Multidisciplinary applications of muon radiography using the MIMA detector

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Abstract: The MIMA muon tracker, developed by the INFN Unit of Florence and the Department of Physics and Astronomy of the University of Florence, has been designed to test the application of muon radiography (or muography) to multidisciplinary case studies, to demonstrate its validity as an imaging tool in different fields and to develop dedicated data analysis strategies.

The MIMA detector is a scaled-down version of the muon trackers developed for the "Mu-Ray" INFN R&D project and the MURAVES (MUon RAdiography of VESuvius) "Progetto Premiale", financed by the Italian government. Thanks to its compactness, MIMA allowed the use of slightly different technical solutions with respect to the other detectors. Its construction was completed in the first half of 2017 and since then it has been used for several different measurements. In the second half of 2017 the detector was installed in the Bourbon Gallery inside Mount Echia, a hill in the center of Naples containing a complicated system of tunnels and cavities that have been dug over many centuries. The installation of the MIMA tracker was required to validate with an independent detector the results obtained in two previous measurements by the Mu-Ray tracker. After this measurement, the detector has been used in the Tuscany region, mainly for investigating two possible fields of application: geo-hydrological risk assessment and mining activity. The preliminary results of these tests and the future perspectives are shortly presented in this paper.

Keywords: Particle tracking detectors; Image filtering; Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators); Search for radioactive and fissile materials

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1 Introduction

Muon radiography is currently one of the most promising non-invasive techniques allowing three-dimensional radiographic surveys of large volumes composed by any kind of material. This technique makes use of atmospheric muons, elementary particles which are continuously originated by cosmic-rays bombarding the upper layers of the Earth's atmosphere and that hit the ground surface with a rate of approximately $(100 \div 200)\,\mathrm{Hz/m^2}$ at the European latitudes. Roughly said, muons have characteristics similar to electrons (belonging anyway to a different lepton family) but a mass 200 times larger approximately. Being heavy and not subject to the nuclear interaction, these particles result to have a high penetrating power, thus representing appropriate projectiles for probing the internal structure of material volumes with linear size ranging from tens of centimeters to hundreds of meters, depending on their energy. The atmospheric muon energy flux, ϕ, has important dependencies on the energy and on the observation angle. For a fixed zenith angle, θ, the energy spectrum can be approximated, at energies exceeding 10 GeV, by a power law with negative exponent, $\phi \propto E^{-\alpha}$, where $\alpha \sim 2.7$ is the so called differential spectral index [1]. The angular dependence of the muon flux changes with the muon energy and can be approximated with a $\cos^n(\theta)$ function, where $n = n(E)$. While for energies around 100 MeV $n \simeq 2$, at much higher energy it becomes progressively smaller, so that the muon flux at energies around 100 GeV is approximately independent on the zenith angle. As a result of these non-trivial dependencies of the muon flux, the required data acquisition time changes from case to case. In particular, in the measurement of volcanic edifices, for which the detection of quasi-horizontal muons traversing hundreds of meters of rock is required, the data acquisition time can be of the order of several months to get a clear

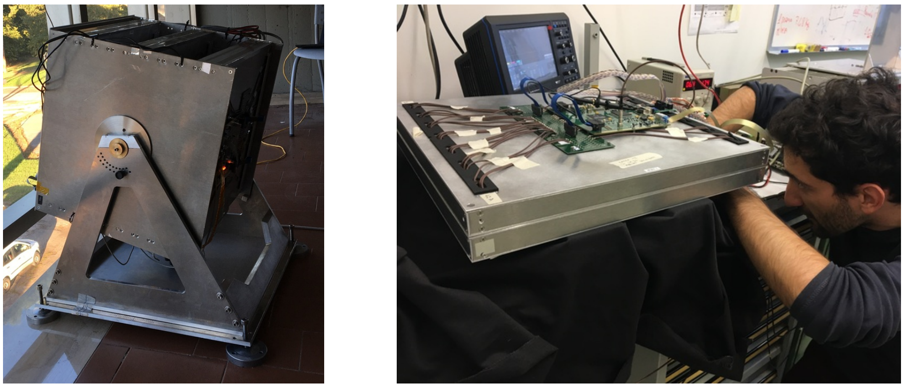


Figure 1. Left: the MIMA tracking detector. Right: the MIMA detection module made of two independent tracking planes.

description of the internal structure in terms of density distribution. A review of the muographic methodology and different applications can be found in [2].

The applications carried out with the MIMA (Muon Imaging for Mining and Archaeology [3]) apparatus and described in this article refer to situations very different from those in the volcanological field. Making use of this compact portable muon tracking system in collaboration with researchers from fields other than Physics, we are investigating the application of the muon radiography technique to multidisciplinary cases where the matter volumes under study are from few meters to a few tens of meters thick. The detector's exposition time in this kind of applications is of the order on 1 ÷ 2 months for a measurement taken from a single point of view.

1.1 The MIMA project and its prodromes

First simulations of simplified case studies [4], assuming cavities or metal deposits hidden inside inaccessible material volumes characterized by an uniform density, were performed by our group since 2012 using the GEANT4 [5] software. In these simulations a small detector was placed underground to track muons passing through underground cavities or dense objects. To define an appropriate detector's acceptance and its expected performance we considered a tracker's angular resolution of 10 mrad, based on the experience gained within the Mu-Ray collaboration. These preliminary simulations allowed also a first test of the 3D imaging method described in [6, 7], exploiting track back-projection. To allow simulating the atmospheric muon flux inside GEANT4, a specific *gun* was implemented, based on the experimental measurement of the muon flux at ground level by ADAMO, reported in [8].

In 2016 the MIMA team began the construction of a tracking detector optimized for applications in the field of muon radiography. The MIMA tracker was designed as a light, rugged, low power muon detector. This detector was conceived as a portable apparatus to allow on-field tests of muon transmission radiography in different fields of application, following a multidisciplinary approach. The full team taking part to the measurement campaigns is in fact composed of physicists, geologists, archaeologists, engineers and technicians specialized in mechanics and electronics.

The MIMA detection system, shown in the left image of figure 1, is composed of six tracking planes, positioned as three XY pairs, each of which assembled as an array of 21 scintillator strips

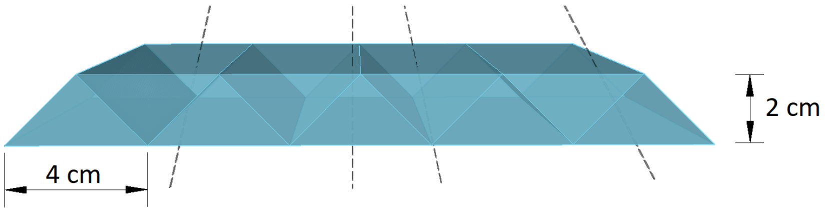


Figure 2. Geometrical size and configuration of the MIMA scintillator strips.

with triangular section readout at both ends by silicon photomultiplier sensors (SiPM). The fiducial area of each plane has a surface of $40 \times 40\,\mathrm{cm}^2$. The particular shape of the strips is derived from a FERMILAB design which, using a clustering algorithm taking into account the signals produced by particles crossing adjacent strips, partially overlapped, allows achieving a spatial resolution around 3 mm in the muon hit point reconstruction [3, 9], rather better than using the so called "digital algorithm" with a 20 mm readout pitch.

Considering muons trajectories traversing all the three XY tracking modules, the resulting geometrical factor is approximately $1000\,\mathrm{cm}^2\,\mathrm{sr}$. A single XY tracking module undergoing laboratory tests is shown in the image on the right of figure 1 .

The front-end electronics (EASIROC chip [10]) and read-out circuits, fixed on top of each plane, and the master data acquisition board implementing trigger logic and data collection, controlled by a Raspberry PI computer, have been inherited from the MURAVES experiment with few modifications to account for the slightly different detector's characteristics. The MIMA detector can be set in data taking mode by simply providing the power supply. An additional Ethernet line can be used for remote control and data quality checks. The total power consumption is 30 W approximately, thus allowing the apparatus to be operated using a small photo-voltaic system, if no mains electricity is available.

The tracking modules are housed in a protective aluminum box and the resulting assembly, a $50 \times 50 \times 50\,\mathrm{cm}^3$ cube, is operated on-board an altazimuth mechanical support which allows fixing the detector's pointing direction by setting the associated zenith and azimuth angles. MIMA is designed as a robust and portable instrument to be easily installed inside mines, in tiny spaces inside archaeological sites and inhospitable sites in general. The masses of the systems are approximately 50 kg for the detector and 20 kg for the optional mount.

The next sections present some of the field measurements performed so far using this experimental apparatus and some ideas for the next operations.

2 Muon radiography in the Archaeo-mining field

Probably the most suitable applications of muon transmission radiography are in the fields of Archaeology and mining. Thanks to its robustness and portability, the MIMA detector properly fits this type of applications and between 2017 and 2019 it has been installed in the Bourbon tunnel in Naples and several times at the Temperino mine near Livorno, both in Italy. The main purposes of these two muographic surveys are the identification and 2D or 3D reconstruction of hidden cavities, the measurement of the 2D angular density map seen from the detector's point of view and the

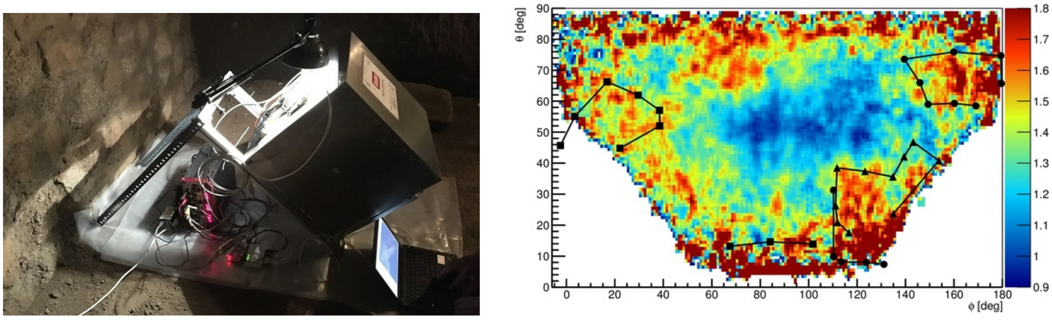


Figure 3. Left: the MIMA detector installed in front of a wall inside the Bourbon tunnel in Naples. Right: 2D angular muon transmission ratio (measured transmission/simulated transmission, θ = elevation and ϕ = azimuth). Values larger than 1.4 have been interpreted as possible voids (approximate geometrical limits of known voids are shown as black lines).

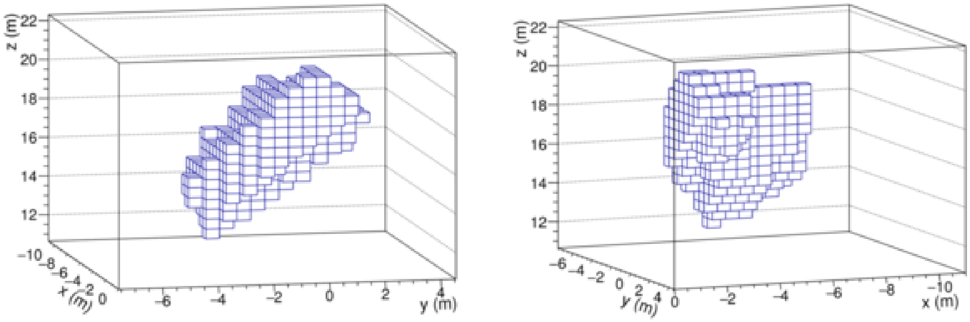


Figure 4. Two views of the 3D reconstruction of the hidden cavity, in a coordinate system with origin at the centre of the MIMA muon tracker [11].

measurement of the 3D density distribution of the rocky layer above the detector. In paragraphs 2.1 and 2.2 we summarize the main results obtained so far in this two field activities.

2.1 A first test measurement with MIMA inside an archaeological site: the Bourbon tunnel in Naples

As a first measurement, in 2017 the MIMA detector was installed in the Bourbon tunnel inside Mount Echia, a small hill on the seaside of Naples. Purpose of the measurement was the localization of two unknown "chambers" inside the 40 m thick tunnel overburden, previously detected from two different points of view using the Mu-Ray prototype detector.

In figure 3 the detector's setup (left) and the measured relative angular muon transmission map (right) are shown. The tracker was still in a preliminary configuration and without a dedicated mechanical support. Nonetheless signals corresponding to possible voids were clearly identified in the muon transmission map (orange-red angular regions with relative transmission larger than 1.4).

The three relative transmission maps measured so far using Mu-Ray and MIMA allowed the development of a 3D reconstruction algorithm based on a triangulation of the measurements [11] (figure 4). In this algorithm the volume under observation is divided into voxels and for each voxel its direction from each measurement point of view is evaluated. The relative transmission values to

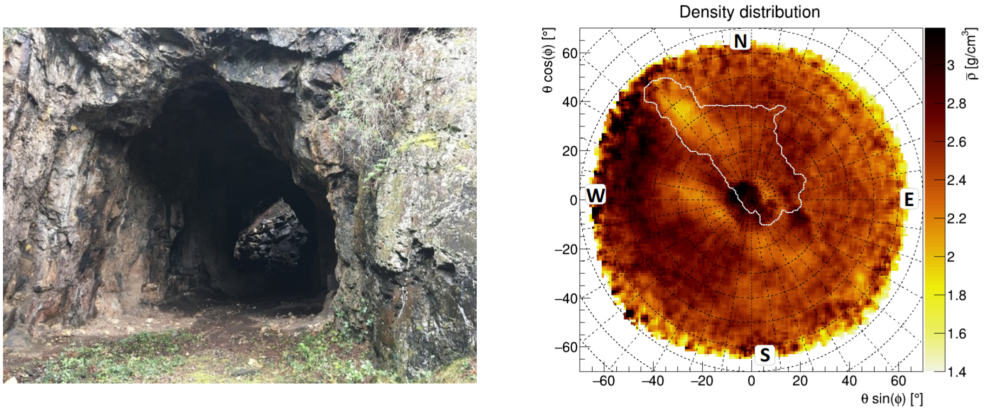


Figure 5. Left: the Big Quarry, located approximately 25 m above the MIMA installation point inside the Temperino mine. Right: experimental 2D average density distribution above MIMA measured from one of the installation points inside the Temperino mine. The detector pointing direction was aligned along the vertical direction. The closed white line shows the angular region corresponding to the Big Quarry as seen from the installation point.

be associated to the void are identified in the three maps and the voxel is interpreted as being part of a void if the corresponding values exceed a predetermined threshold value.

2.2 A detailed study of the Temperino mine inside the “San Silvestro” Archaeo-Mining Park in Campiglia Marittima

After the important experience at the Bourbon tunnel in Naples, the MIMA group started a collaboration with the “San Silvestro archaeo-mining Park” in Campiglia Marittima near Livorno, in Tuscany, finally adopting the so called “Temperino” mine as a laboratory for the development of muography in the mining sector. This site has both historical and archaeological interest. Since the Etruscan age this mine was exploited to extract minerals, therefore it is rich of excavations dating back to very different periods. The main starting purpose of the MIMA group was to install the detector some tens of meters underground, inside a touristic gallery, and try the identification in 2D of a large known cavity, the so called “Big Quarry”, easily accessible from the surface of the hill.

Since the end of 2017 the detector was installed in five different position, three of which chosen to allow a detailed study of this large void. The first results of this activity are reported in [12]. In the image on the left in figure 5 the Big Quarry is shown from its entrance. The plot on the right in figure shows the 2D average density distribution in a polar angular reference frame centered along the vertical direction (the distance from the center corresponds to the zenith angle and the rotation angle around the center to the azimuth), as measured from one of the installation sites. This measurement refers to the comparison of a data taking of approximately two months from inside the gallery, at approximately 40 m depth from the surface of the hill, with a 17 days free-sky measurement performed previously at the INFN location in Sesto Fiorentino (Florence). The angular region corresponding to the Big Quarry is sketched as a closed white line representing an angular projection of the image obtained by a 3D laser scan. Part of this angular region corresponds to directions for which the measured average density is below 2 g/cm^3, a sensibly smaller value then the minimum density of materials found in the surrounding of the site, which is approximately

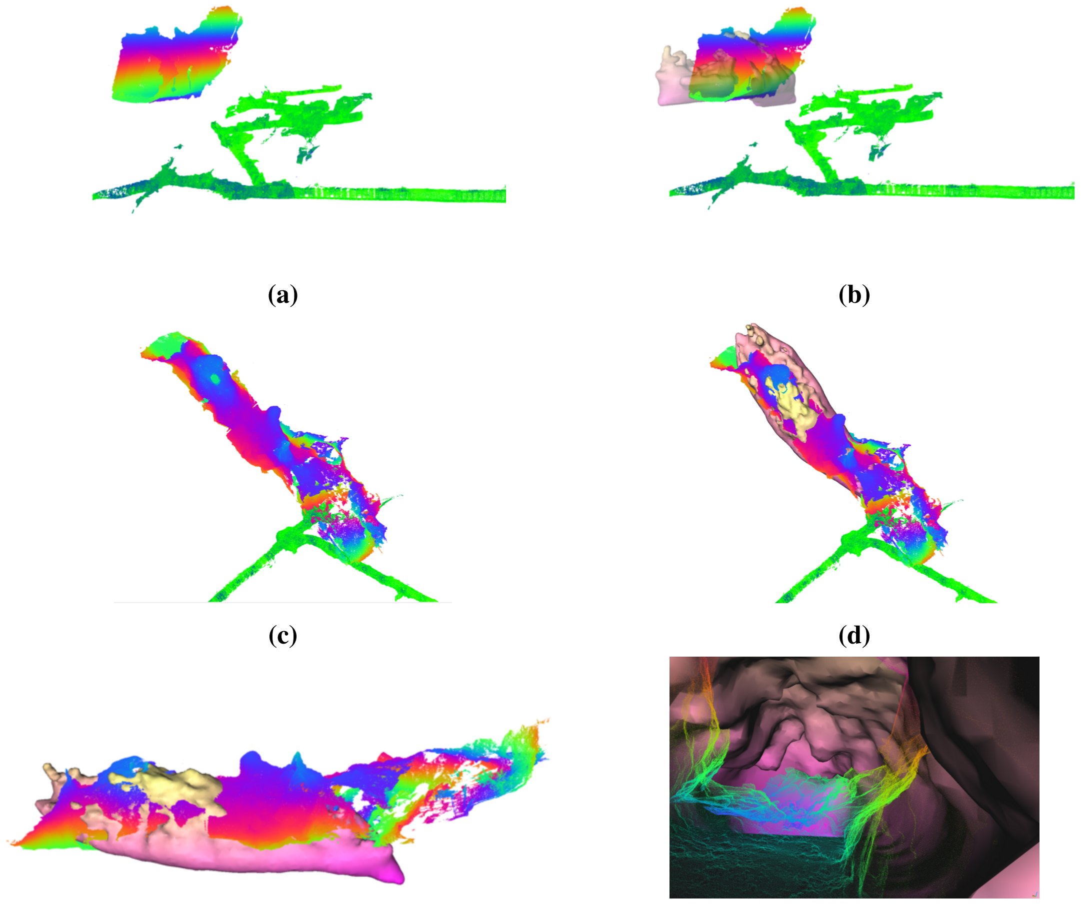

(a) **(b)** **(c)** **(d)** **(e)** **(f)**

Figure 6. Preliminary results of the 3D muographic study at the Temperino mine, included in [9]. a) perspective view of the 3D laser scanner measured points; the lower green points refer to the main gallery, while the upper points have been registered inside the “Big Quarry”, approximately 25 m above the gallery; b) comparison with the 3D reconstruction of the Big Quarry based on muographic measurements; c,d) same as a,b) but seen from the top view; e) closer comparison of results for the Big Quarry; f) a view from inside the Big Quarry.

2.4 g/cm^3 (acid porphyry). Furthermore the rock density is even much heavier around the Big Quarry, located inside a skarn, a compact body composed of hard, coarse-grained metamorphic rock. Other angular regions with low average density are visible in the figure and suggest the existence of further unknown voids. From this 2D distribution, the distance of these “anomalies” cannot be inferred anyway.

Using the innovative technique to localize cavities or dense bodies in the space described in details in [6, 7], we have done a first 3D reconstruction of the anomalous signal corresponding to the Big Quarry. This technique, based on muon track back-projection, takes advantage of the stereoscopic effect which is obtained by exploiting the spatial extension of the detector. The results of a first 3D muographic reconstruction of the Big Quarry, taken from [9], are shown in figure 6, together with a georeferenced scan of the gallery and the Big Quarry itself performed using a 3D laser scanner. Figures 6a and 6b show a view of the 3D laser scanner points without and with the muographic reconstruction of the Big Quarry. Figures 6c and 6d show the same point clouds in plan. Results by muographic reconstruction and laser scanner measurement of the Big Quarry, shown in closed comparison in figure 6e, are in good agreement. Figure 6f is a pictorial view from inside the cavity and shows the good results obtained so far.

3 Civil engineering, territorial protection and geo-hydrological instability

Several possible fields of application of muon radiography can be thought in addition to Archaeology and mining. The expected outcomes can be different and depend on the specific applications.

As shortly discussed in section 3.1 the MIMA detector was installed at two riverbanks damaged by animal digging, for a preliminary study related to geo-hydrological instability. Following this experience, the detector was recently installed inside the inspection tunnel of an important dam in Tuscany (results of this study will be published elsewhere).

Finally a new proposal is shortly presented in section 3.2 concerning the experimentation of the muographic methodology in the study of the Brunelleschi's dome in Florence. This constitutes an application of considerable interest in the field of civil engineering.

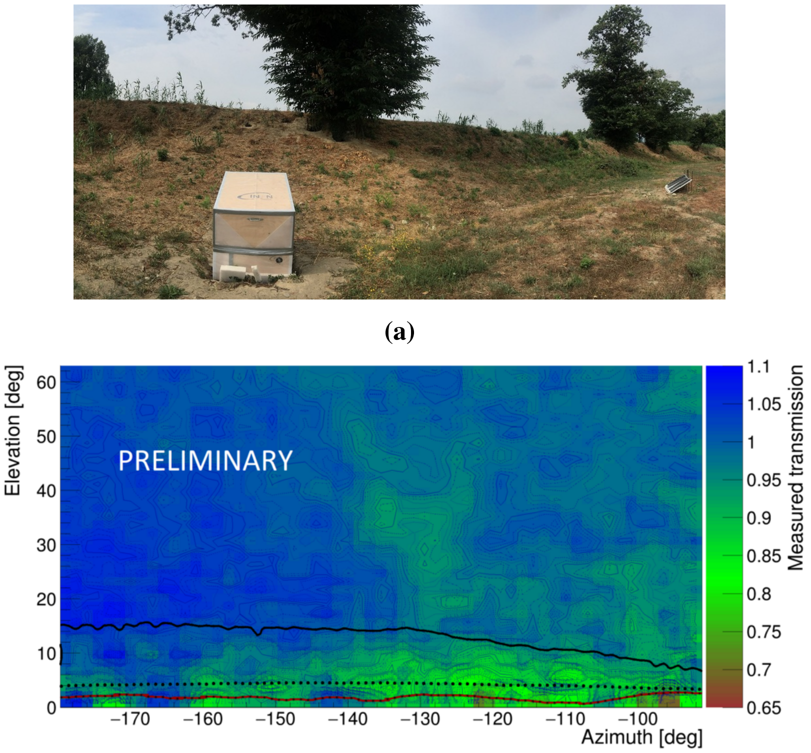
3.1 Applications in the field of geo-hydrological risk assessment

Between 2017 and 2018 the MIMA tracker has been installed at two riverbanks where tracks of animal digging had been found. The main purposes of these measurements were a verification of the performance in identifying hidden burrows inside the embankment and a final comparison with the result of a geoelectric survey, a standard geophysical technique. First results of this measurement have been presented at the EGU conference in 2018 [13].

Picture 7a shows the protective box where MIMA was installed during the measurement in front of the embankment of the Bure stream in Pistoia. On the right side, the small photovoltaic system used for powering the system can be seen.

The preliminary results obtained in this field are shown in figure 7b (final results of a more detailed analysis will be published elsewhere). In this graph the muon transmission is drawn in a reference frame with the elevation angle on the vertical axis and the azimuth angle on the horizontal axis. At elevations below 15° the absorption effect due to the embankment can be seen, while over the top of the embankment, at zenith angles around -130°, the outline of a big tree, located almost in front of the detector, is visible. A more detailed analysis is on-going. Many regions with high muon transmission can be found in the embankment's image, in good agreement with the tracks visible from the surface of the embankment. Unfortunately some problem with the measurement, yet not understood, results in anomalously large (small) transmission values on the left (right) side of the map.

As a general comment after this experience, the application of muon radiography for the study of the embankments presents some important critical issues with respect to other techniques like the geoelectric method. First, the opacity (product of thickness and density) of the investigated structures is not large and the size of the hidden voids is usually small. In addition the measurement must be performed with the detector pointing at very low elevations, at which the muon flux is much lower



(a)

(b)

Figure 7. a) The MIMA detector installed in front of the embankments of the Bure stream in Pistoia. b) Preliminary result of the 2D muon transmission (22 days "target" data taking compared with a 19 days free-sky reference measurement). The sketched lines refer to: the top of the embankment (black continuous upper line), the top of the embankment of the other side of the river (black dotted intermediate line) and the height of the mountains seen in the background from the detector's point of view (brown continuous lower line).

and has a harder energy distribution (muons can penetrate materials more easily) than along the vertical direction. As a result, the expected signal due to the unknown hidden burrows is in general quite small and the measurements require, in case of compact detectors, long data taking time. Measurements may therefore be affected by variation in the weather conditions and detector's performance.

A more recent application of the MIMA apparatus (still on-going and not yet published) concerns a muographic survey of the structure of a large dam performed from its inspection tunnel. In this case the opacity of the structure and the required measurement direction are more favorable to this kind of study with respect to the case of the riverbanks. The main purpose of such a test is a feasibility check for the identification of any deviations of the dam's structure from design or modifications occurred during the dam's life and caused by water infiltration, telluric movements or other events. Results will be published elsewhere.

3.2 Applications in the field of civil engineering

The last application we present in this paper represents an example of application of muon radiography to civil engineering. The basic idea, triggered by Prof. Arch. C. Blasi, is a muographic study of the Brunelleschi's dome in the S. Maria del Fiore cathedral in Florence, one of the most famous

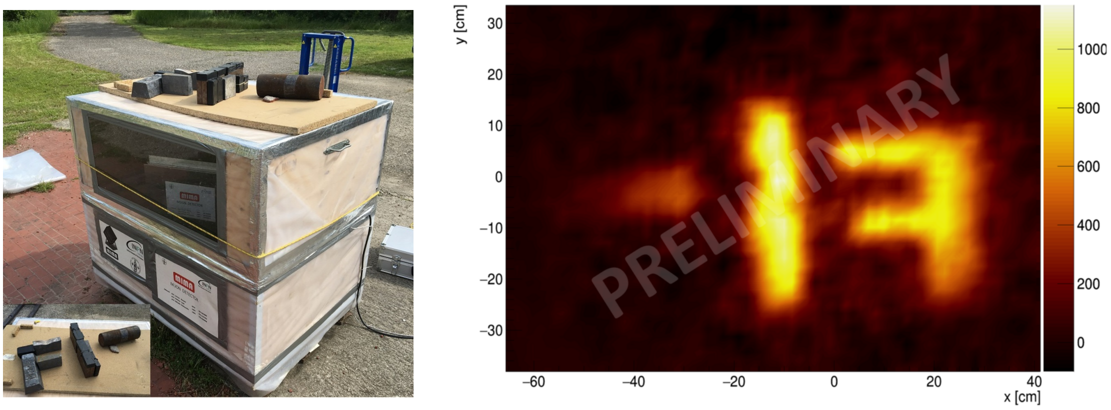


Figure 8. Left: setup used in 2019 by the MIMA group for testing metal block imaging by muon transmission radiography. Lead and iron blocks were arranged to form the word “FI-”. Right: preliminary result obtained focusing the image on a horizontal plane 60 cm from the center of the detector (approximately the real distance).

domes in the world built during the Italian Renaissance. This study is suggested to investigate about the existence of metal reinforcements inside the dome’s wall, as speculated by some experts, in addition to the visible wooden chain running all around the base of the dome. In recent conservation works on one of the semi-domes of the transept of the cathedral a metal chain has been found by chance and its arrangement followed by means of a georadar (GPR), thanks to an existing walkable path surrounding the structure.

The search of a similar metal chain at the main dome using a GPR is more complicated, both for the size and thickness of the structure and for the difficulty in accessing the dome’s surface where to move the GPR on.

In collaboration with Prof. Blasi and a team of the Los Alamos National Laboratory (LANL) involved in muon tomography activities, who were the first involved in this discussion, we have proposed a muon radiography scan of the Brunelleschi’s dome using a small muon tracker like the MIMA detector. In the meanwhile we have started simulations and real measurements using the MIMA apparatus with simplified target structures to address the search at the dome. Two preliminary measurements have been performed so far concerning the imaging of metal objects and the measurement of the 2D angular distribution of muon transmission through a concrete structure simulating the dome’s wall.

The performance for detection and imaging of metal blocks was tested together with the students of the “Particle and applications” course of the degree course in Physics and Astrophysics of University of Florence. Figure 8 shows (left) the experimental setup outside the INFN building in Sesto Fiorentino and (right) the preliminary result of the measurement obtained with a 9 days data taking, after applying the track back-projection method ([6, 7]).

The measurement of muon transmission through the dome’s wall was simulated assembling a concrete wall in the open space of INFN in Sesto Fiorentino, as shown in the left photo in figure 9, and lasted approximately two months.

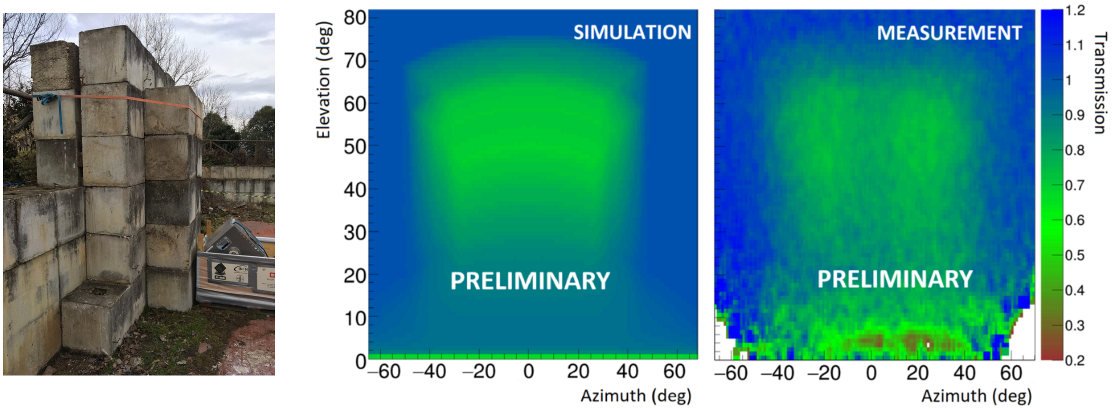


Figure 9. Left: installation of MIMA in front of a 1.5 m thick concrete wall. Center and right: simulated and measured 2D angular muon transmission map. In the measurement the shape of the wall is visible and reproduces nicely the expectations, while two additional features can be easily identified: a central vertical region with high transmission, due to a 7 cm gap left at the center of the assembled wall, and a very low transmission region at very low elevations, due to the mountains on the background.

4 Conclusions and future perspectives

Many applications of muon radiography in various sectors are currently being explored by different research groups in the world. In this article we have summarized some of the experimental activities carried out by the MIMA group in Florence since 2017, showing some encouraging preliminary results in the fields of Archaeology, mining and geo-hydrological risk assessment, concerning the identification and imaging of hidden underground voids. Further areas of application are under development, specifically in the fields of geo-hydrological risk assessment and civil engineering and new experimental activities will be explored in the future by the MIMA group, in an attempt to make muography a globally accepted technique for non-invasive geophysical prospecting.

Acknowledgments

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