IL NUOVO CIMENTO **43 C** (2020) 126
DOI 10.1393/ncc/i2020-20126-0

COMMUNICATIONS: SIF Congress 2019

Muography applied to Archaeology: Search and 3D reconstruction of hidden cavities

M. D'ERRICO([1])([2])

([1]) *INFN, Sezione di Napoli - Napoli, Italy*
([2]) *Dipartimento di Fisica Ettore Pancini, Università degli Studi di Napoli Federico II - Napoli, Italy*

received 29 January 2020

Summary. — Muon radiography, also known as *muography*, is an imaging technique which exploits cosmic-ray muons to obtain an image of the internal structure of large volume bodies, such as volcanoes, pyramids or hills. It is in principle very similar to the common X-ray radiography, it indeed can provide the density distribution inside the object of interest measuring the absorbtion degree of muons after crossing the body along different directions. Muography allows also to reveal the existance of unknown void regions, underground or inside large bodies; this feature is of particular interest in the field of Archaeology giving the possibility to discover hidden cavities using a non-destructive technique. In this paper the application of muon radiography in the archaeological field will be presented, focusing particularly on the development of a novel approach to threedimensional imaging, where the usual bidimensional muographies, taken from at least three different positions, are combined in order to localise cavities in space and reconstruct their shape.

1. – Introduction

Cosmic-ray muons are continuously generated in the high atmosphere of the Earth mainly from the decay of kaons and pions, particles produced in the interactions between primary cosmic rays, mostly protons, and nitrogen or oxygen nuclei.

Muons are elementary particles very similar to electrons but with a mass 200 times larger; they can be exploited in muon radiography to investigate the internal structure of big bodies (pyramids, volcanoes, hills, . . .) thanks to their very high penetrating power, which allows them to cross several hundreds of meters of rock without being completely absorbed.

The physical principle of muography is very similar to the usual X-ray radiography but X-rays are replaced by muons. The technique is based on the attenuation of the muon flux in the absorber, owing to electromagnetic processes; the measurement of the

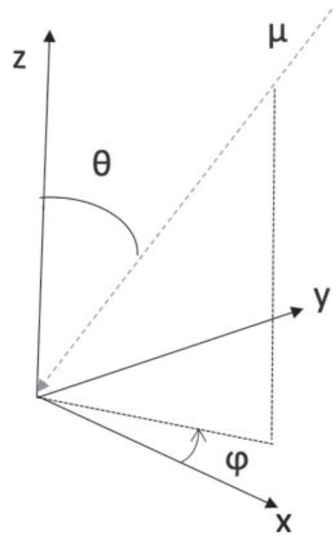

Fig. 1. – Definition of the angular variables, the zenith angle θ and the azimuthal angle ϕ.

surviving muon flux reaching the *muon telescope* allows to obtain an estimation of the average density of the object under study along each muon path.

Cosmic-ray muons come from all directions and their flux is measured as a function of the angle θ with respect to the vertical (or the elevation angle $\alpha = 90^\circ - \theta$) and the azimuth angle ϕ of the direction, referred to the local coordinate system (see fig. 1); a muography provides a bidimensional map in the coordinates (θ, ϕ) of the attenuation of the muon flux including all the detectable coming directions (depending on the geometrical acceptance of the used particle tracker).

To perform these measurements, the *muon telescope* must ensure good tracking performances, provide good angular resolution and guarantee stability in time and position. Technologies in use are basically of three types: nuclear emulsion detectors, scintillation detectors and gaseous detectors. In the following sections we will focus on scintillator-based detectors.

Muography has been successfully applied in several fields, such as Volcanology, Civil Engeneering, Archaeology and others. This paper will present the archaeological applications and the results of one case-study.

2. – Muography in Archaeology

The first application of muon radiography on an archaeological issue was performed by the nobel prize Alvarez, to search for unknown burial chambers in the second pyramid of Giza [1]. Despite the fact that this attempt resulted in the evidence of non-existance of burial chambers in the inspected volume, the notable power of this technique in Archaeology was established.

The principal aim of exploiting muography in Archaeology is indeed the search for hidden cavities inside large dimentions objects, such as pyramids, or deep underground. The existance of an unexpected void region in the space inspected with muons translates in an excess of particles reaching the detector from the corresponding directions where

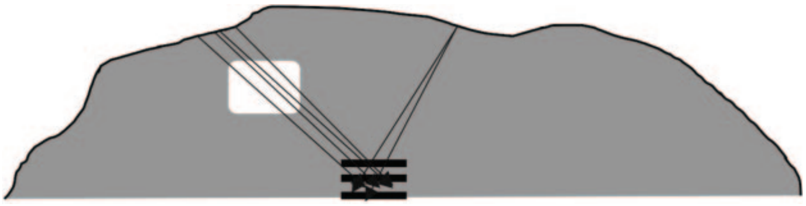

Fig. 2. – Scheme of the search for underground cavities with muon radiography (not in scale).

less than expected material has to be crossed. A schematic drawing of this application is represented in fig. 2.

The main advantages of muography in this field are the higher spatial resolution with respect to other ordinary techniques, which allows to be sensible to even void regions with a dimension of the order of $1\,\mathrm{m}^3$, the possibility to investigate the space up to several tens of meter deep underground and the fact that this technique is completely non-destructive. This last feature, in particular, encouraged the ScanPyramid's Collaboration to perform muon radiographies of the pyramid of Cheops in Egipt exploiting different technologies (emulsion and gaseous detectors) [2]. This application resulted in the discovery of a new unknown chamber, which is the first great breakthrough in the pyramid of Cheops without any damage to the construction.

The biggest drawback is that, in order to apply this technique the possibility of installing the telescope under the region to be explored is needed.

3. – Discovery and 3D reconstruction of a cavity at Mt. Echia site

Mt. Echia is a headland in the center of Naples (Italy) with a maximum altitude of about 60 m a.s.l. and mainly composed of yellow tuff, a soft volcanic rock (fig. 3). This site represents the early settlement of the city in the 8th century BC. In the course of history a very complex system of underground tunnels and cavities has been excavated

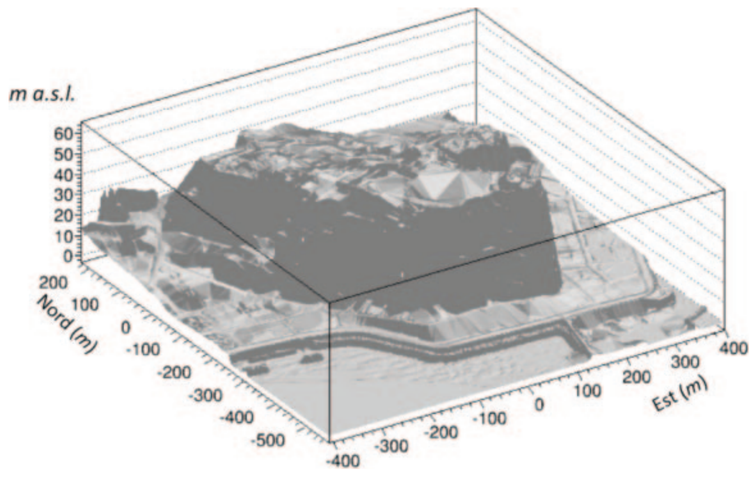

Fig. 3. – Mt. Echia topography, obtained from a Digital Elevation Model (DEM).

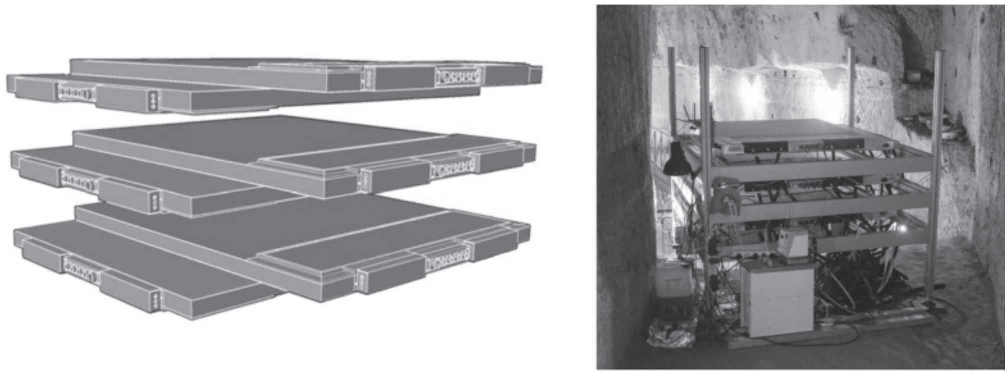

Fig. 4. – A scheme of the MU-RAY telescope arrangement under Mt. Echia. The detector has three xy tracker planes installed horizontally with a 0.50 m distance between the outer planes.

which is still being studied and is subject of systematic investigations. It is also easily accessible through the so-called Bourbon Tunnel, that was excavated around the middle of the 19th century.

This site has been chosen to test the validity of muography to search for hidden cavities for two main reasons:

- the presence of known cavities could be exploited to verify the capability of the muographic technique to recognize the presence of voids above the detector position;
- according to speleologists and archaeologists the existance of other hidden cavities was highly probable and muography could be the proper method to find them.

The MU-RAY [3-5] and MIMA [6] detectors, both realized by a collaboration involving Universities of Naples and Florence and INFN sections of Naples and Florence, have been used to acquire data from three different positions. From the first two bidimensional measurements a first hint of the presence of an unknown cavity emerged [7]. Then, in order to remove the ambiguity of the signals an addictional measurement has been performed from a third point.

A novel method to realize a *three-dimensional muography* [8] has been applied to these data; it combines in a single analysis three (or more) muographies taken from different positions, in order to localise cavities in space and reconstruct their shape.

In the next sections methodologies and results of the bi- and three-dimensional imaging at Mt. Echia will be explained in more details.

3˙1. *The detectors*. – The MU-RAY detector is an electronic muon telescope, based on scintillator bars coupled to wavelength shifting (WLS) fibers read out by silicon photomultipliers (SiPM). It consists of three tracking layers, each provided of both X and Y view planes, with a total sensitive area of $1\,\mathrm{m}^2$. At Mt. Echia, the detector has been installed horizontally as shown in fig. 4. The MU-RAY basic sensitive element to crossing muons are plastic scintillator bars of triangular cross-section [9]. Each bar has a length of 107 cm, a 3.3 cm base and a height of 1.7 cm. They are extruded with a central 2 mm hole through which a 1 mm diameter wavelength shifter fiber (BICRON BCF92) is threaded.

The bars have a TiO_2 coating (0.25 mm thick) that increases the internal reflectivity and screens them from outside light sources. The light signals produced by muons in the plastic scintillator bars are conveyed to photosensors (SiPM) by the fibers. A single plane (each layer has two planes, one for each view) is subdivided in two arrays of 32 scintillator bars. The angular resolution in the measurement of the muon trajectory with this configuration was around 6 mrad. Muons are tracked up to a maximum angle of 60 degrees with respect to the view axis of the tracker, *i.e.*, to the direction perpendicular to the tracker planes. A dedicated front-end electronics and data-acquisition have been developed with very low power consumption. Each plane is equipped with two Front-End Electronics (FEE) boards based on the ASIC chip EASIROC [10]. The passage of a penetrating charged particle through the detector provides a fast digital signal each time a muon crosses a detection plane. A time coincidence of the signals from the six planes triggers the data acquisition. The analog information related to the amount of energy released by muons in each bar is digitised by Analog to Digital Converters (ADC), acquired by Data Acquisition (DAQ) boards and stored for offline reconstruction of the muon tracks. The maximum possible acquisition rate of the detector was about 270 Hz, while the measured trigger rate underground was just about some Hz.

The MIMA detector is a smaller muon tracker very similar to MU-RAY. It consists of three XY planes, each composed of two orthogonal arrays of 21 scintillator bars (fig. 5). The first and the last planes have bars with a triangular cross-section (an isosceles triangle with 4 cm basis and 2 cm height), while the middle plane is formed by scintillator bars of rectangular section. Unlike MU-RAY, MIMA does not have WLS fibers, but the SiPMs are in direct contact with the scintillator. The coordinates of the muons are measured with a resolution of about 3 mm. The outer XY planes are 0.34 m apart. Muon tracking is carried out with an angular resolution of about 14 mrad.

3˙2. *Bidimensional muographies.* – Muons lose energy when they pass through matter. The possibility of exiting a certain material depends on their initial energy, the thickness x and the density ρ of the material. The minimal energy a muon needs to survive can be evaluated from the muon *stopping power* law, *i.e.*, the energy loss rate, $\frac{\mathrm{d}E}{\mathrm{d}X}$, where

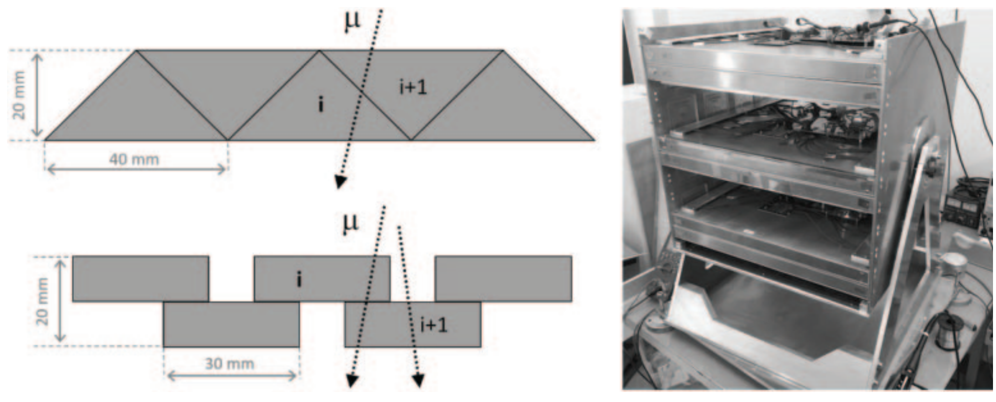

Fig. 5. – Left: geometrical configuration of the scintillating bars with triangular and rectangular section. Right: the MIMA tracker under test after assembling three complete modules inside the mechanics.

$X = x\bar{\rho}$ is the *opacity* with $\bar{\rho}$ the average density along the muon path x:

$$E_{min} = \int_0^{\bar{X}} \frac{\mathrm{d}E}{\mathrm{d}X'}\mathrm{d}X'. \tag{1}$$

The muon telescope measures the number of muons arriving from each direction (α, ϕ),

$$N_\mu(\rho, \alpha, \phi) = \Delta T_\mu \cdot S_{eff}(\alpha, \phi) \int_{E_{min}}^{\infty} \Phi(\alpha, \phi, E)\mathrm{d}E, \tag{2}$$

where $\Phi(\alpha, \phi, E)$ is the differential flux of cosmic-ray muons from the direction (α, ϕ). The quantity in eq. (2) depends on the effective area of the detector,

$$S_{eff} = S \cdot A(\alpha, \phi) \cdot \epsilon, \tag{3}$$

where $\mathrm{A}(\alpha, \phi)$ is the geometrical acceptance and ϵ the global efficiency of the detector. To avoid the sistematic uncertainties introduced by acceptance and efficiencies, the quantity (2) is divided by the *free-sky* muon flux, *i.e.*, the flux without any body between sky and the detector, obtained by dedicated calibration measurements performed pointing the detector directly to the sky:

$$N_{fs}(\alpha, \phi) = \Delta T_{fs} \cdot S_{eff}(\alpha, \phi) \int_{E_0}^{\infty} \Phi(\alpha, \phi, E)\mathrm{d}E, \tag{4}$$

where E_0 is the minimal energy for a muon to be detected.

The ratio between $N_\mu(\alpha, \phi)$ and $N_{fs}(\alpha, \phi)$ is the *transmission*,

$$T(\alpha, \phi; \rho) = \frac{\displaystyle\int_{E_{min}}^{\infty} \Phi(\alpha, \phi, E)\mathrm{d}E}{\displaystyle\int_{E_0}^{\infty} \Phi(\alpha, \phi, E)\mathrm{d}E}. \tag{5}$$

To search for the existance of unknown void regions the measured trasmission has to be compared with its expected distribution, $T^{exp}(\alpha, \phi; \rho)$ evaluated in the hypothesis of constant mean density and fully filled space over the detector position. The map of thickness values from the point of view of the telescope can be estimated exploiting the information provided by the *Digital Terrain Model* (DEM) of the region of interest (fig. 3).

The *relative transmission*

$$R(\alpha, \phi) = \frac{T^{meas}(\alpha, \phi)}{T^{exp}(\alpha, \phi; \rho)} \tag{6}$$

represents the final result of the muographic measurement and it should take values close to 1 if no voids have been encoutered along the corresponding directions; on the contrary, the presence of a cavity can be recognized if a region of the muographic image is characterized by values of R significantly higher than 1, which means that more muons than expected reached the detector (*i.e.*, less material had to be crossed).

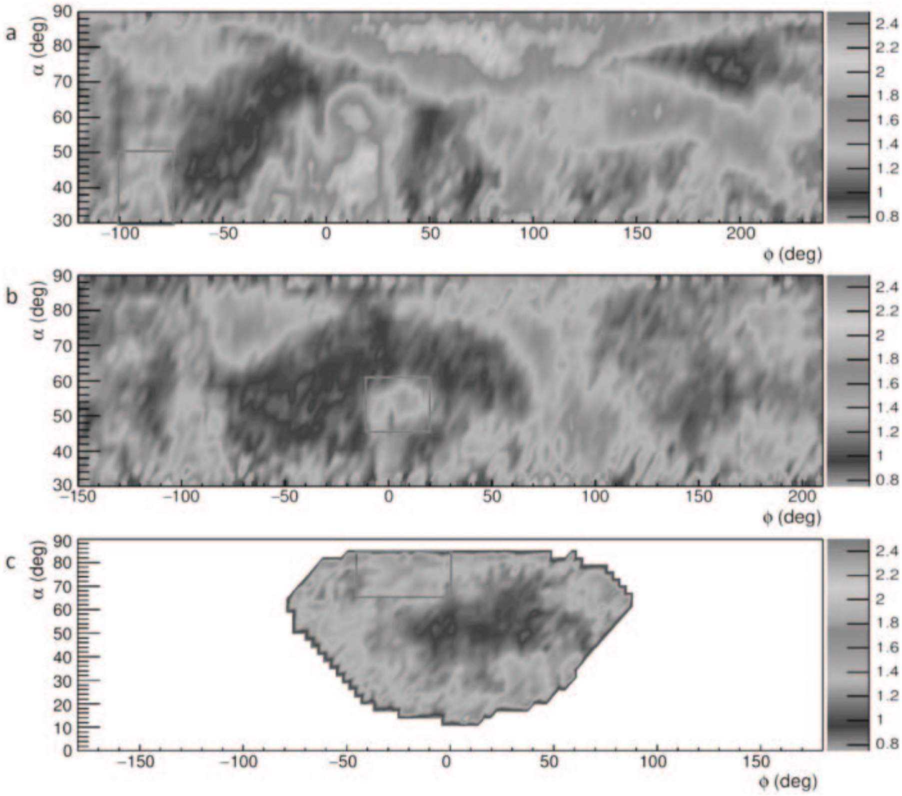

Fig. 6. – The relative transmission $R(\alpha, \phi, \rho)$ observed at the three locations ((a), (b) MU-RAY, (c) MIMA) in the reference systems of the corresponding muon trackers. The angular regions associated to the hidden cavity are indicated with rectangles. The plot was obtained using the software ROOT.

Three bidimensional radiographic images have been provided by locating the MU-RAY telescope in two different points and MIMA in a third point. In fig. 6 the muographies obtained from the three different positions, *i.e.*, the relative transmission (eq. (6)) evaluated for each direction, are shown. From the first studied location, all the existing cavities, within the acceptance of the detector, have a signal correspondence in the muography. As an example, in fig. 7, the black dots map the correspondence between the three-dimensional model of a known chamber and the relative muographic signal. Apart from the confirmation of the suitability of this technique in this kind of application, a first hint of the presence of a hidden cavity emerged from the first two measurements (taken with MU-RAY, figs. 6(a), (b)) and was later confirmed by MIMA (fig. 6(c)).

3˙3. *Three-dimensional muography.* – The muographies in fig. 6 have been analyzed in order to combine the provided information obtaining a three-dimensional reconstruction of the possible hidden structure. First of all, a clustering algorithm has been applied to select significant signal regions where the relative transmission R (eq. (6)) takes values above a fixed threshold.

In order to reconstruct in space the hidden cavity, we started by defining a grid of points in a cubic volume that encloses the region of space where the cavity is supposed

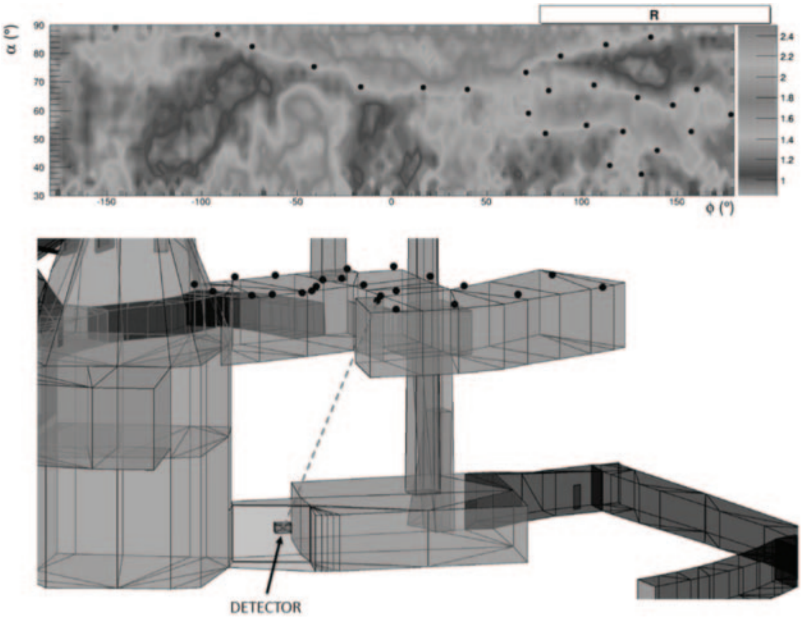

Fig. 7. – 2D map showing the ratio between the measured and the expected muon transmissions at Mt. Echia. Black points enhance the correspondence between the muographic signal and the known existing chamber reproduced in the three-dimensional model.

to be. As a general criterion, a point was considered to be located inside a cavity if in each of the three projective muographies it corresponded to a direction lying inside a signal cluster as defined above.

This procedure was tested by simulating the presence of cavities of different shapes and having a similar size with respect to the supposed hidden cavity. Each simulated cavity has been approximately located at the presumed position of the hidden cavity. The results of the simulations are shown in fig. 8 for two different chosen shapes: a sphere and a cube. The reconstructed images (on the right side) include the real simulated object in both cases, even though it is not perfectly accurate in the geometric reproduction.

Figure 9 shows two views of the 3D muographic image of the hidden cavity in the reference system associated to the MIMA detector position, as obtained following the procedure described above. It appears as an inclined cavity with a width of about 4 m, a height of 3–4 m and a length of about 7 m.

This result demonstrates that this approach to three-dimensional muography enhances the discovery potential of the muon radiography technique, especially in the case of complex underground systems.

4. – Other applications

Muography has been successfully applied in several other fields. A copious quantity of applications has been developed in volcanology, with the aim of performing an imaging of the internal structure of volcanoes. Indeed it is possible to use this technique to measure the mass distribution inside the cone of a volcano providing useful information to better understand the volcanic present and future activity. Much work has been

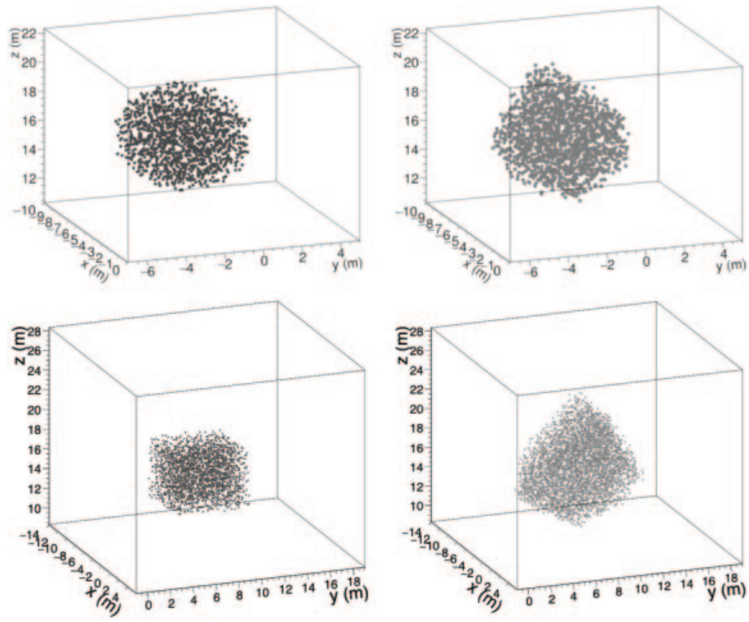

Fig. 8. – Results of the application of 3D imaging algorithm to simulated cavities of different shapes: a spherical cavity (top) and a cubic cavity (bottom). On the left side the real simulated object, while on the right the image reconstructed with the three-dimensional muography method.

done by Tanaka and collaborators [11-13] and other groups [14, 15]. Currently, our group is approaching the imaging of the uppermost part of the Mt. Vesuvius, an active, very dangerous, volcano in Naples, Italy. The MURAVES (Muon RAdiography of the VESuvius) [5, 16-18] experiment has already started with this aim and three equal muon telescopes, an upgraded version of the MU-RAY muon tracker, are being installed on a flank of the volcano, at an *in situ* laboratory.

Other applications are being developed in the fields of civil engeneering and security. A technique different from the muography by absorption, that is muography by multiple

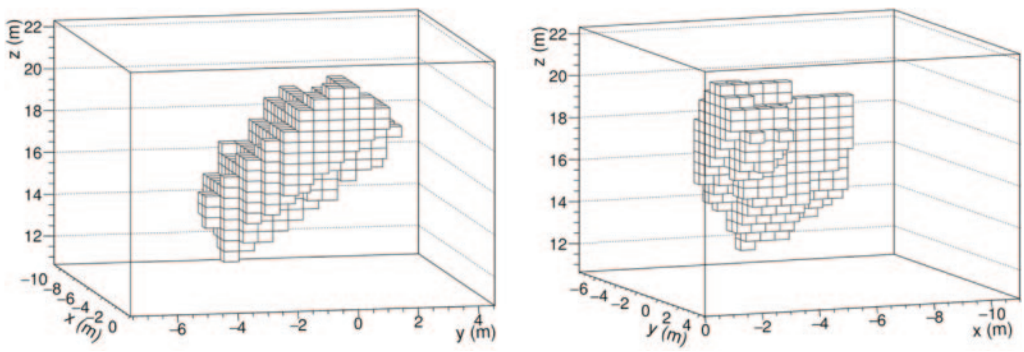

Fig. 9. – Two views of the 3D reconstruction of the hidden cavity, in a coordinate system with origin at the position of the MIMA muon tracker.

scattering, is also used, expecially in these fields. This technique exploits the deviation of the incoming particle directions due to multiple Coulomb scattering to obtain information on the nature of the materials crossed by the particles between two tracking planes. It can be useful, for instance, to identify the presence of high-Z (probably radioactive) materials.

5. – Conclusions

Muography is a very useful, innovative and non-invasive technique to perform density measurements on large volume objects. It has been successfully applied in several fields such as Volcanology, Archaeology, Civil Engeneering and others. A particular application in the field of archaeological studies is the search for cavities hidden underground. In this paper an example has been presented: the discovery of a hidden cavity under the surface of the Mt. Echia, a little hill in the city of Naples, and its three-dimensional reconstruction exploiting only muographic data.

Two different muon trackers have been used to perform bidimensional muon radiographies of the site from three different points of view. Once a hint of the existence of an unknown cavity has been observed, the three obtained muographies have been combined to enhance the discovery and reconstruct the three-dimensional shape of the cavity, with a novel algorithm tested before on simulated data. This result proved that the exploited reconstruction algorithm allows to obtain a sufficiently accurate reconstruction of the location and volume of a hidden underground cavity if at least three muographies intercepting the object can be provided.

* * *

The research presented in this paper was conducted by the Mu-Ray/MURAVES Collaboration. The author thanks all the members for their support and comments that greatly improved the manuscript.

REFERENCES

[1] Alvarez L. W. *et al.*, *Science*, **167** (1970) 832.
[2] Morishima K. *et al.*, *Nature*, **552** (2017) 386.
[3] Anastasio A. *et al.*, *Nucl. Instrum. Methods A*, **718** (2013) 134.
[4] Anastasio A. *et al.*, *Nucl. Instrum. Methods A*, **732** (2013) 423.
[5] Ambrosino F. *et al.*, *JINST*, **9** (2014) C02029.
[6] Baccani G. *et al.*, *JINST*, **13** (2018) P11001.
[7] Saracino G. *et al.*, *Sci. Rep.*, **7** (2017) 1181.
[8] Cimmino L. *et al.*, *Sci. Rep.*, **9** (2974) 2019.
[9] Pla-Dalmau A. *et al.*, *Nucl. Instrum. Methods A*, **466** (2001) 482.
[10] Callier S. *et al.*, *Phys. Procedia*, **37** (2012) 1569.
[11] Tanaka H. K. M. *et al.*, *Nucl. Instrum. Methods A*, **575** (2007) 489.
[12] Tanaka H. K. M. *et al.*, *Earth Planet. Sci. Lett.*, **263** (2007) 104.
[13] Tanaka H. K. M. and Ohshiro M., *Geosci. Instrum. Method. Data Syst.*, **5** (2016) 427.
[14] Ambrosino F. *et al.*, *J. Geophys. Res.: Solid Earth*, **120** (2015) 7290.
[15] Lesparre N. *et al.*, *Geophys. J. Int.*, **190** (2012) 1008.
[16] Ambrosino F. *et al.*, *JINST*, **10** (2015) T06005.
[17] Noli P. *et al.*, *Ann. Geophys.*, **60** (2017) 1.
[18] Saracino G. *et al.*, *Ann. Geophys.*, **60** (2017) 1.