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Author(s):

Gary E. Hogan, LANL, P-25
Konstantin N. Borozdin, LANL, NIS-2
Christopher Morris, LANL, P-25
William C. Priedhorsky, LANL, NIS-DO
Alexander Saunders, LANL, P-25
Larry J. Schultz, LANL, P-25
Margaret E. Teasdale, LANL, P-25

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Detection of High-Z Objects using Multiple Scattering of Cosmic Ray Muons

Gary E. Hogan, Konstantin N. Borozdin, Christopher Morris, William C. Priedhorsky, Alexander Saunders, Larry J. Schultz, Margaret E. Teasdale[1]

Los Alamos National Laboratory, Los Alamos NM 87545 USA

[1]Present address: Department of Marine Science, University of Hawaii, 200 W. Kawili St., Hilo, HI 96720

Detection of high-Z material hidden inside a large volume of ordinary cargo is an important and timely task given the danger associated with illegal transport of uranium and heavier elements. Existing radiography techniques are inefficient for shielded material, often expensive and involve radiation hazards, real and perceived. We recently demonstrated that radiographs can be formed using cosmic-ray muons[1]. Here, we show that compact, high-Z objects can be detected and located in 3 dimensions with muon radiography. The natural flux of cosmic-ray muons[2], approximately 10,000 m^{-2}min^{-1}, can generate a reliable detection signal in a fraction of a minute, using large-area muon detectors like those used in high-energy physics.

Conventional radiography uses the absorption of x-ray or gamma radiation to provide image contrast. The flux in an image pixel is determined by Beer's Law, $N = N_0 \exp\left(-L/L_0\right)$, where L is the path length through the object and L_0 is the mean free path for scattering and/or absorption[3]. The precision of radiographic measurements is limited by the Poisson counting statistics of the transmitted flux, $\frac{\Delta L}{L_0} = \frac{1}{\sqrt{N}}$, and the inability to penetrate dense materials. Even the most penetrating gamma rays (few MeV) are attenuated by an e-folding in 2 cm of lead. Objects much thicker than this can be penetrated only by a very large incident dose, which is harmful for living organisms or radiation sensitive cargo such as photographic film.

By contrast, our images are formed by the analysis of muon angular deflections caused by multiple Coulomb scattering. Muons undergo a random walk in direction, which yields a Gaussian angular distribution with width $\theta_0 = \frac{13.6 MeV}{\beta cp}\sqrt{\frac{L}{L_0}}\left[1 + 0.038\ln(L/L_0)\right]$, where L_0 is the radiation length, p is the particle momentum in MeV/c and βc is its velocity[4]. Since radiation length drops rapidly with atomic number, in 10 cm a 3 GeV muon will scatter, on the average, 2.3 milliradians in water (L_0 = 36 cm), 11 milliradians in iron (L_0 = 1.76 cm), and 20 milliradians in lead. If the scattering angle in an object is measured, and the particle momentum is known, then the fractional path length, $R = L/L_0$, can be determined to a precision of $\frac{\Delta R}{R} \cong \sqrt{\frac{2}{N}}$, where N is the number of transmitted particles. Thus each particle delivers, via its deflection, information on the density along the path it traversed. In comparison, absorption radiography only contributes a binary count to a pixel.

The natural background of muons is free and available everywhere on the Earth. The muons are produced via interactions of primary cosmic rays in air. They are highly penetrating, having already traversed the equivalent of several meters of water by the time they reach sea level. Additionally, cosmic ray muons illuminate an object from a wide range of angles. This is helpful for 3D tomographic reconstruction.

Our newly developed technique allows the study of small and medium-sized objects such as passenger cars, sea containers, and commercial trucks. To obtain a reasonable cargo screening capability, we must produce a clean detection decision in a reasonable time. Complicating factors include the clustering of muons in showers and their distribution in momentum. The natural flux includes low momentum muons that scatter easily and high momentum muons that scatter less.

Consider, for example, a truck containing normal cargo, such as a flock of sheep (40-cm thick bags of water), in which is hidden a small (10-cm thick) volume of high-Z material such as lead. A muon that passes through a sheep will scatter with a mean angle, θ_0, of about 5 milliradians, but a muon that passes through the lead will scatter with a mean angle of about 20 milliradians. By measuring the actual scattering angles of all the muons that pass through the truck, and watching for an excess of muons that scatter through large angles, we can find the high-Z object.

To prove that these complications could be overcome, we developed a small-scale experimental detector system. The detector consists of stack of delay line drift chambers that measure a total of eight X and eight Y locations for each muon. The active area of each chamber[8] was 60 x 60 cm^2. The top half of the stack measured the incident muon track, while the bottom half measured the track after scattering. There was 27 cm high volume in the middle for test objects. Calibrating the instrument with no scattering material in the object area, we determined that our position precision was about 400 μm (FWHM). Data was taken using a Windows® based data acquisition program developed at Los Alamos[9]. A pair of 30 cm square plastic scintillators placed below the lowest detector was used for triggering. Given the limited acceptance angle of this configuration, the expected trigger rate was about 850 counts·min^{-1}, consistent with the observed rate of 750 counts·min^{-1}. A tungsten cylinder (W) of 5.5 cm radius and 5.7 cm height was used as a test object, supported by a Lexan™ plate (L) and steel support beams (B).

The path of a charged particle through the test material is stochastic and can only be approximately reconstructed. In our experiment and simulation, we used a simple technique for this reconstruction. We approximated multiply-scattered tracks as having only a single scattering event, and located the point of scatter by extrapolating the incident and scattered rays to their point of closest approach. The scattering signal from each muon was assigned to voxels (3-D pixels) along its track using a maximum likelihood technique that distributed the signal along the track according to the uncertainty in determining the point of scattering. Each scattering point was weighted by its scattering angle θ. We found that a $\theta^{1.5}$ weighting provided the highest contrast between high and low-Z objects in our images.

Figure 1 shows slices through the reconstructed, 3-dimensional image of the tungsten cylinder from a 2_ hour run. With this long run, the tungsten is seen with sharp edges, and the steel support beams are visible as well, clearly distinguishable from the tungsten object. For a

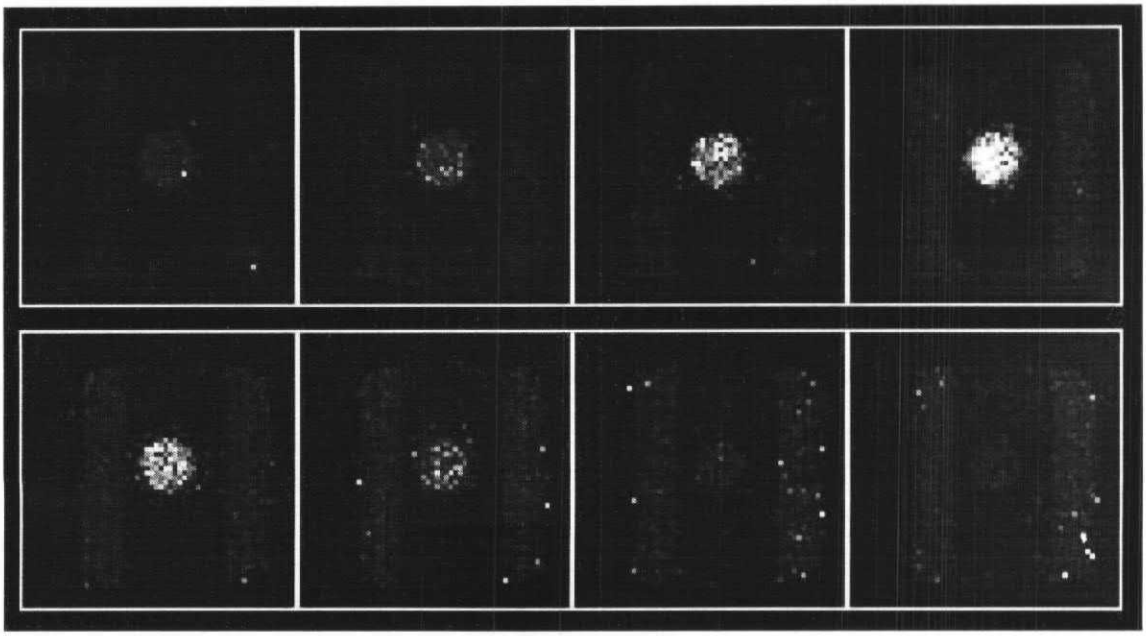

Figure 1. Reconstruction of test object based on an experimental run of 100,000 muons. The eight planes shown are horizontal slices through the test volume, moving top to bottom.

To compare these results with theory, and to establish a platform for investigating larger, more complex radiographic scenarios, we developed a Monte Carlo simulation code that i) generated cosmic ray muons with the appropriate distribution of energies and incident angles; ii) propagated them through a test volume, calculating their scattering in each 0.2 cm cubic resolution element; and iii) generated the positions at which they would be detected in four detector planes (two above and two below the test volume). The muon spectrum, angular distribution, and rate were appropriate for sea level[2]. Their scattering and propagation within the targets were calculated according to the multiple scattering law[4] described above. The geometry and densities of experimental test objects were incorporated in the simulation, and the same reconstruction technique used for the experimental data was applied to the simulated data. The simulation accurately matched the tungsten experiment, both in the reconstructed image, and the distribution of scatter angles[1,5].

We used the simulation to model a hypothetical shipping container monitor. The overall geometry is similar to our experimental setup. The detector pairs, assumed to have our experimental resolution of 400 μm (FWHM), are spaced 1 meter apart (*h*) and spanned a 4.5 meter high (*l*) test volume. The resolution of the image would be improved if the pairs were more widely spaced (larger *h*), allowing better localization of the scattering point; however, this might demand too large an instrument in a practical application. The simulation modeled a steel container (3 mm walls) that contained high-Z objects ("pigs", the informal name for shielded casks), surrounded by dozens of low-Z objects ("sheep"). The "pigs" (9 x 9 x 12 cm^3 bricks of uranium) were detected at high confidence in a 1-minute simulated exposure. The signal in the 3 x 3 x 3 cm voxel (3-D pixel) at the location of a brick was, in arbitrary units, 54 ± 24, while the background in an adjacent volume was 1.9 ± 1.1. This means that a threshold chosen to detect the object with 90% confidence will reject false positives from the background with 20σ confidence. Clearly, we do not expect any false positives due to statistical background fluctuations in this simulation.

We have augmented the reconstruction algorithm by multiplying the scattering signal by the muon momentum. In the analysis above, we assumed a rough knowledge of the momentum ($\Delta p/p$ of 50% in a log-normal distribution). This knowledge significantly improves the reconstruction. If the momentum is unknown, our 90% threshold will reject false positives from background with 3.5σ confidence. Momentum information can be obtained inexpensively by measuring the multiple scattering in several layers of known material. This could be done by a scatter-detector sandwich that continues below the lowest detector plane. We have determined via simulation that using two planes of scattering material in this sandwich provides the needed $\Delta p/p$ of 50%. In these reconstructions, we ignore muons with momentum greater than 20 GeV/c, because the small "scatter" angles introduced by measurement errors appeared significant in our momentum-weighted algorithm. We also reject all rays with a scatter angle less than 5 milliradians to achieve higher contrast between high-scattering and low-scattering material in the image.

The results so far are encouraging, and there is room for further improvement in both detection and reconstruction techniques. For instance, the displacement of the muon track (i.e. the minimum distance between the incident and scattered path) also provides a measure of multiple scattering, because multiply-scattered muons are more likely to undergo a significant displacement, while a single-point scattering event necessarily has zero displacement. To achieve maximal contrast in images of different objects, one may vary weighting algorithms and apply different angular cuts.

We have confirmed that muon radiography of relatively large objects, on the order of the size of a commercial truck, can be performed in a reasonably short time (~1 minute). The method is particularly useful in detecting a high–Z target against a low-Z background. The sensitivity of the method might be further improved by the application of a more elaborate reconstruction technique.

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