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Tomographic Imaging with Cosmic Ray Muons

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Abstract Over 120 million vehicles drive into the U.S every year. Many would be capable of transporting hidden nuclear weapons, and all are capable of carrying enough nuclear material to make a nuclear weapon. In most cases, the chances of intercepting such a threat depend largely on the observation powers of the immigration officers who briefly question hundreds of drivers/passengers every day. The chances of detection would be greatly improved if each officer had a scan available showing any dense objects in each vehicle as it reached the checkpoint. The DHS plans to use x-ray radiography at many locations, but the present capabilities of these systems are limited by the fact that they cannot be used on occupied vehicles and that the energy of the interrogating beam is too low to penetrate the vehicle and contents in many scenarios. We present a new technique that overcomes these limitations. Specifically, tomographic density scans can be developed passively and unobtrusively as the car stops at the checkpoint by observing the pathways taken by natural cosmic radiation as it enters and leaves each vehicle. The advantages of this technique are that it: is passive; does not require radiation above natural background and thus can be used for occupied vehicles; will not trigger salvage fuses; is transportable; and is selective to high-z dense materials. When coupled with passive radiation detection, muon interrogation can provide safe and robust border protection against nuclear devices or material in occupied vehicles and containers.

Introduction

Of the threats posed by terrorist actions, the most frightening is the detonation of a nuclear device in a major city. The toll of the deaths, destruction, and economic loss caused by such an action would be enormous. Recent events, along with scholarly evaluations of the probability of a terrorist group producing a nuclear weapon suggest the likelihood of such an event is significant (USDOT, 2001). The size of the risk and the enormous consequence of such an event have moved the United States in the direction of trying to develop strategies to prevent it.

One of the strategies is to make nuclear material unavailable to terrorists by controlling the material at its source. Considerable resources are being devoted to programs worldwide to reduce the inventories of both highly enriched uranium and weapons grade

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plutonium (SNM), and to improve controls over these materials. Unfortunately, inventories and accounting of SNM is not complete enough to exclude the possibility that sufficient material to construct a nuclear device is already on the black market or in the hands of terrorist groups. Since it is unlikely that these efforts will be absolutely effective, particularly in view of the recent breakdowns of the non-proliferation regime, other controls need to be implemented to achieve an adequate defense against terrorist nuclear devises.

An additional reduction in risk can be obtained by increasing the likelihood of detection of illicit transport of these materials at transportation checkpoints, such as border crossings. Custom agencies around the world have begun using a set of radiation detectors and x-ray scanners at border crossing for this purpose (Siciliano, 2000). However, passive counting does not provide robust detection of hidden SNM because all of the signals can be obscured using a relatively small amount of high atomic number(Z) , such as lead tungsten, hydrogenous (polyethylene), and neutron absorbing (lithium or boron) shielding. More sophisticated counting techniques, such as directional gamma and neutron counting, and better energy resolution improve the sensitivity and limit some options for hiding SNM. However, because of practical counting time limits and natural background rates, small well shielded quantities can be moved through the best of passive systems.

Photon (X-ray or gamma-ray) radiography provides a method of examining cargo and transport vehicles for the presence of hidden material. Penetration and scatter background limit the utility of this technique (Katz, 2007). New scanning photon radiography machines in combination with neutron scatter and radiography and x-ray back scatter might provide an approach for detecting shielded, hidden SNM. The potential doses to vehicle occupants and to operators limit this technology option to examining only a small fraction cross border traffic.

Muon Tomography

Here we present results from a study of a new technique that is capable of passively detecting shielded weapons grade uranium or plutonium, SNM, in a short time by using the multiple scattering of cosmic ray muons as a radiographic probe (Borozdin, et al., 2003). This technique is selective to high-Z materials, both the SNM and shielding materials.

When an energetic charged particle moves through material, its trajectory is the result of the convolution of many small deflections due to Coulomb scattering from the charge of the atomic nuclei in the medium. The net angular and position deflection of the trajectory are very sensitive to the charge (Z) of the atomic nuclei. High energy particles are more strongly affected by materials that make good gamma ray shielding and by SNM than by the materials that make up normal cargo such as people, paper, aluminum and steel.

The earth is continuously bombarded by energetic stable particles, mostly protons. These interact in the upper atmosphere because of the nuclear force, producing showers of

particles that include many short lived particles called pions. The pions decay producing muons. Muons interact with matter primarily through the Coulomb force, and have no nuclear interaction. The Coulomb force removes energy from the muons more slowly than nuclear interactions. Consequently many of the muons arrive at the earth's surface, as penetrating, weakly interacting charged radiation. The flux at the earth's surface at sea level is about 1 muon/cm^2/min of muons in an energy and angular range useful for tomography (Eidelman, 2004).

Conventional radiography takes advantage of the absorption of penetrating radiation. For X-ray radiography (Roentgen, 1896), the areal density of a pixel in the image is determined by its absorption or scattering of the incident beam: $N = N_0 e^{-\frac{L}{L_0}}$ (Beer, 1852), where L is the path length (areal density) through an object, and L_0 is the mean free path for scattering or absorption. The precision of radiographic measurements is limited by the Poisson counting statistics of the transmitted flux, $\frac{\Delta L}{L_0} = \frac{1}{\sqrt{N}}$. The maximum mean free path for photons in high-z elements occurs at a few MeV. The mean free path is approximately 25 gm/cm^2 for all materials at this energy. This corresponds to less than 2 cm of lead. Penetrating objects of tens of L_0 requires very large incident dose.

An alternative is provided by a new kind of tomography (King, 1999, Hartouni & Morris, 2000). Charged particles, such as protons or muons, interact with matter by multiple Coulomb scattering. The many small interactions add up to yield an angular deviation that follows a Gaussian distribution to a good approximation: $\frac{dN}{d\theta_x} = \frac{1}{\sqrt{2\pi}\theta_0} e^{-\frac{\theta_x^2}{2\theta_0^2}}$ (Rossi, 1952). The width of the distribution is related to the scattering material: $\theta_0 = \frac{14}{p\beta}\sqrt{\frac{L}{X}}$, where p is the particle momentum, β is the velocity divided by the velocity of light, and X is the radiation length. Here we have dropped logarithmic terms that are on the order of 10%. In a layer 10 cm thick, a 3 GeV muon will scatter with a mean angle of 2.3 mrad in water (X= 36 cm), 11 mrad in iron (X= 1.76 cm), and 20 mrad in tungsten (X= 0.56 cm) . If the muon scattering angle in an object can be measured, and it's momentum is known, then the path length, $\Delta l/l$ can be determined to a precision of $\frac{\Delta l}{l} = \sqrt{\frac{2}{N}}$, where N, the number of transmitted muons, is very nearly equal to the number incident. Thus each transmitted muon provides information about the thickness of the object.

Muon momentum information can be obtained inexpensively by measuring the multiple scattering resulting from several layers of scatterer of known thickness. These scatterers can be the detectors themselves if multiple layers are used. The precision of momentum determination is approximately given by $\frac{\Delta p}{p} = \frac{1}{\sqrt{2N_P}}$, where N_P is the number of

scattering layers (the factor of two arises because x and y are measured independently). Even with just two planes, one obtains $\frac{\Delta p}{p} = 0.5$, which is adequate for a first-order momentum correction.

The flux of muons through a 10 cm cube of material in 60 seconds is sufficient to measure its thickness in radiation lengths to a precision of 14%. With these statistics a cube of tungsten can be distinguished from a cube of steel at the six standard deviation level.

We have demonstrated a suitable detector technology, drift tubes, developed tracking algorithms in a medium scale experiment. Here we report the results of this work. Additionally, we have used the GEANT Monte Carlo Transport program to validate reconstruction and detection algorithms for muon tomography for border security applications.

Experimental demonstration

We have constructed a set of planes 12 planes of 0.05 m diameter 3.65 m long drift tubes configured with three crossed x-y sets of detectors both above and below a sample volume, the large muon tracker (LMT). A photograph of the LMT is shown in Figure 1. A complete description of the apparatus is given elsewhere (Green, 2006).

Signals from the detectors were amplified and discriminated with a commercial comparator board and were digitized with VME time to digital converters (CAEN® 767B) , and read into a computer using PCDAC. The detectors measured position to a precision of about 400 μm full width at half maximum (FWHM), and angles to about 2 mrad FWHM. These include the instrumental contributions from multiple scattering in the detectors, residual alignment errors

The data were processed with a simple reconstruction technique. The sample volume was segmented into 2x2x2 cm^3.The median scattering angle was calculated for all muons with entering and exiting trajectories that insect the voxel within an adjustable distance d. Tis distance was set to the size of a threat object (5 cm) for the ROC work presented below. For imaging it was set to the voxel size. Because of the limited solid angle of this device, tomographic reconstructions suffer from considerable vertical blur are noisy and have not used in this study. sp. been

This experiment has some limitations. A robust tracker that fits time zero and eliminates the need for a fast trigger has recently been implemented, increasing the solid angle significantly. The experimental data cover a limited solid angle of less than one steradian. The counting rates are a factor of 4-5 below those that would be obtained in four sided scanner.

Despite limitations, the LMT has provided an important test bed which has been used to develop our techniques and algorithms and which has been used to validate the cosmic

ray generator used in Monte Carlo simulations. Two very important accomplishments from the work with the LMT have been the development and demonstration of automatic calibration of the drift tube positions and drift time to position look up tubes using cosmic rays, and a time zero fitter that eliminates the need for a prompt trigger for obtaining tracking information.

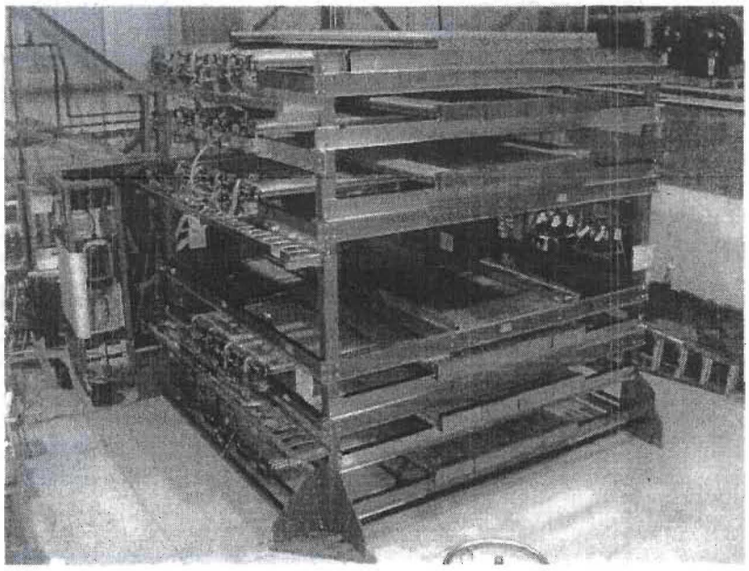

Figure 1) The experimental apparatus.

Data from the LMT have been processed with a simple reconstruction technique. Because of the limited solid angle of this device, tomographic reconstructions are noisy and are not used here. The lack of larger angle muons adversely impacts the tomographic results. For this analysis the sample volume was segmented into 2x2x2 cm^3. The mean scattering angle was calculated for all muons with entering and exiting trajectories that intersect within a voxel.

Examples of reconstructions are shown in Figure 3-Figure 4. One object is the letters LANL machined from 25 mm thick lead, and the other is a 12 kg right circular cylinder of tungsten. The objects in the reconstruction shown in Figure 2 are sitting on top of 1.9 cm thick aluminum table and in the reconstruction shown in Figure 3 they have been placed at different elevations in a 40 gallon barrel of sand. This demonstrates the ability of muons to detect objects in a dense medium atomic number (Z) matrix. Both the tungsten object and the lead letters are visible in this simple reconstruction.

A reconstruction of a human with a 1.8 kg lead object in his pocket is shown in Figure 4. This illustrates the relative sensitivities of multiple scattering to low-Z and high-Z materials

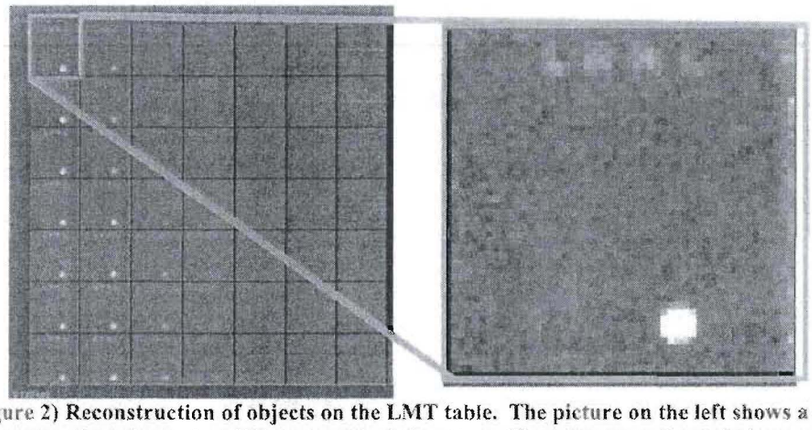

Figure 2) Reconstruction of objects on the LMT table. The picture on the left shows a set of x-y reconstructions formed at different vertical elevations. The picture on the right is an expanded view vertical slice where the objects are most clear. The letters LANL are formed from 1 inch thick lead. The object near the bottom of the reconstruction in picture on the right is a 12 kg right circular cylinder of tungsten

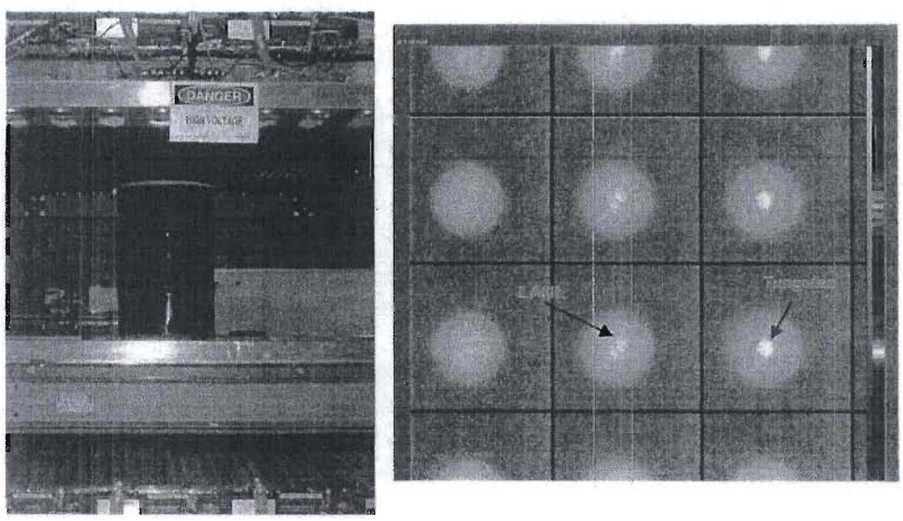

Figure 3) Threat object and LANL letters in a 500 lb barrel of sand.

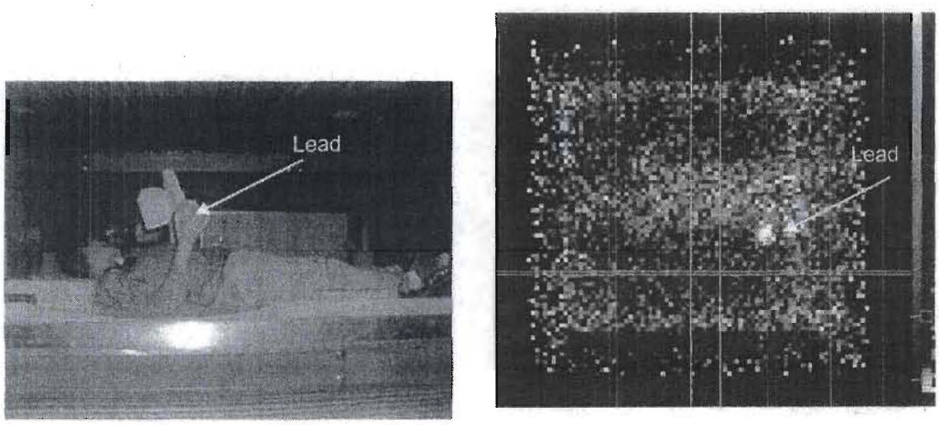

Figure 4) One hour long exposure of human with 1 kg of lead in his pocket.

The exposures shown here vary between 60 and 90 minutes. These exposures are longer than would be useful for homeland security applications.

A study of how quickly a nuclear threat object can be identified has been performed using a 10x10x10 cm^3 cube of lead to represent the threat. This were mounted in the LMT along with an automobile engine and transmission. Photographs of the set up are shown in Figure 5.

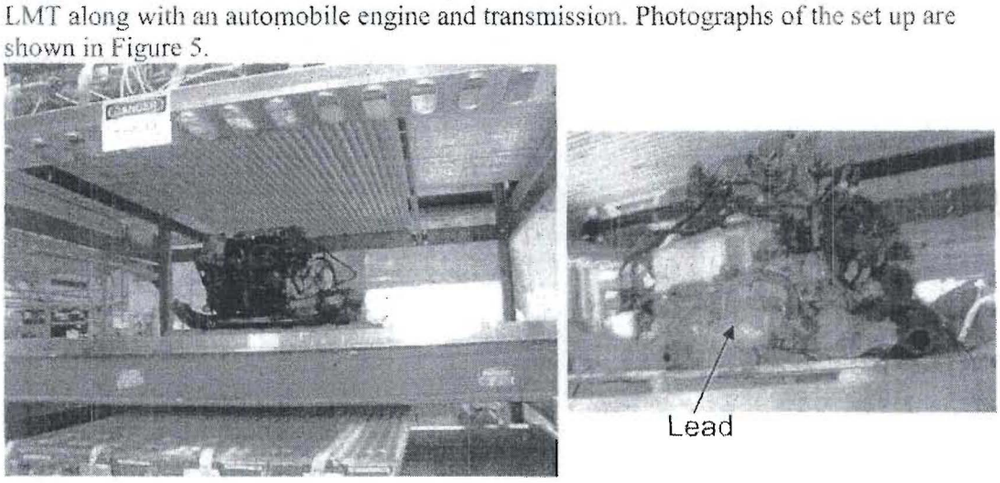

Figure 5) Photographs of the engine in the LMT. The location of the lead is shown in the figure on the right.

Approximately 160 minutes of data have been analyzed to obtain the image shown in Figure 6). What is plotted is simply the mean scattering angle for all trajectories that pass through each voxel. In spite of the simplicity of this analysis, the lead stands out dramatically.

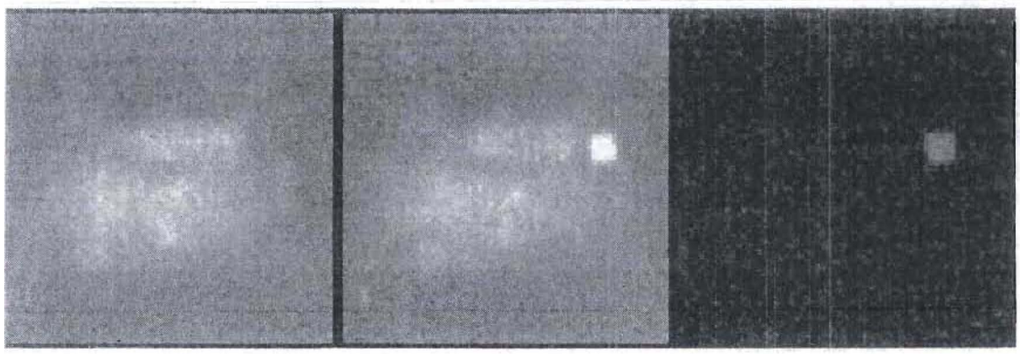

Figure 6) mean scattering angle for a slice through the scene 50 cm above the base plate. The left panel shows the engine, the middle panel the engine plus the 10x10x10 cm^3 lead sample, and the right panel the difference.

We have broken the data set into smaller 1, 2, and 4 minute intervals, and analyzed each independently. The average picture from the long run with only the engine was subtracted from each of the individual short runs, and the resulting maximum 10x10x10 cm^3 voxel value was histogramed for all of the runs with and without the lead. These histograms, an example is shown in Figure 7, were used to calculate the ROC curves, shown in Figure 8.

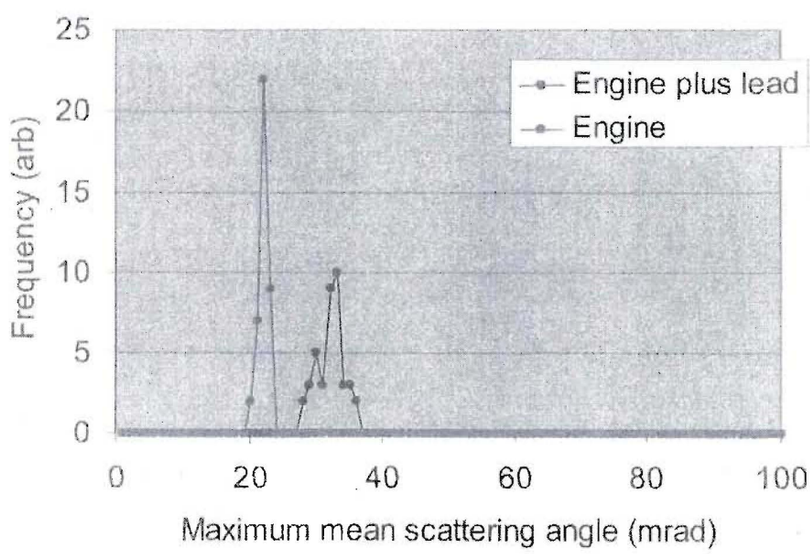

Figure 7) Histograms of the peak value of mean scattering angle, with a 10x10x10 cm^3 average applied to the 2x2x2 cm^3 voxels in a set of 40 4 minute reconstructions with the engine in the LMT.

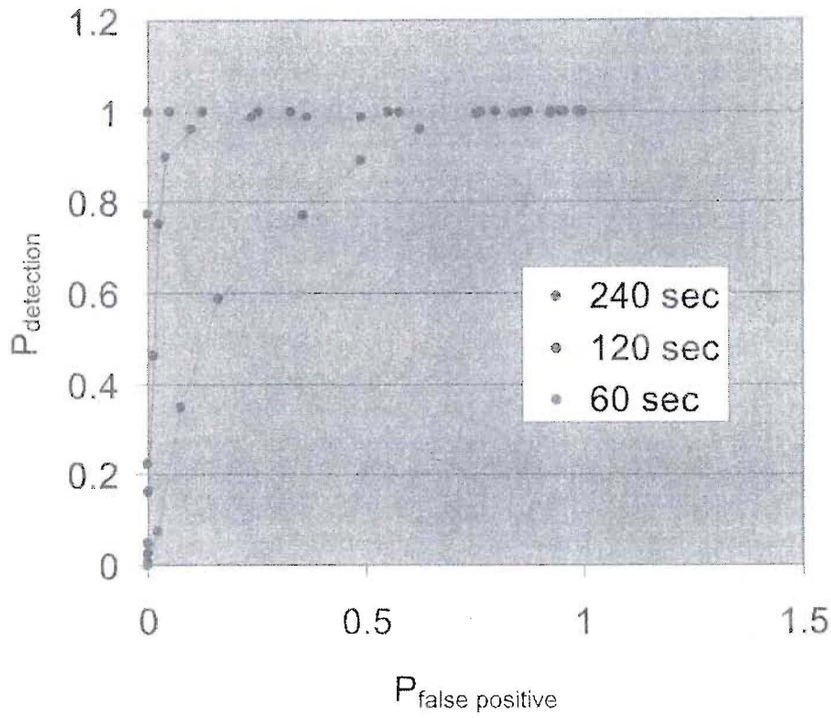

Figure 8) ROC curves for identifying the lead object mounted in the LMT with the engine

From the ROC curves shown above it is apparent that the lead objects can be identified perfectly (given only 40 trials were used) with zero false identifications in 4 minutes. When scaled to sea level muon fluxes and full solid angle these times can be divided by 5. Fifty percent knowledge of momentum, which models suggest can be obtained by analyzing position residuals from the tracking, is expected to reduce counting times by another factor of 1.5-2.

It is important to point out the this data were obtained using position calibrations for the tubes that were obtained using cosmic ray data and an automated calibration procedure that found the relative positions of each end of all of the tubes, and prompt time for the drift tubes was determined by fitting it as a parameter in the trajectory fits, i.e., there was no need for a timing scintillator (Green, 2006).

Detecting Nuclear Threats with Muon Tomography

Currently, portal monitors and other radiation detectors are deployed at many sites to detect the surreptitious transport of nuclear materials. Although these detectors are quite effective at detecting radiation, innocuous alarms from a variety of radioactive cargo make their use cumbersome and the potential for shielding nuclear material allows for their defeat as a nuclear threat deterrent. The absence of a radiation signal does not

eliminate the possibility of a nuclear treat. Muon tomography (MT) provides a method that is effective at detecting high-Z (atomic number) material in liter sized volumes. The same detectors that are used to detect and track muons can be used to measure radiation from a nuclear device, as well as to identify the presence of enough shielding to hide the nuclear signal.

Radiation dispersal devices (RDD) can be constructed using only grams of active material. Such small quantities can be easily hidden from any radiographic technique in an object the size of a passenger vehicle, truck, or cargo container. However, nearly all of the candidate materials for a RDD are either strong gamma ray or beta ray emitters. The radiation signature from the quantity of material needed to construct an effective RDD is enormous and is easily detectable. However, several inches of high-Z shielding (lead) can attenuate the radiation signal and make it difficult to detect.

Here we report on measurements we have made using an array of sealed drift tubes that has been assembled for a neutron beta decay experiment in Los Alamos to demonstrate the sensitivity of these tubes to ionizing radiation. These tubes do not include ^{3}He in their gas mixture so they could not be used to demonstrate neutron sensitivity. We will do this as a part of a different experiment that is currently under construction.

Gamma ray efficiency

We have used a set of 1-10 μCi sources to measure the efficiency of a single layer of drift tubes and a "100 %" high purity germanium counter. The efficiency was defined to be the number of detected gamma rays divided by the total number emitted from the source. The energy spectra, measured with the germanium detector, are shown in Figure 9. The energies ranged from 60 keV to 1330 keV.

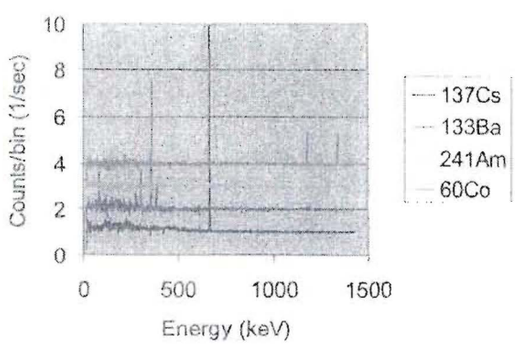

Figure 9) Gamma-ray energy spectrum from check sources.

The efficiency results are plotted versus energy in Figure 10. For these measurements the gamma sources was located 1 m from the germanium detector, and it was placed inside a three sided array of 12 foot long drift tube modules. In a full scale MT scanner there will be 12 layers of drift tubes. The gamma ray efficiency will be about 12 times higher than measured here, ~10%.

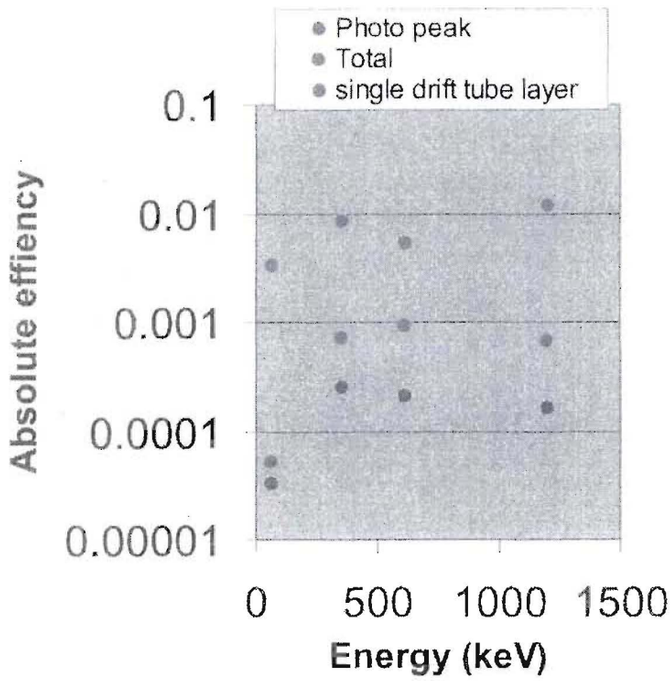

Figure 10) Comparison of high purity germanium detector and drift tube counting gamma ray efficiency.

The ratio of the counting rates to the background is similar for the two detectors.

^{90}Sr Tests

Recent articles in the popular literature have pointed to radioactive sources that were used as heat and electricity generators in the FSU as source material for an RDD. Apparently a common material in the devices is ^{90}Sr. There are no gamma-rays emitted by ^{90}Sr. It beta decays with a 2.65 MeV endpoint energy. Since this endpoint is greater than twice the electron mass (1.022 MeV), there are Bremsstrahlung x-rays generated in interactions between the stopping electrons and surrounding material. In Figure 11 we show the spectrum of x-rays from a small source (2 mCi) of ^{90}Sr measured with a high purity germanium counter.

The spectrum can be observed to have no discrete lines. This makes it impossible to identify the isotope using spectroscopy. The x-rays extend up to 1.5 MeV, a high enough energy to require moderately thick shielding to attenuate the flux.

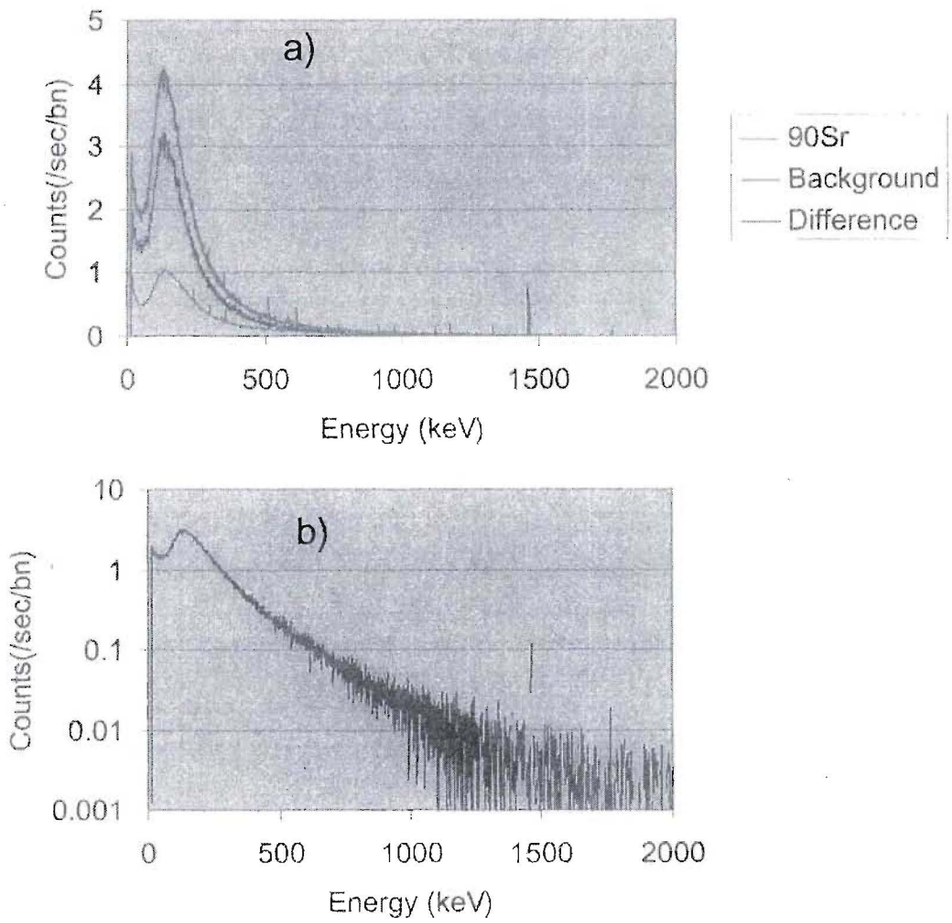

Figure 11) Spectrum of x-rays from ^{90}Sr source measured with a high purity germanium detector. a) Normalized spectra with the source, without the source and the difference on a linear scale. b) Background subtracted ^{90}Sr Bremsstrahlung spectrum.

There are typically several (8) grams of ^{90}Sr in the Russian sources. We have made some measurements in order to establish the amount of shielding needed to hide such a source from detection in MT. We measured the counting rate with a 2 mCi source in an aluminum holder and it a steel pipe, the rate with the source in a one inch thick lead cast, and the rate with the source behind two inches of steel. From these measurements we calculate that 4 inches of lead or 10 inches of steel would be required to shield the signal from a 1 kCi source (3.7 gm) to the level observed from the 2 mCi source used here, assuming exponential attenuation. These are underestimates of the required shielding, because the spectrum "hardens" as shielding is added because the high energy x-rays

have longer mean free paths, and the shielding is less effective for the remaining high energy x-rays.

Counting rates from the ^{90}Sr source in the drift tube assembly leads to the counting rates shown in Figure 12.

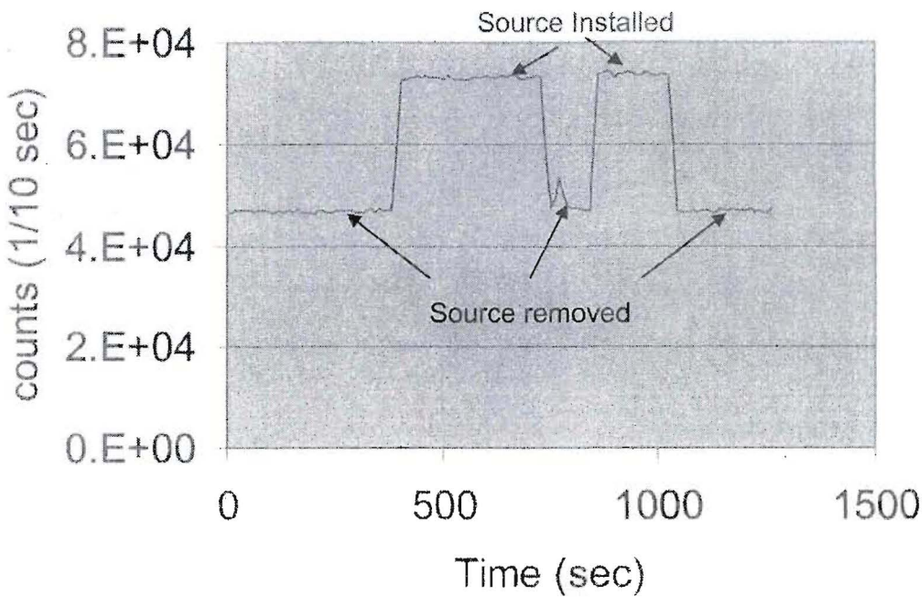

Figure 12)Drift tube counting rates from the 2 mCi ^{90}Sr source.

The signal to noise ratio, $r = \frac{f-b}{\sqrt{b}}$, where f is the counting rate with the source installed and b is the background counting rate, exceeds 100 for 10 second counting intervals. One conclusion is that 6 inch thick lead shielding would be required to obscure the signal for the large amounts of material required for effective RDD's. Although the weight of a 12" cube of lead is only about 700 lbs and is easily within the weight limit of most cars or light trucks, such a shield would be immediately detected with MT.

^{238}U Tests

We have also performed tests with depleted uranium (DU). Weapon grade uranium (HEU) contains about 8% of ^{238}U and 92% ^{235}U. A terrorist weapon might vary anywhere from 80-92% enriched in ^{235}U. ^{235}U emits only easily shielded low energy gamma rays. ^{133}Ba is often considered to be a good surrogate for the energy spectrum from HEU. The 1 MeV gammas from the ^{238}U are much more penetrating. Much Russian and US HEU is obtained from material that has been irradiated in a reactor. This material generally

contains significant contamination of ^{232}U and has a much stronger gamma ray signature than uranium directly separated from natural sources. The gamma ray spectrum from ^{238}U is shown in Figure 13.

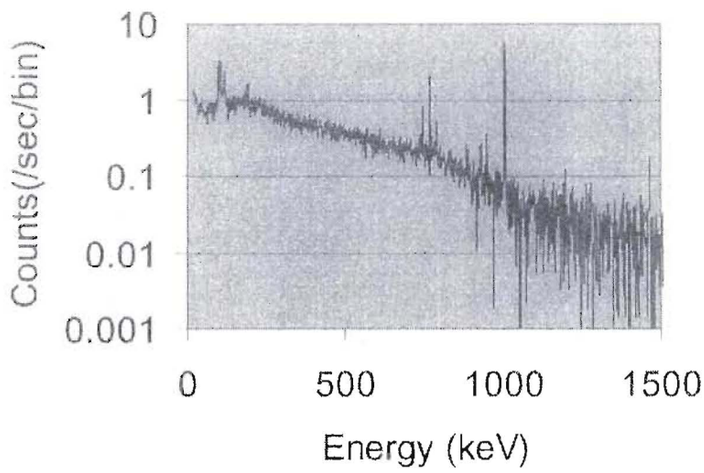

Figure 13) Energy spectrum taken with a germanium detector from a 5 kg ^{238}U sample.

The spectrum shows discrete lines as well as a continuum. The continuum arises from Bremsstrahlung x-rays produced by beta decay of the xxx daughter of ^{238}U decay. The x-rays increase the counting rate from the material by a factor of nearly 20. This extra counting rate leads to a highly significant signal when the DU is placed in the drift tube assembly. This is shown in Figure 14.

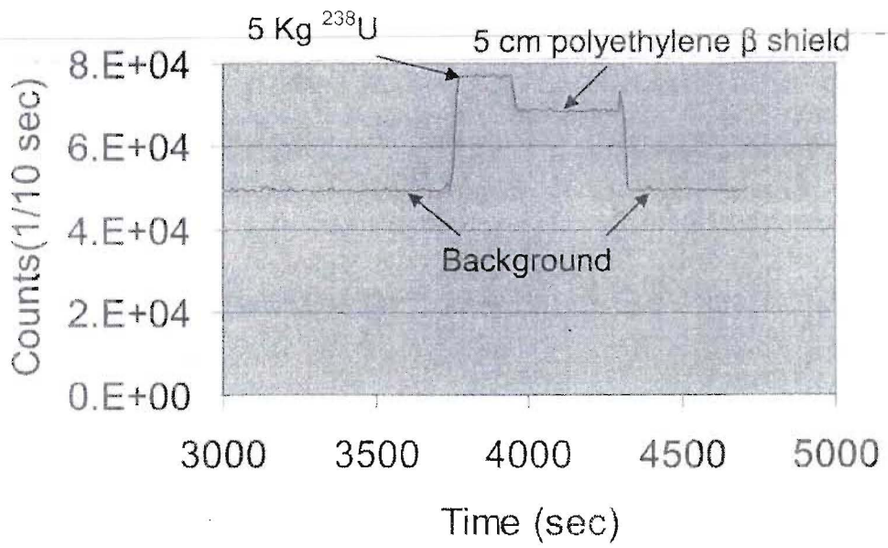

Figure 14) Counting rate from 5 kg depleted uranium sample in the drift tube veto assembly.

The signal to noise is 70 after the beta shield is put in place. A 20 kg sample would be highly detectable, especially with the expected order of magnitude increase in gamma ray efficiency provide by a full MT scanner. A 5 kg sample of HEU would produce a signal about 12 times smaller. Detecting a signal of this size may be challenging.

The self shielding produced by normal cargo tends to reduce the background counting rates in portal monitors by up to 10% when the cargo is present. This reduction can mask a radiation increase. This places a limit on how well excess radiation from cargo can be measured. MT provides an integral measure of the cargo measured in mass units weighted by radiation lengths. This may provide a good estimate of the self shielding of natural background so that small signals can be detected

In addition to the gamma and x-ray signal ^{238}U spontaneously fissions, producing neutrons. The large solid angle and high multiplicity of counter used for MT should provide for efficient neutron counting, if ^{3}He gas is added to the drift tubes and some moderating material is added to the walls. 5 kg of HEU emits about 5 neutrons per second from the 8% of ^{238}U. A distinctive feature of these neutrons is that they are emitted in correlated bursts with a mean multiplicity of 2.1 (Shultis & Faw, 2002). These neutrons can cause further fissions in surrounding material increasing the multiplicity.

Fusing neutron, neutron multiplicity, gamma ray and tomographic data from an MT scanner may provide a highly effective way to detect several kg quantities of HEU, considered the most challenging of nuclear material to find. Of course larger quantities are distinctive in the tomography as well as in their neutron and gamma signals.

Monte Carlo simulations

In order to examine how well this technique works for complex objects we have used GEANT to generate cosmic-ray muons with the appropriate distribution of energies and angles, propagated them through a test volume, and generate the positions and angles at which they would be detected in a four sided scanner. The muon spectrum, angular distribution, and rate were appropriate for sea level. We have studied a set of scenes for threat objects in a cargo van.

We have modeled the following scenes:

1. An empty van.
2. A 4′× 8′× 3′ high stack of boron treated plywood with or without an Object of Interest (OOI) inside. The total weight of the plywood is about 1800 kg.;
3. A Welding machine. Two 0.75 inch steel plates, top and bottom, are included in order to try to spoof the reconstruction technique.
4. A box of clutter. Reduced density concrete powder (0.5g/cm3) is filled with randomly placed objects of 4 different shapes: half of a sphere, rectangular block of 2 different sizes and a parallelepiped. Each individual piece of clutter is randomly placed, rotated and offset with respect to the center of the given piece of clutter. The material for each of the pieces is randomly assigned to be plastic, glass, steel (1.25g/cm3) or AlBeMet (2.54g/cm3). The total weight of the scene is approximately 3200kg.
5. A layered container with an outer layer of 10 cm thick steel and an inner layer of boreated polyethylene..

A visualization of the model for each of these scenes is shown in Figure 15. Each scene was modeled with and without a 10 cm cube of tungsten hidden in the cargo. The empty van was modeled with the tungsten under the engine and above the differential.

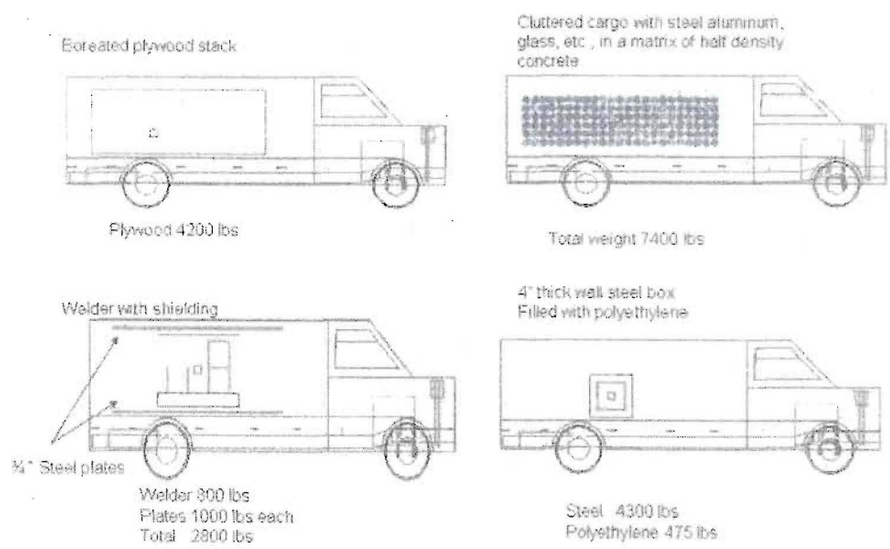

Figure 15) The four scenes that have been modeled are depicted here a) 3 foot high stack of 4 by 8 foot sheets of boreated plywood; b) a box of clutter; c) a welding machine; d) a 4 in thick steel box filled with neutron shielding.

The plywood is difficult for active interrogation. The hydrocarbons in the plywood provide a considerable amount of moderating material and the boron quickly absorbs the moderated neutrons. (Plywood alone increases the fission signal from active interrogation because the fission cross sections are much large for moderated neutrons than for fast neutrons). The welding machine is clutter, but radiographically looks like a common object. The box of clutter is intended to look like a box of complex junk. The special three layer container is a composite shield in which nuclear material is hidden from passive counting with medium mass materials.

For reconstruction of these scenes we used a maximum likelihood based tomographic algorithm. The foundations of this algorithm were developed in a Ph.D. dissertation in 2003 (Schultz, 2003). We developed a fast, robust implementation of this approach with results described below (Schultz, 2007).

A composite of reconstructions of the four cargo scenes is shown in Figure 16). The nature of each of these scenes is clearly visible from the reconstructions. None of the scenes except for the layered box is difficult for automatic identification of threat objects using a simple density threshold for 1000 cm^3 volumes.

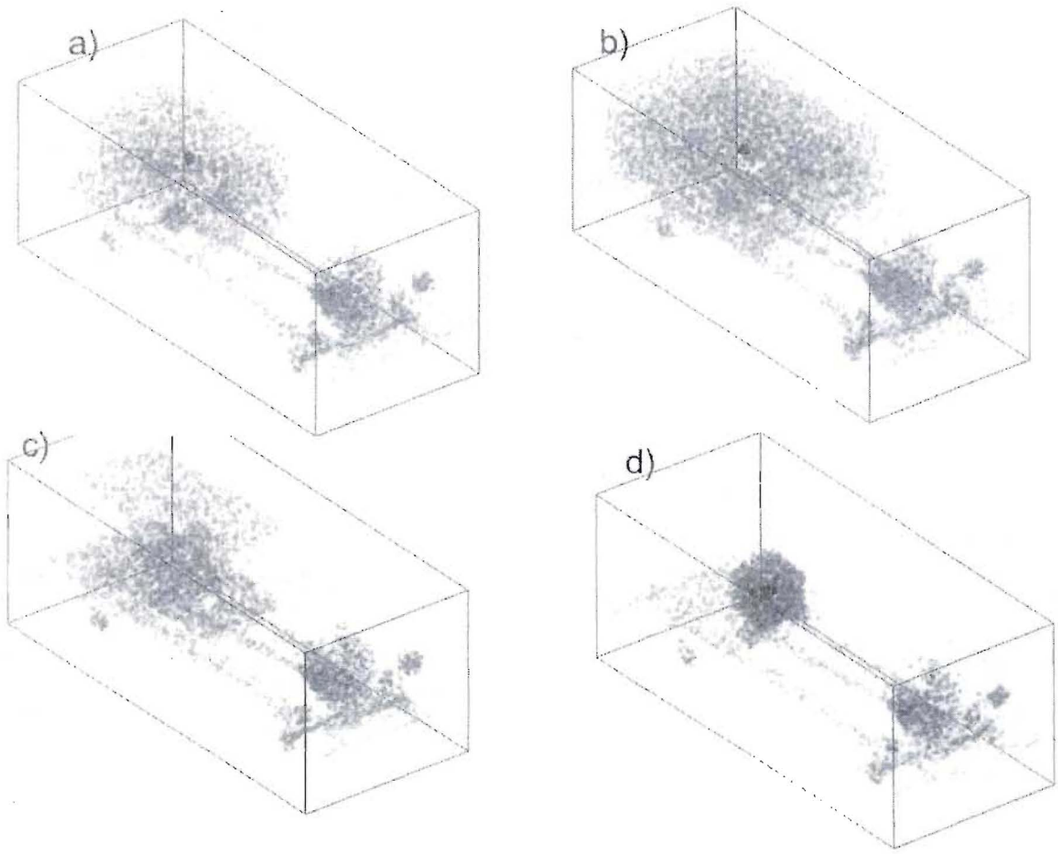

Figure 16) Reconstructions made from 1 minute cosmic ray exposures for each of the scenes described above. The color scale is adjusted to show high density materials as red, medium density materials (steel) as blue and low density materials (hydrocarbons, water and aluminum) as green. The threat object is easily distinguished in scenes a-c. Scene d is proving to be difficult. This is discussed in the text.

Threat objects inside layered container are not detected using the regularized median reconstructions we have studied all of the scenes with so far. This is because the regularization tends to rob signal from the object and put it into the steel wall.

The layered object has been interesting: firstly, because it is a difficult and challenging problem; and secondly, because it illustrates the danger of detection becoming too highly tuned. The outer four inch thick steel wall provides a considerable amount of gamma ray shielding. Since material dispersed inside of the steel container in a radiograpically invisible fashion would not be detected passively, the steel container has to be considered a threat object.

Automatic identification of threat objects has been studied by calculating the average reconstructed scattering density for all possible 10cm cubes from the 5 cm voxels. The

maximum values of this quantity for 1000 simulations and reconstructions performed for exposure times ranging from 15 to 120 seconds are shown in Figure 17).

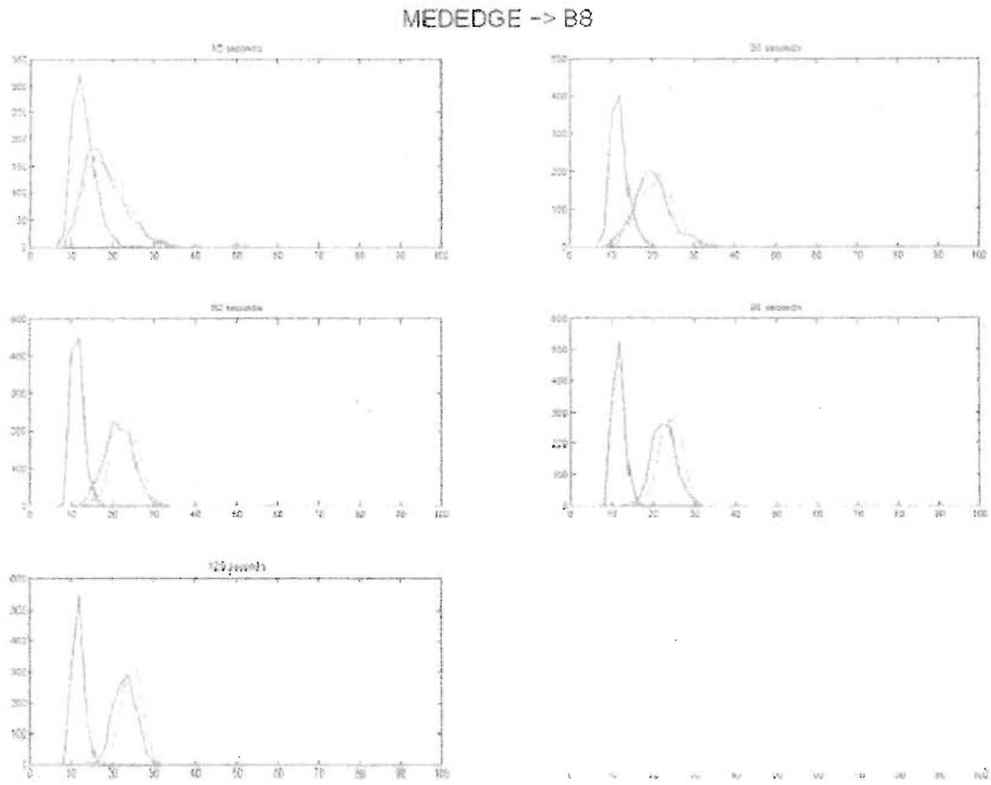

Figure 17) Histograms of the maximum value for the average reconstructed density in van scenes with threat objects below the engine (green), above the differential (red) and no threat object (blue).

These reconstructions have been used to generate ROC curves from the scenes shown in Figure 16). ROC curves show the relationship between the false positive rate (from the empty van simulations) vs. the detection rate for threat objects as the threshold is varied. The ROC curves indicate that distinctive innocent vehicles can begin to be identified with as little as 15 seconds of counting time. By 90 seconds the identification is very good.

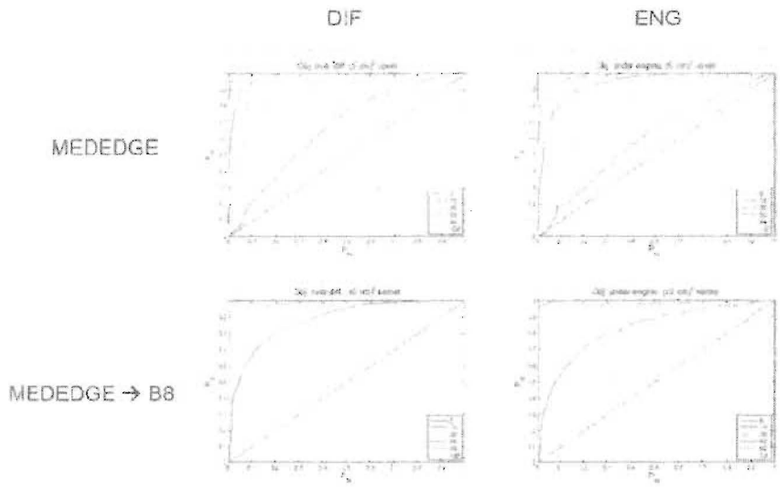

Figure 3) ROC curves generated from 1000 independent simulations. The top row uses 5 cm^3 voxels and the bottom 10 cm^3 voxels. The curves are labeled in seconds of counting time.

The analysis of the layered object and differences between the ROC curves for an object under the engine and above the differential has led to an improved technique for regularizing the reconstructions. We have found that heavily regularizing for longer exposures tends to reduce signal from the threat objects when they are located near a feature such as the engine or inside of the iron box of the layered object. For short exposures, regularization is important for reducing the noise in innocuous scenes in order to reduce the number of unresolved false-positives. A technique which uses heavy regularization at short exposures and little or no regularization at late times has been found to give better results than fixed regularization. Using this method gives the ROC curves shown in **Figure 18**.

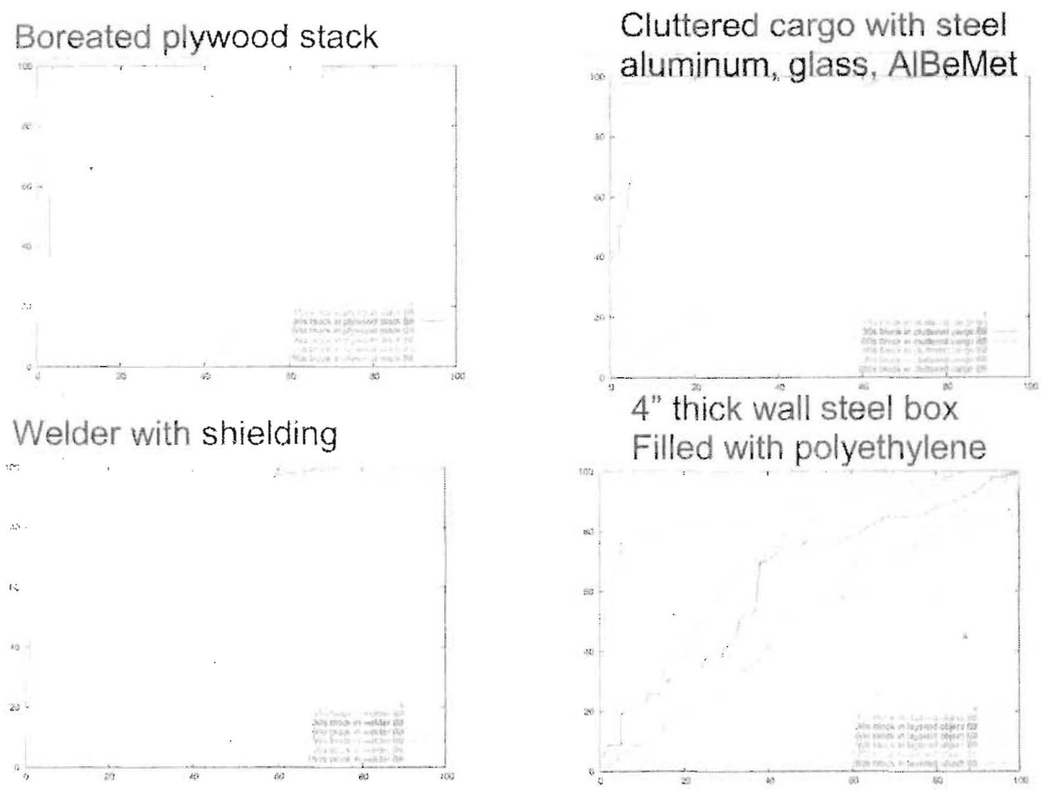

Figure 18) Eight voxel ROC curves for the scenes described in Figures 2 and 3. These ROC curves have been generated using 100 independent simulations.

The impact of momentum uncertainty has been evaluated by adding Gaussian distributed uncertainty to the perfect momentum, and then performing reconstructions and calculating ROC curves. The time needed to obtain similar ROC curves is increased by ~50% when 50% momentum knowledge (obtained from four residual measurements in the tracking detectors) rather then perfect knowledge is assumed. Lack of momentum knowledge has less effect than originally expected because of the robustness of the median reconstruction method.

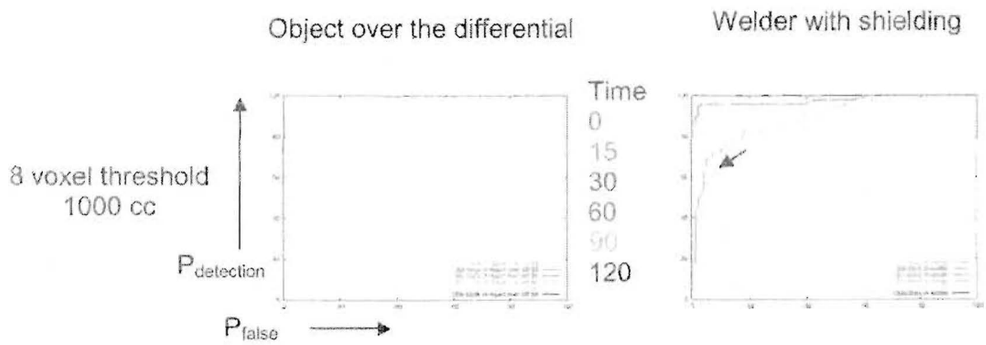

Figure 19) ROC curves using prior knowledge. Left) an ROC curve for the threat object over the differential. Right) ROC curve for the welder scene.

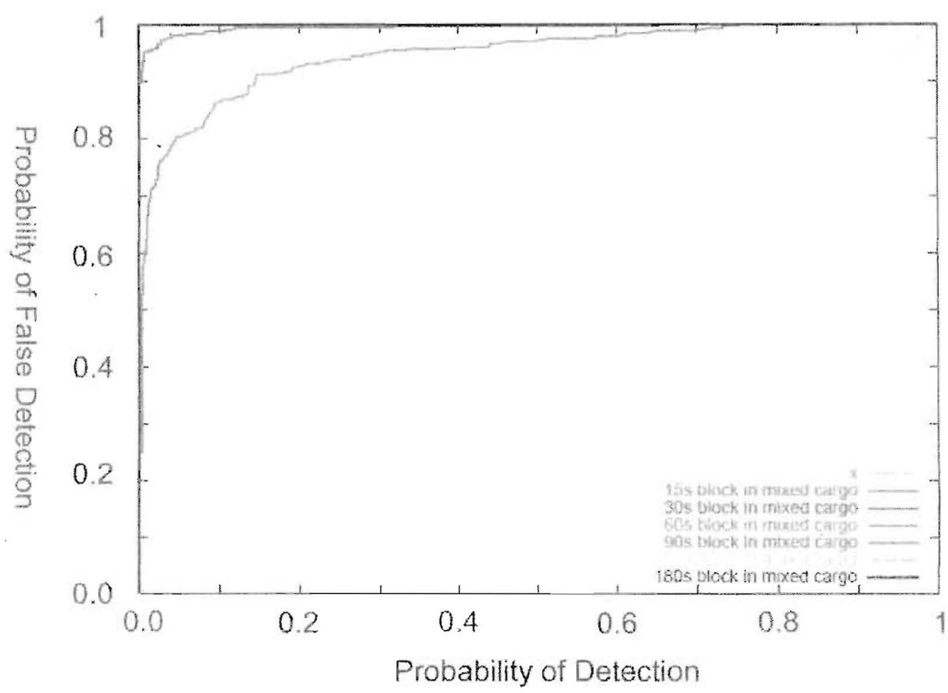

Figure 20) An ROC curve for the mix of cargo scenes describe in the text. Here we have used prior knowledge of the Van. The background subtracted was a 95% confidence level background, not the simple background used in the LMT analysis.

The use of prior knowledge considerably speeds up identification of threat objects. In previous work, where prior knowledge was not assumed and 50% momentum knowledge was used, 90% detection with zero false positives on the data set used for these ROC

curves required ~60 second counting times. The use of prior knowledge reduces this considerably. Some ROC curves obtained using 3 sigma subtraction are shown below in Figure 19 and Figure 20. With this procedure the 15 second ROC curve becomes nearly perfect for the lightly loaded scenes and the ROC curves for the heavily loaded scenes are dramatically improved. Plots of the required inspection times are shown in Figure 21 .

The green curve shows the results that are obtained when the average of many empty van scenes is subtracted from each run before the ROC curve is calculated. This reduces the average level of the signal from the innocuous scenes and results in a factor of two reduction in average scanning time. Finally, the red curve has been obtained by subtracting the average signal plus three standard deviations (three sigma) from the reconstruction at each time. This over subtracts in regions of high density where statistical fluctuations leading to false positives are most likely. This method reduces inspection times by nearly an additional factor of two.

More work is needed to optimize inspection times for this latter method. There is clearly important information that could be obtained by using reconstructions at even shorter inspection times the minimum 15 seconds studied here.

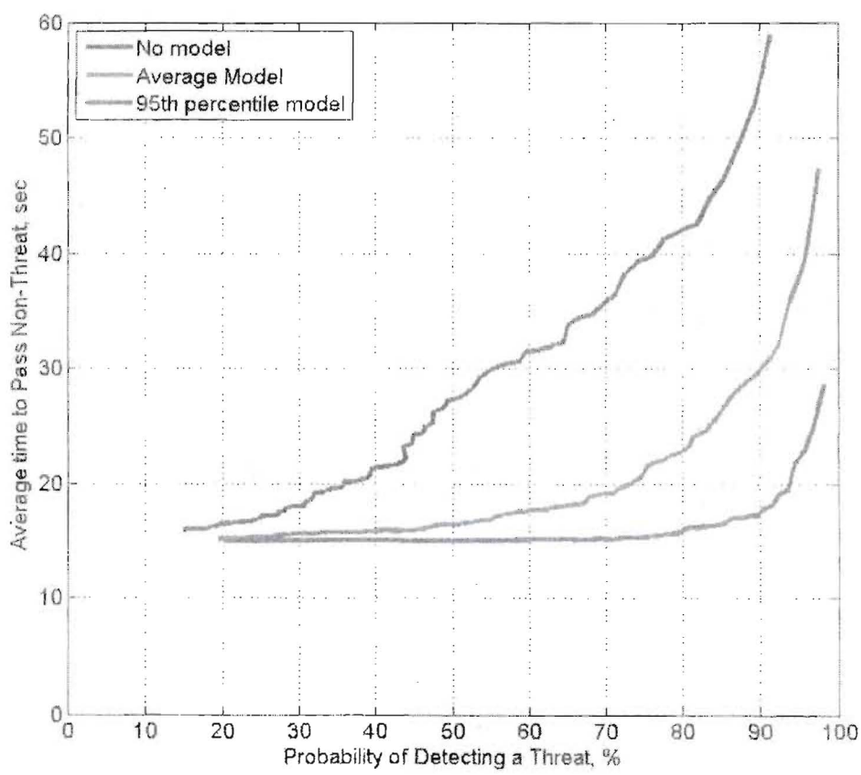

Figure 21) Comparison of average inspection times using no prior knowledge (blue), straight subtraction (green) and 3 sigma subtraction (red) for the mix of scenes described above.

Implementation

A drawing, illustrating how this idea might be implemented at a border crossing, is shown in Figure 22. Two large position sensitive detectors mounted above a counting area would measure incoming trajectories and two below would measure transmitted trajectories. High-Z, high density compact objects would be detected by looking for localized regions resulting in large scattering angle using a combination of the reconstruction technique illustrated above along with more conventional tomography. Addition layers of steel and detectors below the counting volume would be used to measure the energy of the muons.

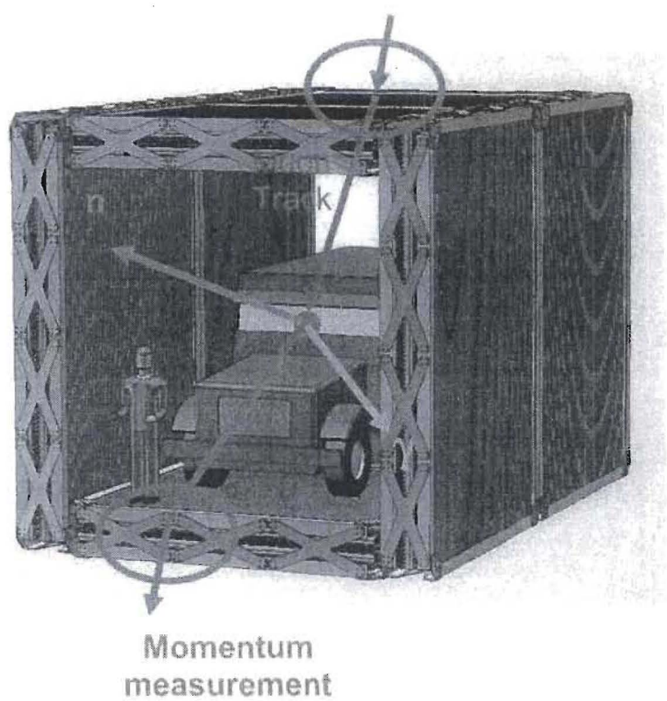

Figure 22 A schematic view of how a counting station might look. Vehicles would be stopped within the area covered by the counting station for a counting period ~20 sec.

Cost eliminates

A rough idea of the cost of such a station can be obtained using estimates based on building large area detectors for high energy physics. An element of the detector might consist of 5 cm diameter aluminum tube with a small diameter (20 μm) wire running down its axis.

The dominant costs of such detectors are in the readout and the mechanics at the end of the tubes. We estimate the cost of a single coordinate measurement will be about \$100/cm, including both planes needed to fully reconstruct the drift time information. The cost of the six planes needed to measure both incoming and outgoing trajectories for an automobile sized counting station, 8 m by 5 m, would be about $\$1.5\times10^6$.

There are several differences between this application and a physics experiment. Cosmic ray counting rates are low when compared with most high energy physics experiment. Consequently, counter lifetimes can reasonable expected to be long (decades). On the other hand, the large inexpensive skilled workforce required to maintain a high energy detector will not be available at border crossings. Detectors will need to be low maintenance. The detectors are envisioned to be sealed to eliminate the need for flowing gas and maintenance of a gas system. The electronics need to be simple and robust and use a readily available commercial computer interface such as USB. We have demonstrated that sealed drift tubes can meet the detector needs.

This technique provides the potential to examine every vehicle and shipping container crossing the US (or foreign) border. All that is needed is enough detectors at border crossing to handle the traffic. Using statistics compiled by the US department of transportation (USDOT, 2001) the total personal vehicle traffic crossing US-Mexico and US-Canada border was 1.3×10^8 for the year 2000. If a single muon tomography machine can analyze a vehicle within 40 seconds of counting/processing time, operating for 12 hours per day, than only about 250 machines would be needed to handle the entire cross border personal vehicle load. (In order to accomplish this goal, one will presumably need to take advantage of the time that vehicles are entering and exiting the machine, and processing will need to occur within the same time window. The total cost of $\$375\times10^6$ is clearly negligible when compared with the economic consequence of the detonation of a nuclear device within the US borders. Queuing times and rate fluxuations may require quadrupling this estimate. A similar size effort would be need to handle commercial cross border truck and sea port transportainers traffic.

The same technique can be used to examine cargo in trucks and transportainers. The long storage time of transportainers in transit in ships at sea suggests a possibility. Special transportainers containing position sensitive detectors could be interspersed with normal cargo. Radiography could be accomplished using coincidence between these monitor transportainers, to sample the cargo in the hold of the ship. Although this technique might not afford 100% coverage, it could take advantage of the transport time to survey some of the cargo in a ship.

Conclusion

A technique for radiographing large objects with cosmic muons has been described. This technique is particularly sensitive to high-Z dense materials. We have performed a considerable amount of experiment (LMT) and theoretical (GEANT/MLEM) analysis on automatically identifying 1000 cm^3 nuclear threat objects in complicated background scenes. We can confidently say that we have demonstrated detection times of ~4 minutes for data taken with the LMT. We expect gains on the order of a factor of 10 reduction in scanning times when we implement full solid angle scanning and momentum estimation, a factor of 2 from momentum estimation and 5 from solid angle.

We have also estimated the times needed in larger and more complicated scenes using GEANT simulations and MLEM reconstructions. These assume the full solid angle, 50% momentum knowledge, and take advantage of fully three dimensional density reconstructions, which reduce the nose levels. These demonstrate that by using prior knowledge, 17 second time scans provide >90% confidence identification of 1000 cm^3 volumes of high Z material with less than 0.2% false positive rates for the scenes studies.

In operation it is reasonable to expect 15 second scan times for occupied vehicle traffic. We have not studied cargo containers with our new more sensitive techniques. Our previous work suggested that <60 scanning times are feasible for a difficult mix of cargo containers loaded to their weight limit. With ML/EM there is every reason to expect these times to be shorter, but 60 seconds is a conservative estimate for cargo container scanning times.

An order of magnitude cost estimate for the capability of searching every incoming passenger vehicle ($\$375\times10^6$) shows the technique to economically viable.

We have also presented results from some studies that have used sealed drift tubes to study the potential of MT for measuring gamma ray signals from nuclear threat objects. A full MT scanner should provide a gamma ray counting efficiency of >10% across a wide rage of energies. Although not discussed above, gamma ray and neutron sources in a cargo volume can be localized using the position dependence of the signal. One conclusion is that RDD devices require enough radioactive material so that shielding them makes them highly visible in the MT images. Also, we have shown that there is a significant and detectable signal form the ^{238}U component of HEU. The largest fraction of this comes from Bremsstrahlung x-rays produced by beta decay of a daughter of ^{238}U alpha particle decay. The radiation signal from 20 kg sample of HEU should be detectable. Smaller unshielded samples may also be detectable when information from MT, gamma, and neutron counting is fused. Twenty kg samples are also highly visible in the MT images.

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