Title: Cosmic Ray Muon Radiography for the Detection of Contraband SNM (U)

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ABSTRACT

Highly penetrating cosmic ray muons shower the Earth at the rate of 10,000 m\(^{-2}\)·min\(^{-1}\) at sea level. In our previous work (Nature 422, p 277 (2003); Review of Scientific Instruments 74(10), pp 4294-7 (2003); Nuclear Instruments and Methods A 519, pp 687-694 (2004)) we presented a novel muon radiography technique which exploits the multiple Coulomb scattering of these particles for nondestructive inspection without the use of artificial radiation. High Z/high density materials deflect muons much more strongly than do lower Z, lower density materials, providing for an information source that is sensitive to SNM and shielding material. We have demonstrated the technique with a small scale prototype and via Monte Carlo simulation are investigating the feasibility of using it for the detection of SNM/shielding in vehicles and shipping containers. Simulated tests suggest that detection of modest sized high-Z objects within medium-Z backgrounds in minute order exposure times may be achievable. We are constructing a large scale prototype for experimental confirmation of these simulations. A significant benefit of this technique is that inspection of manned vehicles can be performed since no artificial radiation is applied.

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**Cosmic Ray Muon Radiography for the Detection of Contraband SNM**

Larry Schultz  
Los Alamos National Laboratory  
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**Collaborators**

- **Project Leaders**
  - C.L. Moms (P-25), W.C. Priedhorsky (ISR-DO)
  - LANL P, ISR, X, CCN, T Divisions
  - M.E. Teasdale, M.Q. Cannon, J.J. Medina (students)

- **University Collaborators**
  - A. Fraser (Portland State University)
  - G. Blauled (University of South Carolina)
  - J. Katz (Washington University in St. Louis)

**Overview**

- **Problem Description**
- **Cosmic Ray Muon Radiography Background**
- **Experimental Demonstration & Simulation**
- **Contraband Detection Approaches**
- **Mid-Scale Demonstration Plan**
- **Summary / Path Forward**

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**Contraband Problem**

- Smugglers may try to bring in a variety of threat material such as U, Pu, or radioactive material.
- To get past gamma-ray detectors, these items will need to be shielded, so there will also be lead or other high Z shielding material. Question: How much shielding?
- A characteristic of high Z material is that charged particles will experience much more multiple scattering as they traverse them than when going through lower Z material.
- So our proposed method of detecting U, Pu, or shielding material is to measure the multiple scattering of charged particles (passive cosmic ray muons, in fact) that pass through a cargo container or vehicle.

**Potential Advantages of Muon Radiography**

- No artificial radiological dose.
- No artificial source required.
- Low-cost muon detection equipment have been used for decades.
- 3D reconstruction enabled by multiple-angle "illumination."
- The heavier the shield, the better.

**Cosmic Ray Muons**

- Primary cosmic rays strike the atmosphere and generate a cascade of secondary particles.
- Muons are the dominant particle at the Earth's surface.
- Most muons can penetrate tens of meters of rock or more.
- Muons arrive at a rate of 10,000 per square meter per minute (at sea level).
- The spectrum of cosmic ray muons (energy, arrival angle) is well documented. Peak at 3 GeV.
- Cosmic ray muons arrive from the upper atmosphere but tend to be absorbed or directed because of atmospheric shielding.
Differential Attenuation Radiography

Searching for Hidden Chambers in Pyramids

Luis Alvarez, et. al.
Science 167, 832 (1970)
Arturo Menchaca, et. al.

Predicting Volcanic Eruptions
Tanaka, Nagamine, et. al.

Multiple Scattering

The particle propagation range due to 2-N interactions with material points

Pinhole is scattered and displaced from the original track.

The total length L is a characteristic property of material that generally DECREASES with INCREASING material Z number.

The Basic Concept

- Track individual muons (possible due to modest event rate).
- Track muons into and out of an object volume.
- Determine scattering angle of each muon.
- Infer Z-level of material within volume from data provided by new tomographic reconstruction algorithms are required.

Experimental Prototype

- D1.04 - Muon detectors ( drift chambers, measure X/Y position)
- B - "Universal" beam
- L - Lead plates to hold objects
- W - Fungus cylinder (5.5 cm radius, 5.8 cm height)
- 21 cm spacing, all detectors
- 32 Y:1.5
- 20 Y:2.0
- 34 Y:2.5
- 31 Y:3.0
- 28 Y:3.5
- 25 Y:4.0
- 22 Y:4.5
- 19 Y:5.0
- 16 Y:5.5
- 13 Y:6.0
- 10 Y:6.5
- 7 Y:7.0
- 4 Y:7.5
- 1 Y:8.0

Reconstruction - Localizing Scattering

- Assume multiple scattering occurs at a point
- Find point of closest approach (PoCA) of incident and scattered tracks
- Assign scattering signal to voxel containing PoCA
- Since detectors have known position uncertainty, signal may be spread over voxels relative to PoCA uncertainty.
- Simply add localized scattering signals for all rays.
PoCA works less well for...

Scenes with large, distributed, or multiple objects

Simulated scene
1x1x1 m cube box (2 mm wall thickness)
new build with solid aluminum and 4 cm radius U sphere in center

PoCA Reconstruction
~1 minute of simulated exposure
Simulated Scenarios

- Vehicle / Container
  - 6 x 4 x 2.4 meter cargo container (3 mm steel walls)
  - No PUV's or vehicle components simulated yet.
- Objects
  - No SNM object
  - Uranium sphere (6 cm radius, 20 kg)
  - Pu sphere (4 cm radius, 5 kg)
  - Lead Cylinder (5 cm radius, 10 cm tall) filled with 800 g of Pu.
  - 1700 kg (r = 40 cm) and 350 kg (r = 20 cm) Fe spheres.
- Backgrounds
  - Otherwise empty container.
  - 11 metric tons of half density Fe spheres (auto differential proxies).
  - Random (air-medium 2) 50 x 50 x 50 cm cubes (new, no results yet).

Steps in Detection

- First, is there something interesting?
  - Almost all vehicles contain harmless cargo and should be cleared quickly.
- Second, is the interesting item a threat?
  - If there is something generating a lot of scattering, is it a big piece of steel or a smaller piece of lead or SNM?
- Third, where is it and what does it look like?
  - To decide what to do next, we would like more information on object size, shape, location, etc.

IS THERE SOMETHING OF INTEREST?
Ray Crossing Algorithm

- Apply a bend angle cut. Keep only high bending rays.
- Apply an approach cut. Keep only rays which approach one another closely.
- Create 3D histogram of the approach locations.

WHAT DOES IT LOOK LIKE?
Maximum Likelihood Tomographic Reconstruction

- Objects
  - 1x1x1 m Fe box (3 mm walls)
  - Two half density Fe spheres (automobile differentials)
  - 20 kg U sphere

ML/EM a Big Improvement over PoCA

- Previous scan: U sphere tortured in Al 1 minute simulated exposure
- ML/EM Reconstruction
- PoCA Reconstruction

IS IT A THREAT?
Support Vector Machine Classification

- Threat object: 20 kg uranium sphere.
- Background: varied from empty container to more than 10 tons of iron.
- Train SVM by providing scattering data for simulated threat / non-threat cases.
- Require that SVM DETECT all threats. Measure the performance by the
  exposure time required to REJECT non-threats.
- Test SVM on classification of additional cases not in the training set.
ML/EM on Experimental Data

A good start but a bit messy:
Quantum errors in track reconstruction are part of the problem.
More work is needed to properly model experimental error.

Contraband Detection Summary

- Encouraging results for a variety of simulated test cases, suggesting feasibility of:
  - Clearing low-Z cargo quickly.
  - Identifying modest sized high-Z contraband within low to medium-Z cargo in minute order exposure times.
- Need to investigate more complex scenes (more complex backgrounds, additional vehicle components such as engines, differentials, etc. and smaller threat objects).
- Simulated results need more extensive experimental confirmation.

Mid-Scale Demonstration Project

- The first small scale experiment used 1x1 meter delay-line drift wire chambers. This technology does not scale up.
- We are currently building a 12 ft x 12 ft x 12 ft mid-scale detector project.
  - Sized to radiograph the trunk of a car or small pickup truck bed.
  - Using 2 inch diameter, 12 foot long drift tubes packed into stackable modules of 16 tubes.
  - Along with muon radiography runs, this will be a test bed for other technologies.
- We are looking at other technologies that may scale up better for full size detector stations.

Initial 12 foot Drift Tube Module

Summary

- The project is entering its third year.
- Have experimentally obtained radiographs of several objects.
- Simulation developed and validated.
- New reconstruction and visualization methods have been developed and are continuing to be refined.
- Mid-scale demonstration project under construction.

To Move Forward...

- More simulation work (existing funds probably sufficient)
  - Exposure time & detection ability vs. object size, placement and backgrounds.
  - What is reasonable smallest object size (SNM+shielding)?
  - Optimize analysis methods.
- Mid-scale Experimental Demonstration
  - Existing funding will not support momentum measurement.
  - Need additional ~$500K to build fully functional unit.
- Deployed Prototype (real vehicle traffic) if above is successful
  - ~$1M plus installation costs.
### Generalized results

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<th>medium</th>
<th>high</th>
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<td>2 min</td>
<td>6 min</td>
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<tr>
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<td>1 min</td>
<td>1 min</td>
<td>6 min</td>
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