LA-UR- 09-03264

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Intended for: Extended abstract for IEEE Nuclear Science Symposium

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Form 836 (7/06)

Soft Cosmic Ray Tomography for Detection of Explosives

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***Abstract*—Charged particle tomography has been gaining ground due to its unique probing characteristics, and the ability of cosmic ray muons to deeply penetrate matter, allowing sensitivity to atomic number, radiation length and material density via detection of the probing particles before and after target traversal. But not all particles completely traverse the target volume. This paper explores the usefulness and information content in the stopped particles, referred to as soft particles. We show, in simulations, that the stopped particles are sensitive to low Z material and therefore provides complementary information to the scattering data.**

I. Introduction

High-energy cosmic rays come from sources outside our solar system. They are streams of subatomic particles, mainly protons and gamma rays. When they collide with the upper atmosphere, they produce unstable pions which very quickly decay to muons. These are ideal probes for tomographic imaging of solid objects: (1) being charged, they are easily localized in space and time using Gas Proportional Chambers; and (2) they penetrate deeply into matter[1] with which they interact electromagnetically via multiple Coulomb scattering.

The amount of scattering is a function of the atomic number, radiation length and material density along the path of the muon. By measuring the path of individual muons into, and out of a volume of interest, one can measure the total scattering along each path and use this data to calculate 3-dimensional reconstructions of the scattering density of a volume of interest. Because the multiple-scattering signal from high-Z, high-density material is very strong, the technology is well suited to the discovery of the illicit transport of high-Z materials, such as special nuclear and radiological materials and radiation shielding materials [1], [2], [3].

The algorithm development is based on estimating the *stopping density* of different materials using maximum likelihood estimation, and it is tested on various Monte Carlo and GEANT simulations.

II. Soft spectrum imaging

Not all incident charged cosmic rays particles traverse the volume of interests, with the lower energy (soft) particles being more likely to be stopped than their higher energy (hard) counterparts. Previous imaging efforts simply discarded the stopped particles. But by understanding the information content of these stopped particles, we have an opportunity to exploit an additional, and possibly complimentary, source of information that does not require additional equipment nor longer exposure times. Because lower energy particles are more impacted by low and medium Z materials than their higher energy counterparts, the stopped particles provide information about low and medium Z materials in the scene.

The presented work was motivated by the desire of using cosmic radiation to find and identify explosive materials brought onto light rail mass transit. To achieve this objective, we develop a new detection technique based of the use of stopping (range radiography) in addition to multiple scattering. This paper presents encouraging results on exploiting soft cosmic ray stopping to image low to medium Z materials. We have developed algorithms to make 3-dimensional image reconstructions from the measured incoming path of each particle and knowledge of the particle having stopped or not. That is, we use single particle statistics related to stopping, and not the more diffuse information contained in the "shadow". The challenge is to device an algorithm whose computational complexity scales well with the size of the reconstructed scene. The resulting *transmission*-tomography provides a useful complement to *scattering*-tomography.

III. Modeling

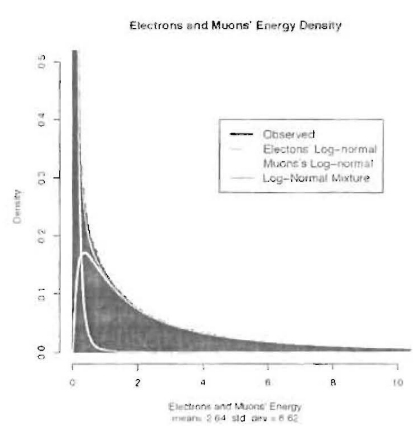

Fig. 1. Energy spectrum of charged cosmic particles

A charged particles with incident energy E entering a

[1] We expect about half of typical 3GeV to traverse one meter of iron.

volume of interest along a path γ is stopped if the energy loss along the path γ exceeds the incident energy, that is

$$R_\gamma = \int \varrho(\gamma(s))ds > E,$$

where $\rho(\cdot)$ is the stopping density. While the energy of an individual particle is not known, we assume that we know the cumulative probability distribution H of the energy. It follows that the probability that a particle stops is $1 - H(R_\gamma)$.

Empirical study of the energy spectrum of charged cosmic particles, a mixture of muons and electrons, is well approximated by a mixture of two log-Normal distributions shown in Figure 1. For our analysis is not impacted by the knowledge that there several types of charged particles because our instruments can not distinguish between them.

Consider voxilizing the volume under study and denote by $\varrho = (\varrho_1, \ldots, \varrho_m)$ the stopping density in each of the m voxels. Given an incident path γ through the volume under study, let $L = (\ell_1, \ell_2, \ldots, \ell_m)$ denote the length of the path through each of the m voxels. If the path does not pass through voxel i, then $\ell_i = 0$. Finally, let Z denote the random variable that takes values zero or one, depending if the particle stops or traverses the volume, respectively. The log-likelihood of the observed data $(\gamma_1, Z_1), \ldots, (\gamma_n, Z_n)$ is

$$\mathcal{L}(\rho) = \sum_{i=1}^{M} Z_i \log(1 - H(L_i^t \rho)) + (1 - Z_i) \log H(L_i^t \rho). \quad (1)$$

Conceptually, we reconstruct the stopping density by maximizing (1). The difficulty lies in developing algorithms that (1) scale well with the number of voxels m, and (2) allow the maximum to be achieved on the border of the parameter set, i.e., $\varrho_i = 0$.

IV. Preliminary results

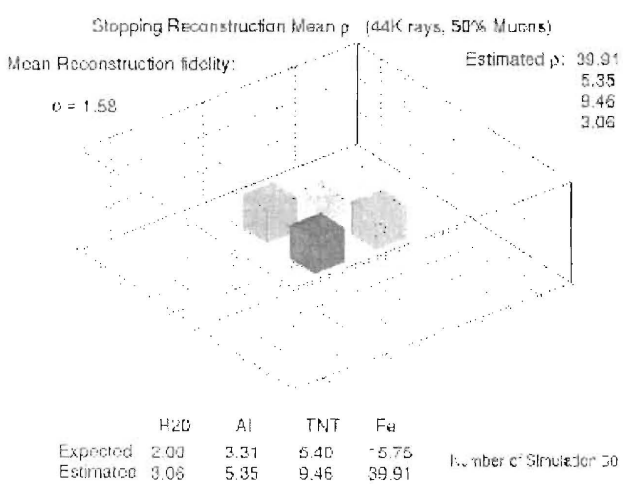

Fig. 2. Reconstruction of four solid cubes of Iron, Aluminum, TNT and water from recorded charged particles observed over 164 seconds.

We have tested our algorithm by applying them to reconstruct simple landscapes using synthetic 164 seconds exposure data from GEANT 4 simulations. Of particular interest was to evaluate the potential value of using stopped charged particles for identifying low-Z materials.

The results are encouraging. Figure 2 shows a typical reconstruction of a landscape containing four boxes, one containing Iron (medium Z), one containing Aluminum (low Z), one containing TNT (low Z of interest) and one containing water (lowest Z). Figures 3 below shows boxplots for the estimated parameters over repeated simulations for 164 seconds exposures. Notice how well the information from the stopped charged particles differentiate between the various materials.

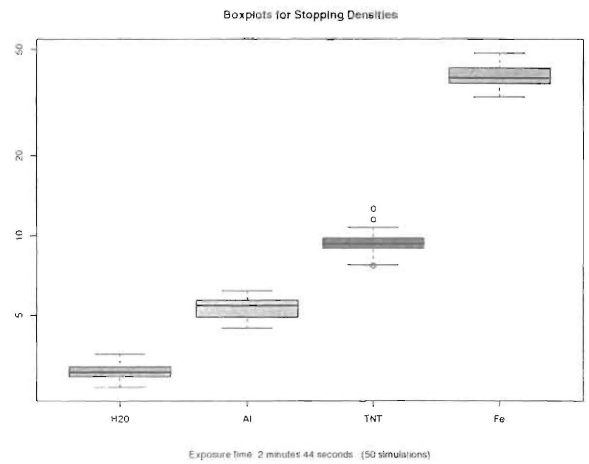

Fig. 3. Boxplot of parameter estimates for 50 synthetic data sets.

V. Conclusion

Analysis of stopped charged particles provide a complimentary view to scattering tomography and helps resolve medium and low Z materials. Combining scattered and stopped particles has the potential of increasing the dynamic range in the reconstruction at little or no costs in terms of exposure times and complexity of the measurement apparatus. This opens the door for a broader range of application for passive tomography, with possible applications ranging from the detection of explosives to passive imaging of buildings and dams.

References

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