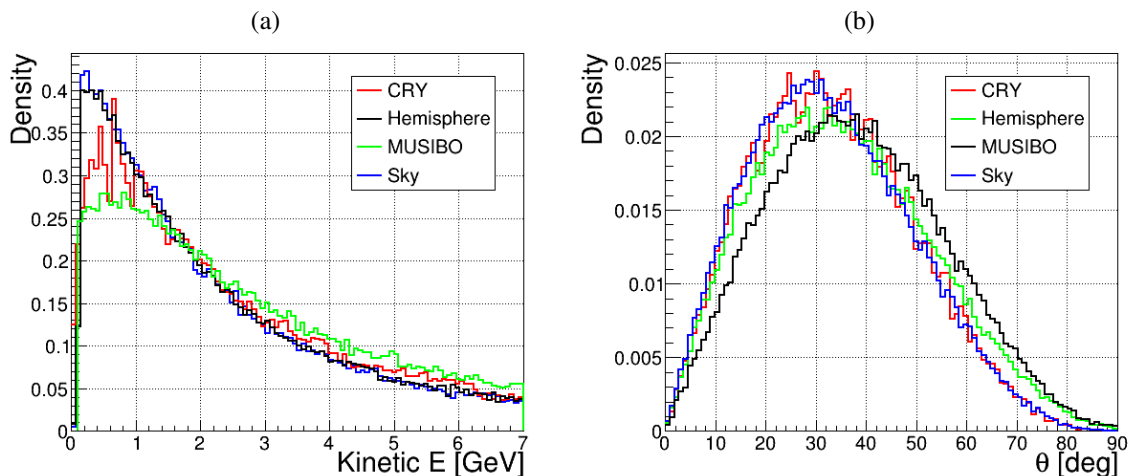
Figure 2. Distributions of *E* kinetic energy (a) and zenith angle *θ* (b) generated using CRY, MUSIBO, and two EcoMug modes, corresponding to flat and hemispherical surfaces.

to reconstruct the positions of scattering points. To remove incorrect events and tracks with little scattering, the angle between the incoming and outgoing tracks has been selected to be larger than 0.5°.

3.4 Image processing

An image processing technique include spatial selection of scattering events. We cut all events lying outside the volume of interest to remove the incorrect PoCA points. Then we apply statistical filtering method to remove noise by finding a median value among voxels in 3D image or among pixels in 2D image projections. The median filter treats each voxel as a matrix and replaces the values of each voxel with the representative median value. Median filtering is a type of nonlinear filtering technique used in image processing to reduce noise while preserving structural features in tomographic images. Median filtering removes noise by replacing the pixel or voxel value at a given location with the median value of the pixels in a local neighborhood around that location. After statistical filtering we apply a k-NN (k-Nearest Neighbours) like algorithm for image processing to remove background from legal cargo. This method allow to clear image of areas with lower scattering density comparing to large scattering density generated by most of illegal materials. In some cases, hidden contraband materials has lower density then material matrix of legal cargo. In this case hidden contraband will be visualized on image as a gap or hole and will be recognized as anomaly and case for additional investigation.

3.5 Simulation of scenario of shipping container

To simulate a scenario of shipping container loaded with cargo with hidden contraband we have created GEANT4 model of standard 20 foot shipping container ($609.6 \times 259.1 \times 243.8 \, \text{cm}^3$) based on drawings from container manufacturers (figure 1(b)) with different types of cargo. There are established tips for container optimized loading. A master case is a bag with bulk materials or carton box that contains multiple units, and sometimes also includes inner packs, which is another level of packaging. To facilitate handling and storage, cargo usually placed on pallets. A pallet is a shipping platform in which multiple master cases are shipped on. Cargo are packed into master cases, which are packed into pallets to be shipped. To produce tomographic image of container we simulated
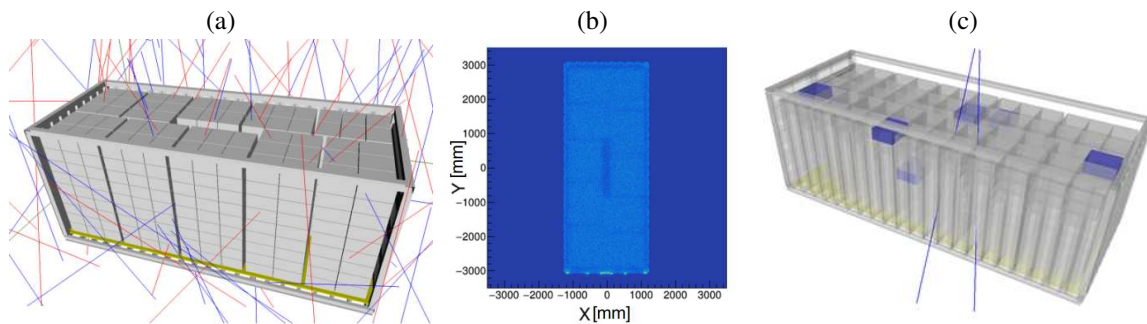
Figure 3. (a) GEANT4 visualization of shipping container loaded cardboard boxes with clothes arranged on pallets. (b) XY projection of PoCA scattering density of container loaded with cloths. (c) GEANT4 visualization of the container in which one bag in each pallet is loaded with explosive (bags in blue color).

1–10 million muons using CRY muon generator with muons sampled on the surface $10 \times 10\,\text{m}^2$ and MUSIBO generator with muons sampled on surface of the box $11.0 \times 5.0 \times 4.5\,\text{m}^3$, which correspond to 60–709.6 seconds of measurement time. Image processing is performed using ROOT package [15].

In order to obtain a clearer image with better signal-to-background ratio and determine positions of hidden illegal goods and an estimate of their density besides image filtering we perform spatial cuts, removing PoCA points outside shipping container area. Next we subtract the image of an empty container from the 3D image of a loaded container. Strict standards of shipping containers make the procedure of image subtraction quite accurate. After subtraction we apply additional spatial cut of an image to dimensions $5.85 \times 2.35 \times 2.35\,\text{m}^3$ which correspond to internal part of 20 foot container.

Figure 3(a) shows GEANT4 visualization of cardboard boxes with clothes arranged on pallets. The 2D projection of the image is characterized by uniform distribution of scattering density and each palettes can be resolved (figures 3(b)) and 3(c)). Low-Z materials can be identified on these images by analysing scattering density distribution and compared with those expected from the custom manifest.

We consider the scenario of illegal material hidden among boxes with legal goods. For this in each palette one randomly selected box of is loaded with explosive material (density $1.812\,\text{g/cm}^3$). Reconstructed tomographic images filtered according to the previously described procedure are shown for three simulated scenarios: explosive hidden inside legal cargoes such as cloths, bananas and dry pasta shown in figure 4(a), (b), (c), correspondingly. Figure 5 shows for comparison radiographic images of the same geometry simulated with Geant4 using energy spectrum of 9 MeV X-rays. As can be seen from comparing figures 4 and 5 sensitivity of the two techniques is similar. However, muon tomography has advantages on not relying on ionization sources and providing more informative and useful 3-dimensional data, for which more sophisticated analysis methods can be applied.

3.6 Simulation of scenario of the semi-trailer truck

Smuggling of counterfeit tobacco products is a global issue that has been a concern for governments, and public health organizations for many years [16]. Customs and Border Protection currently perform inspections for general contraband using X-rays. Hiding contraband behind denser materials makes inspection difficult. We consider a scenario with smuggling tobacco products hidden within wood pellets, wood bricks or wooden boards. The density of woods varies from about 0.3 to 1.6 g/cm^3. The GEANT4 model of the semi-trailer truck ($13.6 \times 2.7 \times 2.45\,\text{m}^3$) was created (figure 6). Differences among species or samples of the same species are due to varying proportions of wood substance and void
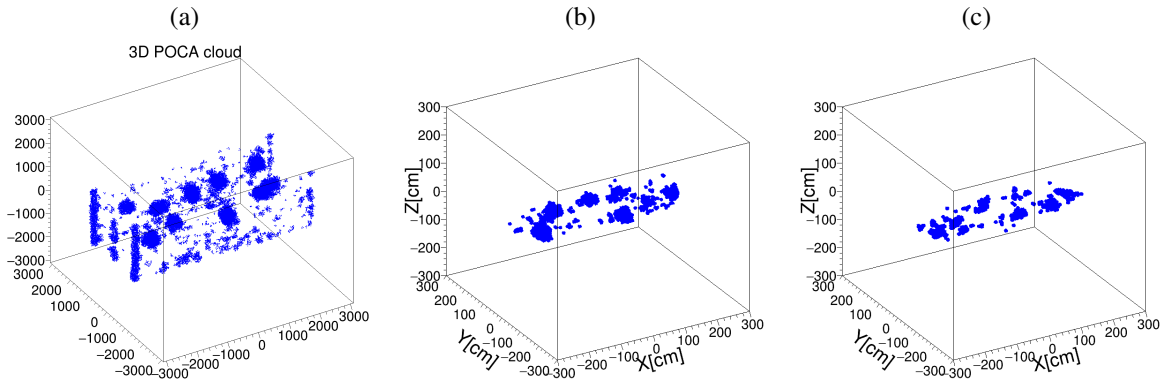
Figure 4. Reconstructed muon tomographic images for scenarios of explosive hidden in container among cloths (a), bananas (b) and dry pasta (c).
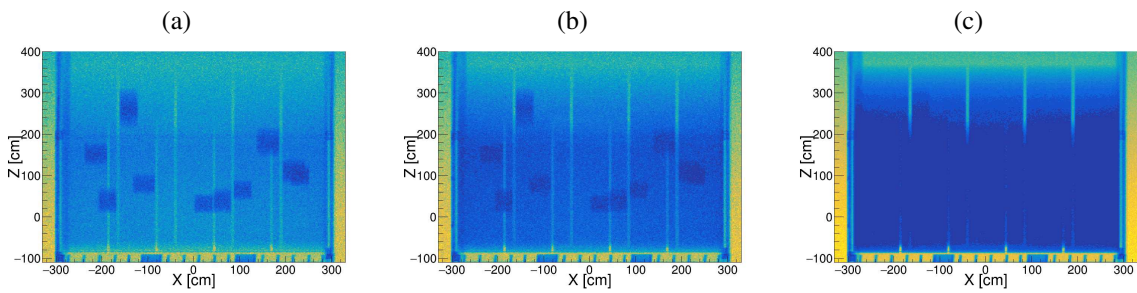

Figure 5. Radiographic images simulated in Geant4 using 9 MeV X-rays for the same scenarios of explosive hidden in container among clothes (a), bananas (b) and dry pasta (c).
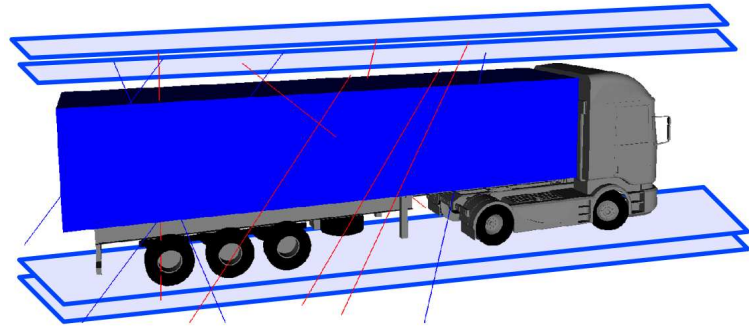

Figure 6. Schematic view of geometry of CRT scanner with plane detectors for scanning the truck.

volume. For simulation the density of cigarettes is estimated at 0.18 g/cm³ and for wooden boards we used the density of 0.8 g/cm³. In this simulated scenario, stacks of wooden planks measuring 2 m × 1 m, they are arranged in two rows in height, two rows in width and six rows in length. We simulated 2–20 million muons using CRY muon generator and muons sampled on the surface 20 m × 20 m and MUSIBO generator with muons sampled on surface of the box 21.0 m × 5.0 m × 4.5 m which correspond to 80–826.4 seconds of measurement time. The simulated results are presented in figure 7. It can be seen that the contraband cigarettes that replace the stacks of wooden planks can be identified.
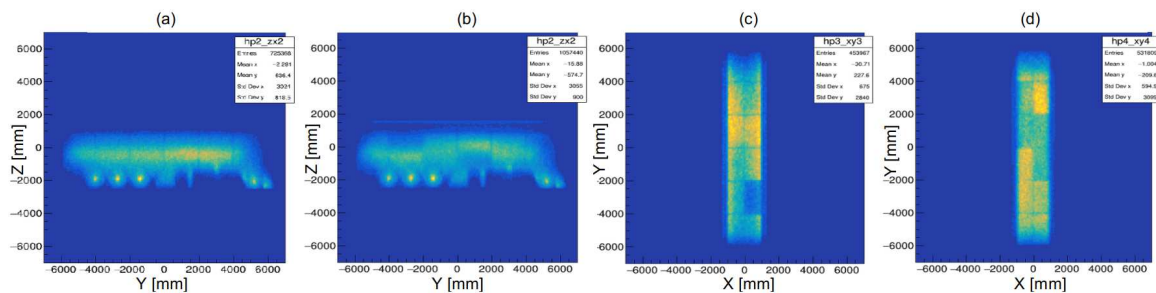
Figure 7. 2D projections of a tomographic image of loading a truck with legal cargo (a), 2D projections of a tomographic image of loading a truck with smuggled tobacco (b), upper (c) and lower (d) projections of tomographic sections of 100 cm high of the body of a semi-trailer-van, with stacks of wooden planks and contraband tobacco hidden among them.

4 Conclusions

The work has presented the performance evaluation of the cosmic ray muon tomography scanner developed for the SilentBorder project. A complete Monte Carlo simulation chain is constructed for sampling and transporting cosmic-ray muons and simulation of realistic smuggling scenarios. A comparative study of three different particle generators (CRY, MUSIBO and EcoMug) shows that the reconstructed images are very similar, so we mainly use the CRY generator since not only muons but also other secondary cosmic rays are included in the simulation. GEANT4 models of container/truck with and without smuggling materials were constructed and analysis framework has been tested for example smuggling scenarios. For a simplified detector design, a simple PoCA algorithm successfully reconstructed the contents of containers/trucks and detected materials hidden in a legal low-Z cargo. We are developing a wide database of GEANT4 cargo models to describe various scenarios for hidden objects within permitted cargo and to generate synthetic data sets needed to train artificial intelligence tools to automatically detect contraband. Based on our performance evaluation, we concluded that muon tomography is capable of producing images of hidden low-Z materials and can be a powerful tool for the harmless detection of various types of contraband.

Acknowledgments

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