Experimental Results Supporting the Concept of One-Sided Muon Tomography

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Summary

Naturally occurring cosmic-ray muons have been shown to exhibit properties ideal for imaging the interior of structures containing material of high density and atomic number. The commonly used method for 3D imaging requires two modules of detection in order to measure muon scattering. This paper provides experimental results for a novel 3D imaging method that uses a reconstruction algorithm common to medical imaging and only one module of detection in order to measure the attenuation of the muon flux at several angles of rotation around a structure.

1. Introduction

Muons are charged particles created as a result of the interaction of cosmic radiation with the upper layer of the earth's atmosphere and are naturally present at the surface of the earth at a constant flux of approximately 1 $cm^{-2}min^{-1}$. On average, they have very high sea-level energies (approximately 3-4 GeV), and this, coupled with their large mass ($\sim 206m_e$) allows them to penetrate deeply into matter with relatively minor changes in trajectory before being attenuated [1]. In the field of nuclear medicine – in particular with X-ray computed tomography (CT) – images of human anatomy can be reconstructed by actively administering small doses of radiation to a patient and measuring its distribution as it exits the body [2]. This paper presents experimental results that support the recently published concept of 'one-sided muon tomography' [3] – an imaging method analogous to X-ray CT in that particle detection occurs only after its transmission through a structure. A single muon detection module was used to measure the distribution of the attenuated muon flux through a structure from several points of view, and a 3D image was reconstructed based solely on these measurements. This method produces images that highlight the presence and spatial distribution of high-Z material and can be used to examine the internal contents of structures for the purpose of waste management, non-proliferation, and accident assessment [4].

2. Non-Destructive Imaging Using Cosmic-Ray Muons

2.1 Multiple Coulomb Scattering and Two-Sided Muon Tomography

The common method for using muons to produce a 3D image exploits the multiple Coulomb scattering (MCS) experienced by the particles as they pass through matter. Figure 1 shows a schematic of the Cosmic Ray Inspection and Passive Tomography (CRIPT) prototype system which has been built at

Canadian Nuclear Laboratories (CNL) to utilize this concept [5]. This 'two-sided muon tomography' concept uses detector modules located above and below the volume of interest to allow the trajectory of individual muons to be tracked and the magnitude and location of scattering events to be determined. This information can then be used to reconstruct a 3D image of the internal structure of the volume. This method is efficient at discriminating between materials of high and low atomic number and can be used for the purpose of imaging nuclear fuel for safeguards and waste management [5].

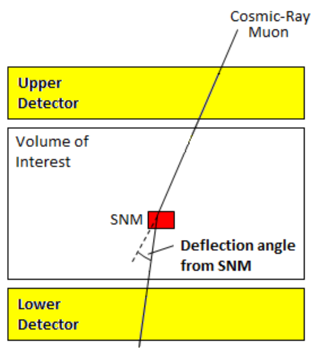

Figure 1   Schematic of the two-sided muon tomography concept.

2.2 Attenuation and One-Sided Muon Tomography

In the field of nuclear medicine, X-ray CT is a type of diagnostic scan that involves irradiation with a controlled X-ray source to generate images of a patient's anatomy. The scanning apparatus (shown in Figure 2) includes an X-ray source and detector that are rotated around the central axis of the patient, measuring the distribution of transmitted X-rays on the exit side of the body [2].

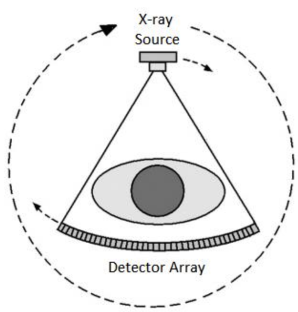

Figure 2   Schematic of the X-ray CT concept.

At each discrete angle of rotation, the measured data represents a 2D projection of the 3D distribution of X-ray attenuation coefficients within the patient. The objective is then to reconstruct a 3D image of the types of tissue within the patient based solely on these measured projections [2].

Structures containing material such as lead or SNM have a much higher probability of completely attenuating this type of radiation. The high energy and large mass of cosmic-ray muons allow them to penetrate more deeply into matter than X-rays, and they too experience ionization (at a rate of approximately 2 MeV per gcm^{-2}) and eventual attenuation [1]. It has been demonstrated that it is feasible to reconstruct a 3D image by using a single muon detector module to measure the distribution of the attenuated muon flux through a structure from several points of view [3]. Unlike the controlled source of radiation used in X-ray CT, the background flux of muons at sea level has a range of directions and energies. The one-sided muon tomography method relies on a detailed knowledge of this flux and a systematic method for handling the raw detector data in order to employ the use of an iterative reconstruction algorithm commonly used in medical imaging [3].

3. Image Reconstruction from Projections

Figure 3 shows a simple 2D function $f(x, y)$ and its projection $R_\theta(x')$ onto a line that has been rotated at an angle of θ with respect to the positive x-axis.

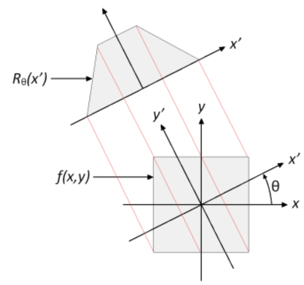

Figure 3 Projection of a simple density function onto a rotated coordinate system.

This process is described mathematically by the Radon transform which relates a 2D function to the collection of line integrals of that function along paths normal to the plane of projection [2]:

$$R_\theta(x') = \int_{-\infty}^{\infty} f(x, y)dy'$$

In the case of X-ray CT, the function $f(x, y)$ represents the distribution of attenuation coefficients within the patient and $R_\theta(x')$ represents the distribution of detected X-rays at one angle of rotation of the source and detector arrangement. In other words, the detector acquires measured estimates of the line integrals of the original density function [2]. In theory it should be clear that if the projections $R_\theta(x')$ are known for an infinite number of values of θ, the original function $f(x, y)$ can be recovered by the inversion of Equation (1). However, since there are finite points of measurement on the detector and finite image pixel positions in the (x, y)-plane, the discrete nature of image reconstruction causes significant challenges in the inversion process [6]. This research uses an algorithm called the algebraic reconstruction technique (ART) which is an iterative approach to approximating the inversion of the Radon transform [2] [3].

4. Experimental Results – 3D Image of a Simple Lead Structure

In order to further verify the validity of the proposed imaging method, a simple experiment was performed using the CRIPT imaging system. The one-sided muon tomography concept requires that muon flux measurements be taken at several angles of rotation around a structure using only one detector module. The CRIPT system is a very large, stationary structure, and so movement of a detector module to different positions is not possible. It was proposed instead that an object be placed in the loading area and rotated about its own central axis (as shown in Figure 4), providing an analogous system to the desired detector motion.

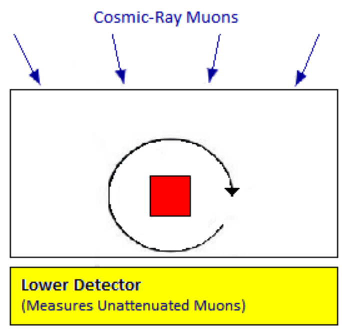

Figure 4 Object rotation within the CRIPT loading area to allow different detection points of view.

In the proof-of-concept study performed on simulated data, it was estimated that approximately 3 days of data collection would be required at 12 angles of detection in order to reconstruct an accurate image [3]. Since the total detection time is significant, a simple object comprised of lead bricks was used to test the reconstruction method before progressing to imaging a more complex structure containing nuclear fuel. The lead was constructed in order to approximate a cylindrically symmetric object. In reality it was a rectangular prism with a square cross-section of 20×20 cm^2 and a length of 80 cm. Its length was aligned horizontally along the y-axis of the CRIPT coordinate system and the distance from its central axis to the lower detector module was measured to be 120 cm.

Since a horizontal detector observes muon events with a range of incident angles, the concept of angular binning was applied in conjunction with the ART algorithm for image reconstruction [3]. Figure 5 (left) illustrates this concept. The detected muon events are first divided into bins on the horizontal detector plane (shown in blue) and then further divided into sub-bins corresponding to the individual angular components of the flux seen by the detector. The angular distribution of muons near the surface of the earth has been well-documented as being uniform in the azimuthal angle and $cos^2\theta$ in the zenith angle [1], as shown in Figure 5 (middle and right, respectively). Consequently, over a finite period of time with the lead structure present, the number of events detected in each angular component of the system can be compared with the value expected if the structure were not present.

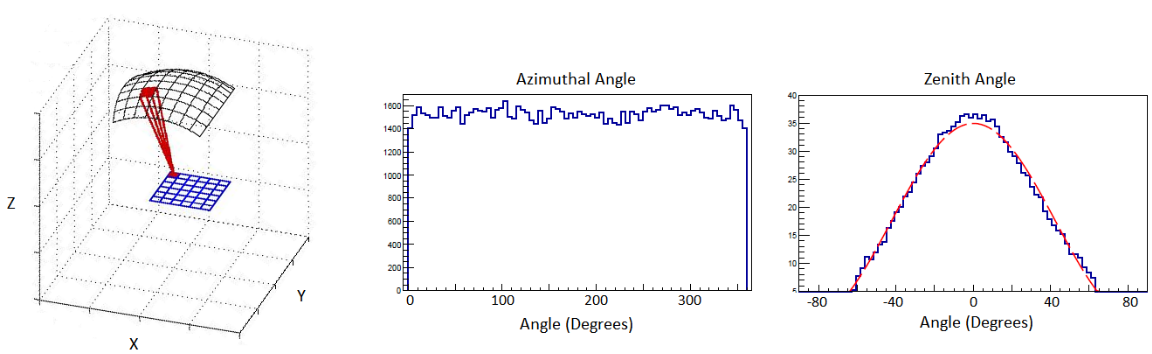

Figure 5 Left: Illustration of the division of muon events into angular bins. Horizontal muon detector shown in blue. A single angular bin has been highlighted in red.
Middle and right: The angular distribution of muons at the surface of the earth.

For this simple experiment, 7.5 days of data was collected with the lead structure present in addition to 7.5 days of data without the structure present. An assumption was made that the measured muon distribution would be approximately the same at any angle of rotation of the lead structure. As such, the entire dataset was split into 12, 15-hour subsets, each representing an angle of rotation spaced evenly over 360˚. The data was handled by first dividing the 1×1 m^2 detector plane into 25×25 bins and then further dividing the events in each bin into 64 angular sub-bins spanning 60˚ in both the x and y-directions (refer to Figure 5, left). The relevant data that was then passed to the reconstruction algorithm was the number of muon events detected in each angular bin subtracted from the number of events that were expected in each bin without the reactor geometry present. In this way, the measured flux in each angular component was normalized to the expected, non-uniform $cos^2\theta$ distribution found in nature.

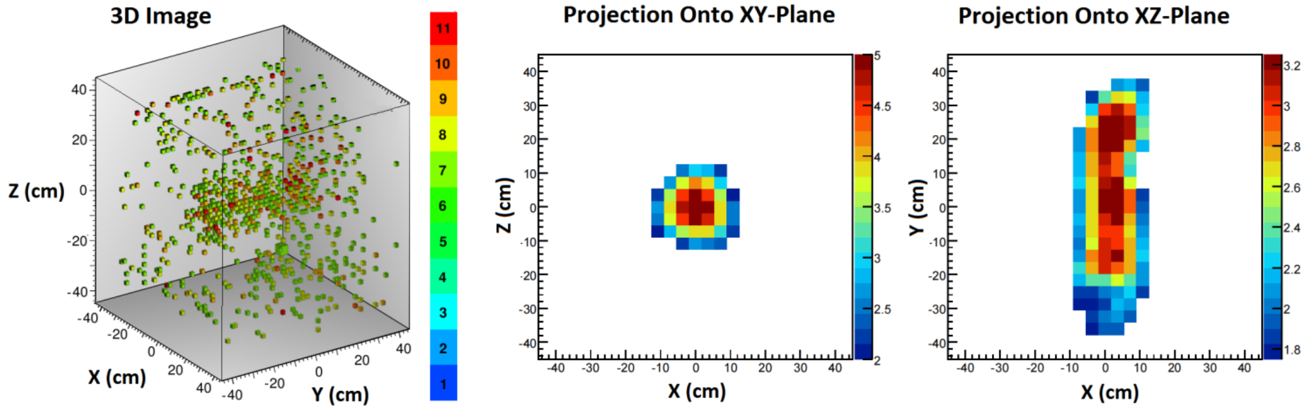

Figure 6 Left: 3D representation of reconstructed image.
Middle and right: Projections of the 3D image onto the xz and xy-planes.

In the 3D image shown in Figure 6, the overall spatial distribution of the lead can be seen, however the resolution is low due to the low level of statistics acquired during the 15-hour subruns. However after projecting the 3D image onto the xy and xz-planes, the relative change in density between the lead and surrounding air becomes more obvious and it can be seen that the dimensions of the reconstructed image are in agreement with the actual structure. The cross-sectional length and width of the reconstructed lead are approximately 80 cm and 20 cm respectively.

5. Conclusion

The experimental results presented in this paper demonstrate that a 3D image can be reconstructed using the one-sided muon tomography technique. The method has been designed for the purpose of using a single portable muon detector to image structures in different locations and this preliminary experiment provides the framework for the development of the required data analysis and image reconstruction software. The next step in this research will be to further test and refine the imaging technique by performing a similar experiment on a more complex geometry containing an asymmetric distribution of nuclear fuel bundles.

6. References

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