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Muon tomography: Tracks reconstruction and visualization techniques

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Summary. — The Muon Portal is a project funded by the Italian Ministry of Research, that aims to develop a system able to detect radioactive materials inside containers, to counteract the illegal transfer, by means of muon tomography. This novel technique bases its functioning on the properties of some particles of the secondary cosmic radiation: the muons. These affect the Earth's surface at a flow rate constant and interact weakly with matter being deflected significantly only when they pass through material with a high atomic number. In this paper the author will focus on issues related to the reconstruction and visualization of tracks within the scanned object, presenting the results of some track reconstruction algorithms such as the POCA and the EM-Likelihood, and integrated techniques of simulation and visualization of tomographic images in 3D with algorithms based on volume rendering and isosurfaces.

PACS 14.60.Ef – Muons.
PACS 25.30.Mr – Muon-induced reactions (including the EMC effect).
PACS 07.05.Rm – Data presentation and visualization: algorithms and implementation.
PACS 29.40.Mc – Scintillation detectors.

1. – Introduction

In the last few years there was an increasing attention by the authorities to support countries in the fight against terrorism. Concern has been expressed about the close links between terrorism and international organized crime, focusing in particular on the illegal traffic of nuclear, chemical, biological and other potentially lethal materials. Terrorist use of radioactive material is a serious threat to health and safety of the population. This traffic requires a broader international control and improved detection services in order to prevent the movement of terrorists and the supply of weapons through effective border controls. The more worrying scenario is undoubtedly linked to the use of nuclear weapons. They are typically composed of a core of fissionable substance (uranium or plutonium) surrounded by moderator material and properly shielded. Their presence can be revealed through X-ray radiography devices or by detection of gamma rays or neutrons emitted from the sample [1, 2]. The conventional radiography techniques use the radiation absorption phenomena on the material and, then, require the measurement of the radiation flux transmitted, that is a fraction of the incident one. They are limited by the penetrating capacity of the X radiation which corresponds to a few cms of lead for energies in the MeV range. Thicker layers would require higher energies, or very intense X-rays flows, dangerous in both cases. Furthermore these techniques, besides being expensive and difficult to implement (some, in fact, introduce additional radiation), are seriously compromised in presence of heavy materials like, for example, lead that shield the nuclear one. In the "Muon Portal" project([1]) it is proposed an alternative to the conventional radiographic techniques (in absorption), represented by multiple imaging, or tomography, by diffusion of cosmic muons. A detection system based on the muon tomography exploits the phenomenon of cosmic muons deflection when crossing a material. The trajectory of a charged particle within a material is the result of the convolution of many small deflections due to the particles diffusion by the atoms that constitute the material: this phenomenon is the Multiple Coulomb scattering. The overall result of these diffusion processes depends strongly on the atomic number of the crossed material. Muons are charged particles (positive and negative) found in abundance in the secondary component of cosmic radiation. The Earth is constantly bombarded by primary cosmic rays constituted mostly by high-energy protons. When a primary cosmic interacts with the Earth's atmosphere, it produces a cascade of secondary products (photons, electrons, muons, etc.), the so-called *shower* or *cascades* of particles. At sea level the flux of the charged particles is almost constant and is equivalent at 10000 particles/min m^2 and most of them are muons (μ) of average energy of 3–4 GeV. The intensity varies with the angle, resulting in maximum for the vertical direction and almost zero for the horizontal one. This means that this is a very penetrating radiation: muons, in fact, interact weakly with matter and they are deviated from their original trajectory only when traveling through a material with medium or high Z. They are not only capable of reach the sea level but also of penetrate thicker layers of rock and earth. The muon tomography proposed in this paper provides several advantages: firstly, the detection capability of the presence of fissile material from the study of information provided by each particle. With this technique it will be possible to identify materials with high atomic number (typically uranium or lead containers), even in the presence of shielding materials at low and medium atomic number. Furthermore it can get a significant reduction in measurement times and an increase in the statistical accuracy of the results. An additional advantage, not negligible, is due to the fact that the secondary cosmic radiation, the subject of this study, is a natural radiation constantly present in every place on Earth, where human beings live. The proposed solution therefore does not introduce additional levels of radiation than those found in nature. Given the characteristics just stated, muon tomography appears to be a useful technique for the inspection of cargo containers and trucks at the border in order to determine the presence of fissile material and thwart nuclear smuggling. In the literature there are some papers that, as an alternative to traditional techniques, propose the use of cosmic radiation as detection technique. Some propose the muon X-ray for border control [3, 4], others suggest to realize muon tomography but using different detection systems, such as gas detectors [5, 6]. Furthermore

([1]) For further details visit our Web site: `http://muoni.oact.inaf.it`.

cosmic radiation is proposed for different purposes, for example for the detection of the internal composition of a volcano [7, 8]. The "Muon Portal" project is the only one that aims to realize a working prototype of a muon tomography detection system. The paper is divided as follows: the second section provides a technical description of the detector. Section **3** describes some details about the simulations in Geant4, and sect. **4** explains how the tracks reconstruction is done. In sect. **5** the reconstruction algorithms are discussed and presented. Then in the sect. **6** some simulation scenarios and results of the initial reconstruction of tomographic images are showed. Finally some conclusions are drawn and some future developments are briefly presented.

2. – Detector design

When crossing a medium or high-Z material, the scattering angle of a muon from the original trajectory has a Gaussian distribution, with mean value 0 and RMS depending on

– the inverse of the muon momentum ($1/p$),

– the material thickness (x),

– the radiation length (X_0), which depends on $1/Z$.

Different materials mean different scattering angles, then it becomes necessary to measure these angles to determine the presence, position, shape and type of materials. In order to assess it, it is necessary to have a system that can detect the passage of the particle and reconstruct the trajectories. The container is treated as a black box: an analysis of its content is executed considering the behavior of particles crossing it, without any other information about what happens inside. The idea of the project is therefore to construct a detector which is constituted by two planes (at least two) that completely cover the extension of the container, placed above it (in order to outline the trajectory of the incident particle) and two planes placed below the container to tracing the outgoing trajectory. In the rest of this section the detector structure will be described in details, highlighting some design choices and giving some indications concerning the detector electronic.

2˙1. *Detector structure*. – The detector is based on eight physical position sensitive planes, each of which corresponds to two physical planes XY. The planes will be positioned as shown in fig. 1: two logical planes are placed above and two planes below the volume of the container to be inspected. The two upper and lower detection planes will be 100 cm spaced, while the internal part of the detector will be 300 cm spaced, to allow the insertion of a standard container. The overall size of the detector will fit that of a real TEU (twenty-foot equivalent units) container, of $6 \times 3 \times 3\,\mathrm{m}^3$. Each logical plane will not only be able to detect the passage of the particle, but also to find the x and y coordinates of the impact point of the muon. This will be achieved through the use of extruded plastic scintillator strips with wavelength-shifting WLS fibers, which will segment the plane in order to give information also on the position. Therefore the two physical planes corresponding to each logical level will be properly segmented depending on the involved coordinate. In order to allow a good tracking ability of charged particles (electrons and muons), the reconstruction of the trajectories before and after the container and to evaluate the magnitude of the scattering suffered by each track, it is necessary to have a good spatial resolution, of the order of a few mm, given the

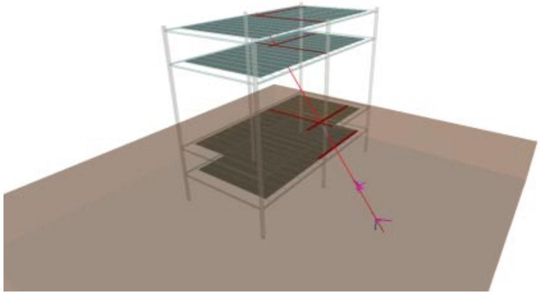

Fig. 1. – Muon portal detector structure.

distance between planes. Each plane will be implemented in a modular structure, designed to facilitate the engineering of the entire apparatus. It will consist of 6 modules, in different orientations for the X over Y planes: each module will consist of 100 bars of plastic scintillator, $1\,\mathrm{cm} \times 1\,\mathrm{cm} \times 3\,\mathrm{m}$. The mechanical structure has been custom designed to provide adequate support for the detector planes, yet minimizing the quantity of material crossed by cosmic muons, and to let to insert between the intermediate planes of detection a metal structure that is a replica of a real container. Simulation of the mechanical stresses due to the weight of the various components and to temperature variations have been studied, together with the problems of alignment during assembly tracking modules.

2˙2. *Strip design.* – Each detection module, as said before, is constituted by 100 strips of extruded plastic scintillator material with WLS fibers, that transport the photons emitted to the silicon photomultiplier (Sipm) which is optically coupled with the fiber and which is located at one of its two ends. A series of tests and simulations have been carried out to evaluate the resulting yield in light of various types of scintillators and fibers and to evaluate different types of configuration of fibers within the strip. We considered scenarios with a single fiber positioned respectively at the top, center or bottom of the strip and scenarios with 2 fibers placed in the same positions but in two different configurations: vertical and horizontal. It was also evaluated the effect of the glue and the gel on the optical yield, considering also the hypothesis to insert the fibers into a central hole in the strip, without the need of gluing the fiber. Currently the configuration that seems more efficient is the one with $1\times1\,\mathrm{cm}^2$ strips cross section with 2 fibers placed within a central hole in the strip and placed in a horizontal position relative to one another. For each geometric configuration Geant4 simulations were performed in order to study the transport of optical photons within the scintillator strips and the fibers WLS, and to compare the results with experimental data. It has been already prepared a project for the construction of the single detection module. A tool, which will be used to pack the strips, enter the WLS fibers and to prepare their surface with a diamond tool for optimal optical coupling to the photosensors, is under construction.

2˙3. *Read-out electronic.* – From the point of view of the readout electronics, the detector will present a very high number of channels to be read: if we consider, in fact, to have 100 strips per module (each with one or two fibers WLS) and to have 6 modules for each physical plane, in total we will have 4800 or even 9600 channels. To simplify all the system it was decided to adopt a system of channels compression that consists to divide the strip of each module into groups of 10 and to number the strip of each group from 1 to 10. In this way the single strip hit will be uniquely identified by a pair of values (n_{group}, n_{strip}). If we consider the design with a single fiber, the number of channels to each module will drop from 100 to 20 and in total we will have a compression factor equal to $2\sqrt{N}$ if N is the number of fibers. It is assumed that the electronics of the sensor will be able to associate the detection points muons to a single path muon using the timing information of detections muons on sensor arrays. The front-end electronics will be based on the use of MAROC3 chips (64 channels each), which have an adjustable gain (channel-by-channel), a fast shaping and a common threshold. Real-time boards based on FPGA FlexRIO will be used, with a sampling rate up to 250 MHz.

3. – Ingredients of the Geant4 simulations

An intense phase of simulations and tests preceded the development of the reconstruction algorithms and it was necessary both to define the design of the detector, in order to fix for example the optimal distances between the various planes and to calculate the acceptance of the whole detector, both to test the functioning of the tomograph. The physical structure of the detector has been modeled with Geant4, a toolkit for simulating the passage of particles in matter. The simulated characteristics are as follows: 4 logical planes XY of $18\,\mathrm{m}^2$, placed at a distance of 1 m, 3 m, and 1 m, respectively. Each plane is segmented in 6 modules, 2×3 in X and 6×1 in Y with 100 strips per module. The container was also modeled according to the actual size: $5.9 \times 2,4 \times 2,4\,\mathrm{m}^3$ with a thickness of 3 mm[Fe] and the dummy support rack such pillars, lateral and grid bars with thickness of 2 cm[Al]. The Albedo effect was also taken into consideration. In order to simulate a real flux of cosmic rays reaching the Earth a CORSIKA simulation with this set of parameters for the muon energy and angular distributions was run:

- Primary protons, $\mathrm{d}N/\mathrm{d}E \propto E^{-2.6}$, $E = 5 \times 10^9$–10^{15} eV,

- shower particles registered at sea level for Catania location,

- average muon energy at ground $\sim 3\,\mathrm{GeV}$,

- angular distribution peaked at 30, $\mathrm{d}N/\mathrm{d}\theta \propto \sin\theta \cos^3\theta$,

- histogrammed parametrization for fast generation.

In the Geant4 simulations all the optical processes were switched off and 5×10^6 events in the detector were simulated.

4. – Events reconstruction

The simulation carried out with Geant4 provides information on the points of impact of the particles of cosmic radiation that is likely to affect our detector in a scanning time of a few minutes. The next step is the reconstruction of the event. It consists of the following 3 phases.

4˙1. *Hit selection.* – This phase consists in the selection and filtering of all hits on the planes. First of all it selects strips that have collected light above a given threshold (in $\mathrm{d}E/\mathrm{d}X$ or *npe*) and that have triggered within $2\,\mu$s. Only the 4-fold events are selected (at least 1 hit in each XY plane), according to the acceptance of the whole system. Then it collects x-y measurements from each plane and smears the hit pixel positions with the resolution ($\sigma \simeq 2.9\,\mathrm{mm}$)

4˙2. *Cluster finding.* – Due to the interaction between the primary and particles present in the atmosphere, a shower of the atoms will arrive simultaneously on the detector surface. Therefore, the presence of clusters of strip hit at the same time is high probable. Adjacent hit strips could define a rectangular/quadratic shape cluster, so, in this phase it is performed a scan of XY hits in each plane to search for clusters (adjacent hit pixels). After a re-split of the clusters in single hits below a pre-defined multiplicity is executed and single hits are replaced with cluster barycenter for the track finding stage.

4˙3. *Track finding.* – This phase collects valid track candidates connecting together every hit at each plane to the other ones at the following plane. Then some techniques of track finding and selection are applied. At the moment we use the Kalman-Filter approach for track finding and the track selection is made according to minimum χ^2 criteria with multiple track candidates.

5. – Reconstrucion and visualization algorithms

The track reconstruction is a challenging task and consists in the elaboration of data from the planes, the x and y coordinates of each logical level, in order to obtain information on the deflection occurred by the muons within the volume scanned. We implemented two different reconstruction algorithms: the POCA and the EM-LM. They differ highly in the approach to the reconstruction and provide different results at different execution times, but both will be useful for the portal muons and will be used to accomplish different functionalities.

5˙1. *POCA.* – The first algorithm used is the Point of Closest Approach (POCA)([2]). It starts from a simplifying assumption: each scattering is a single event or a single atomic nucleus is involved in a scattering. It assigns the scattering angle at that point rather than distributing it to multiple points on the track of the muon as occurs normally by the multiple scattering. The POCA is therefore a purely geometric algorithm that ignores physical scattering phenomena. The functioning of the algorithm is as follows: first of all the incoming and the outgoing tracks are calculated starting from the coordinates of the impact points at the planes that detected the passage of the muon. In 3D, the two tracks will not necessarily be coplanar, indeed in most cases it will not, because of the scattering and of possible errors introduced by the measure, due for example to the angular resolution of the detector. For this, typically, they do not intersect at a single point. Consequently, based on the projection of the incoming and outgoing tracks, the algorithm finds the points where they came closest using a linear algebraic formulation.

([2]) D. Sunday, Available online: `http://geomalgorithms.com/a07_distance.html`.

Then it estimates the scattering point as the midpoint of the line between the two points. This point-of-closest approach is the POCA point corresponding to each muon. Even the scattering angle for each muon is calculated. The pairs (*poca-point*, *scattering-angle*) are returned for all muons where the angle is not very close to zero (POCA point does not exist for parallel lines or where a muon has crossed without scattering). The complexity of POCA is $O(M)$ for a number of tracks equal to M.

5˙1.1. Algorithm steps. The algorithm takes as input a list, for each muon i, of two incoming sensor points (ai, bi) and two outgoing sensor points (ci, di) and returns as output the corresponding list, for each muon i, of the point of closest approach P_i, and the scattering angle θ_i at that point. For each muon from $i = 0$ to M, let us do the following steps:

1) create the incoming track I_i and the outgoing one E_i,

2) using analytical formula find the closest points s_i and t_i for I_i and E_i, respectively,

3) compute the mid-point P_i between s_i and t_i,

4) compute the scattering angle θ_i between the lines,

5) return the list of $\{(P_i\,, \theta_i)|\ 1 \leq i \leq M\}$.

5˙2. *EM likelihood*. – The second algorithm is called the Expectation-Maximization (EM) [9, 10]. To perform the reconstruction, it uses as input the scattering angles and the linear deviations. Even in this case, the scattering angle θ_i is measured between the incoming and outgoing track-vectors of a muon. The linear deviation X_i, instead, is evaluated as the distance between the point at which the track exits the container and the projection of the point where the track would have had to go out if the muon had not undergone scattering. In the track reconstruction phase the EM algorithm distributes scattering along the entire path traversed by the muon instead of assigning the scattering event to a single point like the POCA algorithm. The track traveled by the muon ideally is obtained by connecting the particle point of entry in the container with the scattering point identified by POCA and linking, therefore, the latter to the exit point. This algorithm considers the volume scanned as a discrete space divided into 3D units that are called voxel. Each voxel has a scattering density λ_j and the algorithm models the scattering angle and the displacement data $y_i = (\Delta\theta_i, \Delta X_i)$ with a bivariate normal distribution,

$$\mathcal{L} = \frac{1}{2}\sum^{N}\left(\log|\Sigma_i^{-1}| - y_i^T\ \Sigma_i^{-1} y_i\right) \tag{1}$$

with covariance $\Sigma_i = E_i + p_{r,i}^2 \sum_{j=1}^{N_{voxel}} W_{ij}\lambda_j$ The algorithm is used to maximize $\mathcal{L}$ and find and estimate of λ_j. For further details see [9, 10]. The EM algorithm has a computational complexity equal to $O(IMN)$, with I is the number of iterations, M is the number of muons, and N is the total number of voxels, then the memory request is $O(M + N)$.

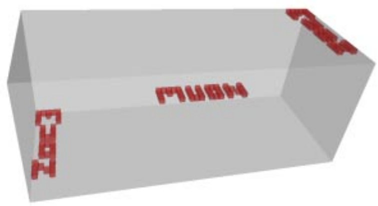

Fig. 2. – "MUON" labels scenario.

5·2.1. Algorithm steps. The algorithm takes as input the file with the coordinates of the impact points and starts computing the scattering angle and the respective lateral displacement for each track:

1) collect data about the scattering angles and the linear deviation $(\Delta\Theta_{x,y}, \Delta_{x_y})_i$,

2) compute muon path length through the voxel (L_{ij}, T_{ij}),

3) compute the weight matrix W_{ij},

4) initialize $\lambda_j = \lambda_j^0$,

5) iterate until convergence/stopping criteria.

6. – Simulated scenario and results

In order to test the reconstruction algorithms various simulation scenarios were implemented in Geant4. Among all, the author reports in this paper two of the most significant: the first one, that is shown in fig. 2, is useful to understand the ability of the algorithm to discriminate materials with different Z, the second represents a hypothetical realistic scenario (see fig. 3).

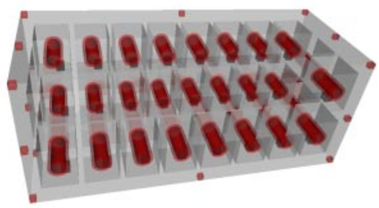

Fig. 3. – Real cargo scenario.

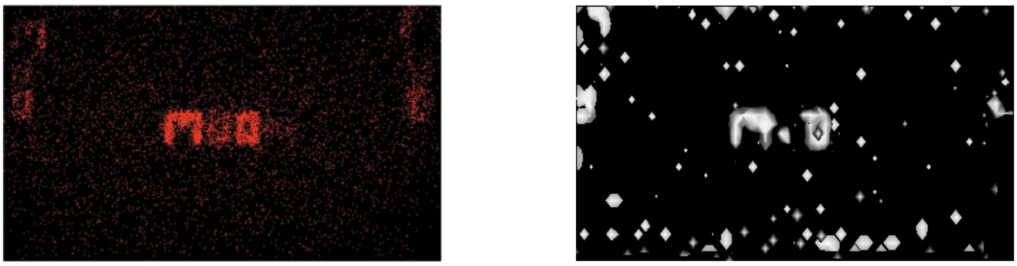

Fig. 4. – Reconstruction results with POCA for the "MUON" labels Scenario.

6˙1. *"MUON" labels scenario*. – In this scenario is simulated the presence inside a container of three MUON shape writings respectively located at the center, on the bottom edge and top of the container. The letters are made of different materials and precisely M=Uranium, U=Iron, O=Lead, N=Aluminium. This scenario is useful not only to understand the system's ability to discriminate different Z but also to evaluate the effect at the edges of the container. Figure 4, shows a reconstruction of the whole container seen from above and made with the volume rendering, and the isosurfaces. The software used for the visualization is VisIvo [11, 12]. Figure 5, instead, shows the reconstruction watching the upper and central cutting planes. As can see from the figs. 4 and 5, the EM algorithm is able to distinguish clearly the various materials and is able to detect the presence of uranium even for the labels to the edges. Some problems of reconstruction and visualization occurs only for the label at the center. Even the POCA algorithm is able to reconstruct this scenario, the letters M and O are clearly distinguishable in the center. However, the POCA fails to see right on the edge, it is unable to distinguish the presence of high-Z material and to reconstruct the shape of the letters.

6˙2. *Real cargo scenario*. – This scenario represents a hypothetical situation with a realistic load consisting mainly of Iron engine and concrete blocks with a structure in Aluminium, among whom are hidden uranium cubes of $10\,\mathrm{cm}^3$. They are located on the eight corners of the container and in the center. This scenario is significant to analyze the ability of the algorithm to recognize the presence of fissile material even in the presence of different types of material. In this second scenario, as is showed in fig. 6 we still see that the EM can provide good reconstructions, by detecting the presence of uranium cubes even in the situation of full cargo. The POCA instead shows its limits in these scenarios: in fig. 7 it can be seen that the presence of multiple layers of material with medium-high Z affects the performance of the algorithm.

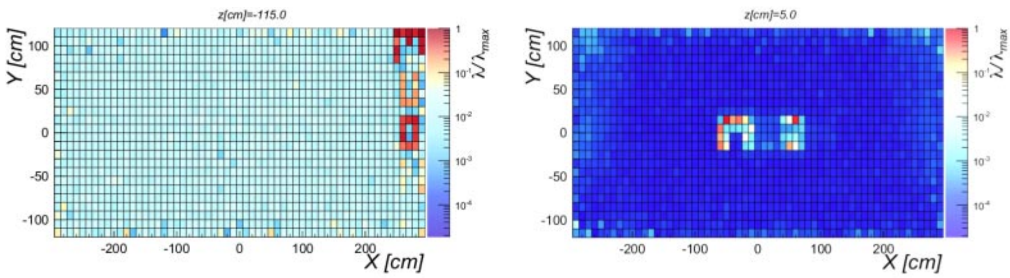

Fig. 5. – Reconstruction results with EM-LM for the "MUON" labels Scenario.

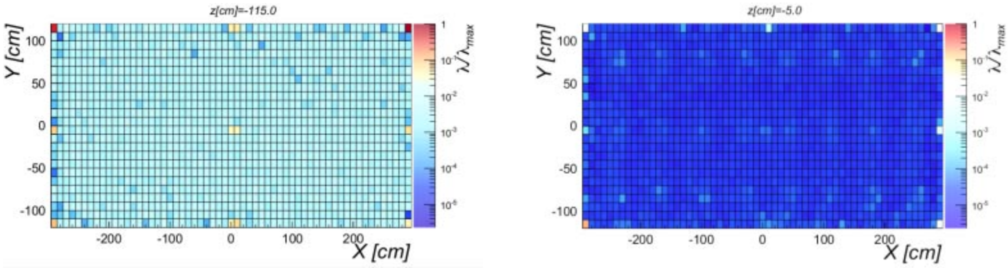

Fig. 6. – Reconstruction results with EM-LM for the real cargo scenario.

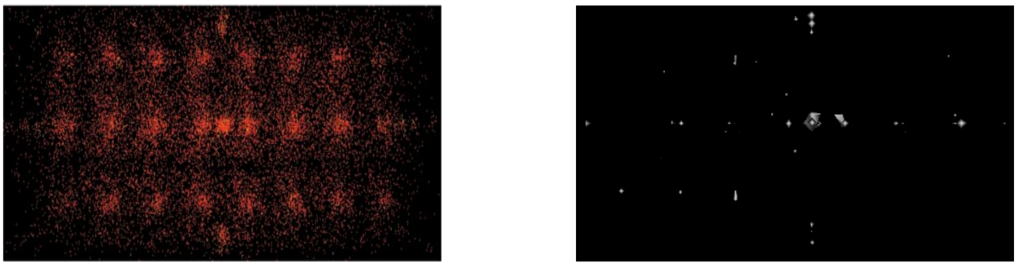

Fig. 7. – Reconstruction results with POCA for the real cargo scenario.

If we compare the behavior of the two algorithms in the two scenarios presented, we can draw the following conclusions: the POCA algorithm has some advantages like a very short running time and the simple implementation, but it has some drawbacks. As seen, in fact, when a muon travels through multiple objects, the scattering point would tend to be located between the objects as a single point from either object. Furthermore the reconstruction is not accurate, tends to occupy the surrounding voxels, leading to have a larger image than the actual one. Unlike the POCA the EM algorithm gives clearer tomographic images, so as to have better identification of medium, high-Z materials. However on the other hand it has critical running times and actually optimization techniques and parallelization are required. Furthermore a lot of fine tuning have to be done, like iteration stopping criteria, need regularization. The algorithm convergence is slow and need to be accelerated.

7. – Conclusions and future works

In this paper the author has presented the actual status of work on the use of algorithms and techniques for reconstructing images from the scattering of cosmic rays muons. Next step will be the development of an integrated reconstruction algorithm that will combine the POCA results with the E-M for better efficiency and accuracy. Some of the future directions of this work are to test the effect of using clustering algorithm to improve the performance of the reconstruction and to avoid some visualization problems caused by POCA algorithm. Furthermore it was began the integration of the reconstruction and visualization software on SCI-BUS (Scientific Gateway Based User Support(3)), a toolset to provide seamless access to major computing, data and networking infrastructures and services in Europe.

(3) For further details visit the web site: `http://www.sci-bus.eu/`.

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