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Atmospheric muons for non-invasive research at the Palazzone Etruscan necropolis in Perugia (Italy)(*)

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Summary. — Through a measurement of atmospheric muons transmission in matter it is possible to study the internal structure of objects in terms of average density. The technique is called "transmission muography" and represents a real imaging technique that allows, in a non-invasive way, to identify and locate any anomalies within the structure studied. In this work, an application of the transmission muography technique to an Etruscan necropolis for the non-invasive search of unknown tombs will be presented. The technique was applied to an area of the Palazzone necropolis (Perugia-Italy) not yet completely explored by archaeologists, providing, from a single muographic measurement, important information on the presence and location of possible others underground tombs.

1. – Introduction: muography in the archaeological field

Transmission muography is a non-invasive imaging technique [1] based on the measurement of the atmospheric muons attenuation by a target. The detectors used for these applications are trackers that allow to reconstruct the muon direction (θ, ϕ) (with θ the zenith angle and ϕ the polar angle). The muon flux at the sea level is on average about $70\,\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ in the vertical direction and decreases as $\cos^2(\theta)$ towards the horizontal direction [2, 3]. The flux values also vary with respect to the geographical position (latitude, longitude and altitude) and the atmospheric conditions [2]. Muons have a high penetrating power (up to some even a kilometers) in matter and, for this

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reason, they can be used to make muographies of large structures such as volcanoes [4, 5] or pyramids [6, 7]. The detectors are installed below or beside the structure to be studied and they passively measure the muon flux in every direction that falls within their acceptance. The acquisition times depend on the target (dimensions and density) and on the detector size and can vary between a few hours for small targets to some months for large targets as volcanoes. Currently, the technique is widespread and it has various fields of application: archaeological, geological, mining, civil security.

In general, two measurements are performed to obtain a two-dimensional target average density image: one by observing the target and one in which there are no objects between the detector and the sky. By comparing these two measurements, the distribution of the target muon transmission is obtained. The expected muon transmission is then obtained through a simulation that contains the known geometric target structure to which the expected densities can be associated. By comparing the measured and expected transmission, anomalies can be identified and an average density distribution of the target can be obtained according to the procedure described in [8]. In this way, it is possible to identify anomalies with higher or lower density compared to the expected values. The images obtained can be either two-dimensional or three-dimensional. In the latter case, it is often necessary to take several measurements at the same site in order to apply the tomographic reconstruction techniques. With the back-projection technique it is possible, under certain geometric conditions [8, 9], to obtain 3D information from a single measurement.

Transmission muography represents a non-invasive support tool in the archaeological field for the search for cavities. The anomalies sought are visible in the images obtained with muography as low density regions compared to neighboring areas. The typical dimensions of these cavities depend on the archaeological site we are studying but typically can vary from a few meters to a few tens of meters. For this reason it is necessary to have detectors with a good angular resolution capable of resolving even the smallest cavities. It is essential to be able to install the detector as close as possible to the target (even inside if possible) in order to be able to observe the small cavities more closely and minimize the thicknesses of material observed, thus decreasing the necessary measurement times. The detectors used in this field must be lightweight and easily transportable.

One of the first archaeological applications in the world was on the Chephren Pyramid in Giza for the search for a hidden chamber [6]. Measurements have recently been carried out at Kufhu's Pyramid [7], in a hellenistic necropolis in Naples [10], at a defensive wall (Xi'an in China) [11] and a feasibility study was carried out to an etruscan tumulus in Northern Greece [12]. In these applications, more than one measurement were performed for the three-dimensional reconstruction of the anomalies. In the following paragraphs, the application of muography to the case study of the Palazzone necropolis located near Perugia (Italy) will be described. The measurement is a contemporary work to those present in the literature and the three-dimensional information on density anomalies was obtained from a single muographic measurement.

2. – Transmission muography at the Palazzone necropolis

2˙1. *The Palazzone necropolis.* – The Etruscan Palazzone necropolis located in the South-East of Perugia (in central Italy) is famous worldwide for the numerous tombs discovered (about 200) and for the countless archaeological finds. In the necropolis a tourist route is present that allows the visit of various hypogeal tombs. They are located at an average depth of a few meters, the deepest currently discovered is the Volumni

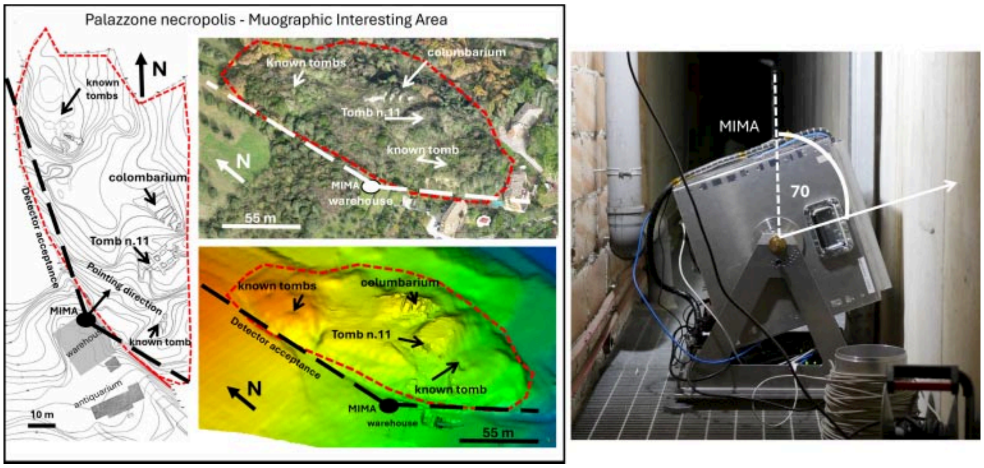

Fig. 1. – Left: the plan of the known tombs within the area of interest (in red), the visualization of the area with and without vegetation (Digital Surface Model) are shown. The colors of the surface at the bottom right indicate the altitude that increases in the North direction. The detector installation point projected onto the warehouse roof with its pointing direction and acceptance is shown. Right: the MIMA tracker inside the Palazzone necropolis warehouse.

Hypogeum which, at about 15 m of depth, presents a complex structure with various rooms that branch off from a main one.

The transmission muography technique aims to identify any anomalies attributable to tombs in an area located to the East of the necropolis only partially explored in which the Etruscan presence is evidenced by some structures of archaeological interest such as the columbarium and Tomb n.11. The identification of any other cavities in this area could represent an opportunity to expand the tourist path and to revaluate the territory. Furthermore, muography represents a valid alternative to other soil prospecting techniques being non-invasive and passive. During this work, collaboration with archaeologists and geologists was fundamental for the interpretation of the results.

The area to be observed is a hill with an altitude difference of 45 m and dimensions indicated in fig. 1 (left). The detector used for the measurements is MIMA (Muon Imaging for Mining and Archaeology) [13] a compact tracker of cubic dimensions $(50 \times 50 \times 50)\,\mathrm{cm}^3$ specifically designed to be easily transported in small and narrow places (figure 1 right). MIMA is composed of plastic scintillators that form three XY tracking planes and has an angular resolution of $0.3°$. The details of the detector are described in [13].

After a study through simulations of the best measurement point to minimize the inclination of the detector and maximize its acceptance in the directions of interest [14], the detector was installed inside the necropolis warehouse (a closed structure) at about 10 m below the ground level. The position of the detector projected onto the roof of the warehouse is shown in fig. 1 (left) in which the known tombs of the area are also indicated. The known Tomb n.11 $(11 \times 9)\,\mathrm{m}^2$ represented the test-cavity of the technique in this site. The detector acquired data for about two months at an inclination of $70°$ with respect to the vertical and at an azimuth centered onto the hill. In this position the detector was able to observe the entire hill under elevation angles of about $50°$.

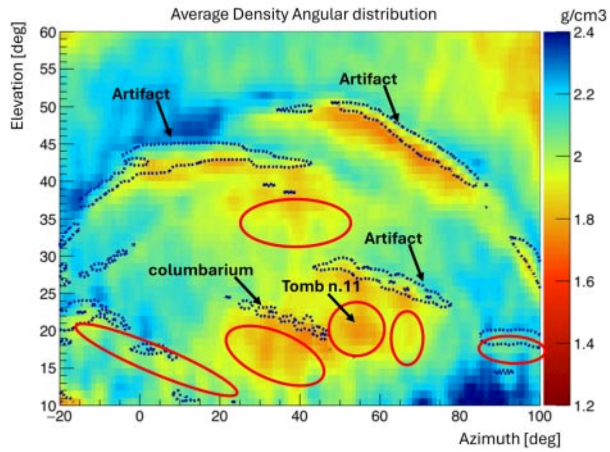

Fig. 2. – The angular average density distribution of the target. The direction at azimuth 0° corresponds to the North direction. As explained in the text, the low density areas attributable to the presence of voids are enclosed by a red line while the low density regions attributable to artifacts are enclosed by a blue line.

2˙2. *Muon Imaging*. – According to the procedure described in **1**, the two-dimensional angular distribution of average density of the observed hill was obtained. More details on the various steps to achieve this result can be found in the works [14, 15]. The typical densities of the territory obtained from geological studies are in the range of $1.8 - 2.4\,\mathrm{g/cm^3}$. In fig. 2 low density areas compared to the density values expected are highlighted: some with an arch-shaped and others with undefined shapes. From a detailed study [16] on the precision of the geometry used for the simulation it emerged that the arch-shaped areas (fig. 2 in blue) are artifacts due to the imperfect geometry of the hill imported in the simulation. The presence of a thick vegetation complicated the process of removing it from the simulation geometry. The artifacts emerge precisely in the detector's view directions parallel to the tangents to the hill surface, indicating the fact that in these areas even a small error on the geometry (for example a few tens of centimeters) can lead to a large error (of the order of a few meters) from the point of view of the detector. Excluding these areas, it is possible to identify low density signals related to the possible presence of cavities, some attributable to tombs already known, others attributable to voids not yet explored (fig. 2 in red). The error in the density values obtained is about 0.1 $\mathrm{g/cm^3}$. From fig. 2 we observe an area at low elevation angles ($< 15°$) and at positive azimuth (between 80° and 100°) with a higher density. This is attributable to the change in lithology that characterizes that area [17].

To locate these low density signals in three-dimensions, two procedures were applied that allow to obtain this information from a single muography measurement. The first procedure named *rays method* is applicable in this particular case study exploiting the knowledge that the tombs are quite superficial; the second follows the *back-projection technique* described in [9] for the focusing of the lower/higher density signal in space and already applied in the geological field [8, 18] . The rays method extends the low density viewing directions (θ, ϕ) from the installation point towards the hill and looks for intersections with the surface of the hill. In this way, since the tombs are superficial,

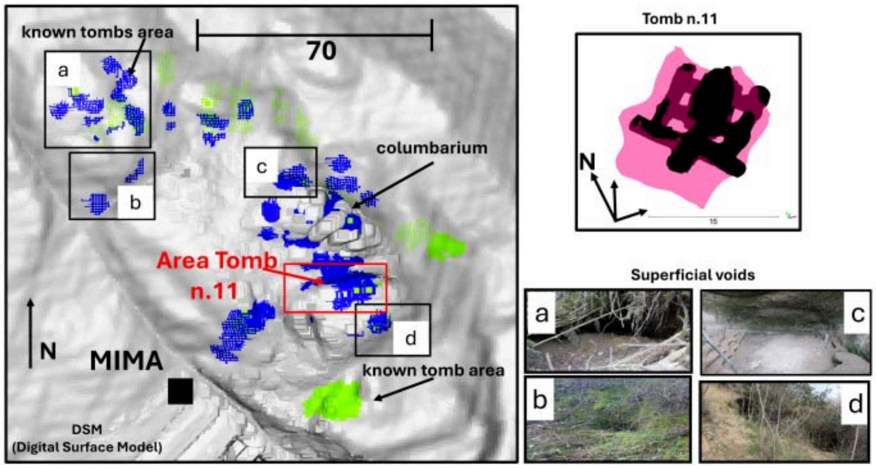

Fig. 3. – Left: in green the areas obtained with the rays method where there could be an access to the cavities, in blue the areas where an air volume has been reconstructed underneath with the back-projection technique. Right: at the top the three-dimensional reconstruction of the known Tomb n. 11 (in pink) compared with the real development (in black) and at the bottom some superficial voids found in the areas identified with the muography.

macro-areas are identified where there could be an access to a cavity. The back-projection technique has been applied only to some signals because some presented low statistics, being at the edge of the detector's acceptance or were too small in size in the angular maps. Furthermore, the technique has a geometric limit of applicability described in [8] linked to the distances between target and the detector and to its characteristics (dimensions and resolution). In this particular case study the distances involved are high enough to conclude that we are at the limit of applicability.

The results of the two methods are shown in fig. 3 left, with the different colors indicating the different methods used: in green the ray method and in blue the back-projection method. The blue areas indicate the projection on the surface in which underneath (within a few meters) there is a volume reconstructed with the back-projection technique. It can be observed how in some areas the two methods coincide and in other the back-projection technique focused the cavity signal in an area closer to the detector than the ray technique. In fig. 3 (top-right) the volume of Tomb n.11 reconstructed with muography compared with the real development is shown (details of this reconstruction can be found in [15]).

After a preliminary inspection in some of the areas identified with the muography, the presence of possible surface accesses was verified (fig. 3 bottom-right). Not all areas were accessible due to the thick vegetation. The results obtained were shared with the archaeologists of the necropolis for more detailed future inspection.

3. – Conclusions

This contribution explores the potential of the muography technique in the archaeological field. The transmission muography technique allowed in a non-invasive way and with a single measurement to estimate with good precision (10%) the presence of low density anomalies related to cavities present within the Palazzone necropolis. The measurement was affected by the thick vegetation problem that did not allow to have a geometry for the simulation that reproduced the target exactly, leading to the presence of artifacts in the two-dimensional density image obtained. Two procedures were then applied for the three-dimensional localization of the anomalies, one called *rays method* that uses the knowledge of the Etruscan surface excavation technique and the other that uses a focusing technique called back-projection already tested in other fields. Through this technique, areas with possible presence of cavities are identified by delimiting the underlying air volumes, finding positive correspondence with surface voids observed in a preliminary inspection.

REFERENCES

[1] Bonechi L. *et al.*, *Rev. Phys.*, **5** (2020) 100038.
[2] Grieder P. K., *Cosmic Rays at Earth* (Elsevier, Amsterdam) 2001.
[3] Particle Data Group (Workman R. L. *et al.*), *Prog. Theor. Exp. Phys.*, **2022** (2022) 083C01.
[4] Tioukov V. *et al.*, *Sci. Rep.*, **9** (2019) 6695.
[5] Ambrosino F. *et al.*, *J. Instrum.*, **9** (2014) C02029.
[6] Alvarez L.W. *et al.*, *Science*, **167** (1970) 832.
[7] Procureur S. *et al.*, *Nat. Commun.*, **14** (2023) 1144.
[8] Borselli D. *et al.*, *Sci. Rep.*, **12** (2022) 22329.
[9] Bonechi L. *et al.*, *J. Instrum.*, **10** (2015) P02003.
[10] Tioukov V. *et al.*, *Sci. Rep.*, **13** (2023) 5438.
[11] Liu G. *et al.*, *J. Appl. Phys.*, **133** (2023) 014901.
[12] Avgitas T. *et al.*, *Muography applied to archaeology*, arXiv:2203.00946 [physics.geo-ph] (2022).
[13] Baccani G. *et al.*, *J. Instrum.*, **13** (2018) P11001.
[14] Borselli D. *et al.*, *J. Adv. Instrum. Sci.* (2024) https://doi.org/10.31526/jais.2024.467.
[15] Borselli D. *et al.*, *J. Instrum.*, **19** (2024) C02076.
[16] Beni T. *et al.*, *Sci. Rep.*, **13** (2023) 19983.
[17] Melelli L. *et al.*, *Geoheritage*, **8** (2016) 301.
[18] Beni T. *et al.*, *Nat. Resour. Res.*, **32** (2023) 1529.