University
of Perugia
Physics and Geology
Departments

XXXVI cycle - PhD in Physics – University of Perugia

End of the first year - Activities sumups

INFN
FI, PG

Applied Physics: Muon Absorption Tomography

Muon Radiography at Palazzone Necropolis Perugia

25/10/2021

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Lorenzo Bonechi (INFN-FI)

PhD Student: Diletta Borselli

Report of the PhD project activity (first year)

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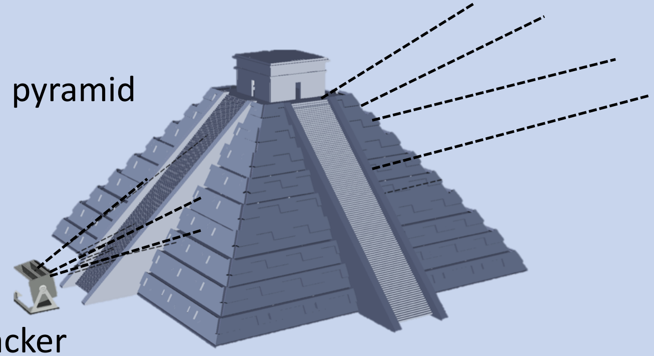
Report of the PhD project activity (first year)

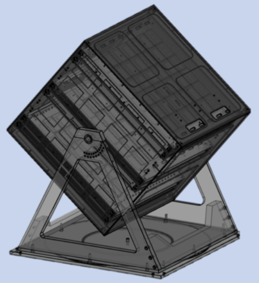
The aim of the project

The aim of the PhD project is the imaging of a zone of the archaeological area «Necropoli del Palazzone» (Perugia) using the muon radiography technique for the search of unknown tombs

Muon radiography is an ***imaging technique*** that allows to create two-dimensional or three-dimensional images of the internal density of the object under study (target) through *measurements of cosmic muons absorption*. The detectors used are charged particle **trackers**.



MIMA Tracker (INFN-FI)



(50 x 50 x 50) cm^3

- ✓ Non-invasive technique
- ✓ Possibility of installing the detectors in small and difficult to access places
- ✓ Various fields of application: archaeological, geological, industrial, civil and nuclear safety, monitoring of large structures

Measurement site: Palazzone Necropolis

Etruscan necropolis III sec. a.C.- I sec .d.C.

The necropolis consists of nearly two hundred chamber tombs, the largest and best known is the Hypogeum of the Volumni

Report of the PhD project activity (first year)

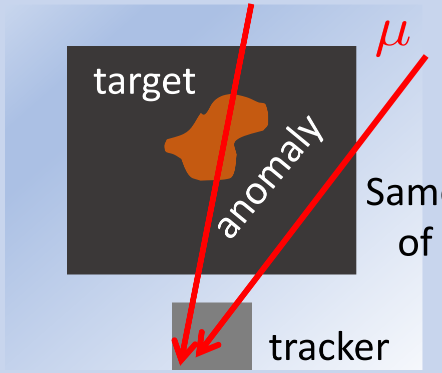
Muon radiography: Target imaging methodology

The <u>number of muons is measured</u> in a given acquisition time t as a function of the observation angles $N_\mu(\theta, \phi)$. It depends on the density and shape of the target, the flux of cosmic muons on the ground and detector acceptance and efficiency.

2D target density map, three steps are required:

1. Target measure

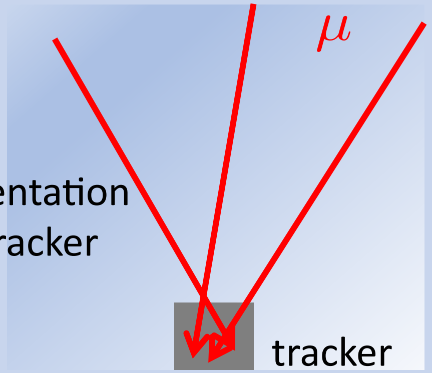
$N_{\mu_{target}}(\theta, \phi)$



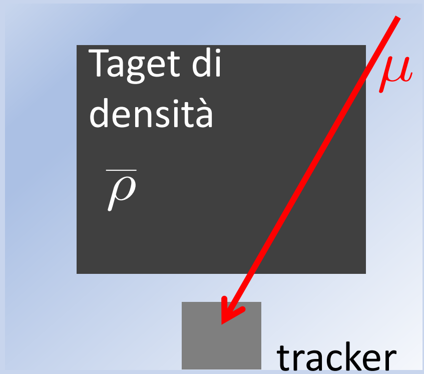
Same orientation of the tracker

2. *Freesky* measure

$N_{\mu_{freesky}}(\theta, \phi)$



3. Simulation in the case of absence of anomalies



Transmission of μ measured

$$T_{misu}(\theta, \phi) = \frac{N_{\mu\_target}}{N_{\mu\_freesky}} \cdot \frac{t_{freesky}}{t_{target}}$$

Simulated transmission of μ

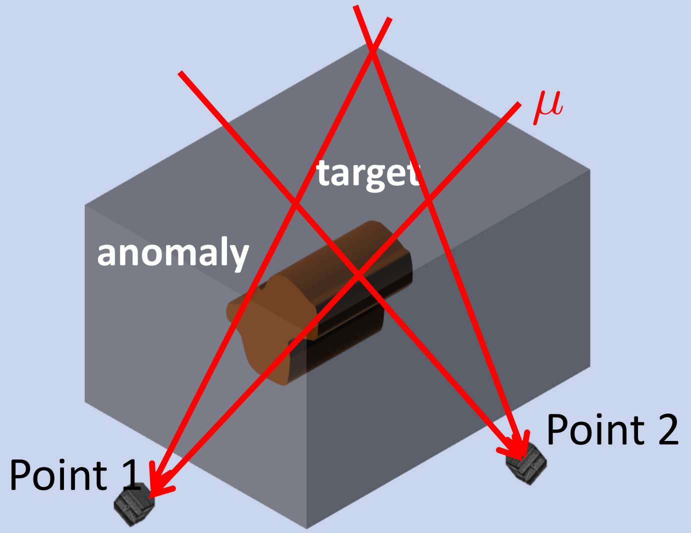
$$T_{simu}(\theta, \phi, \bar{\rho})$$

Varying $\bar{\rho}(\theta, \phi)$: $T_{misu}(\theta, \phi) = T_{simu}(\theta, \phi, \bar{\rho})$ ⟶ **2D angular density map** $\boldsymbol{\rho_{target}}(\theta, \phi)$

3D target density map

- <u>Triangulation technique</u>

  For a **stereoscopic vision** it is possible to install the detectors in several points:



- <u>Backprojection technique</u>: estimate the distance to the anomaly using data acquired from a single measure (applicable only under some conditions).

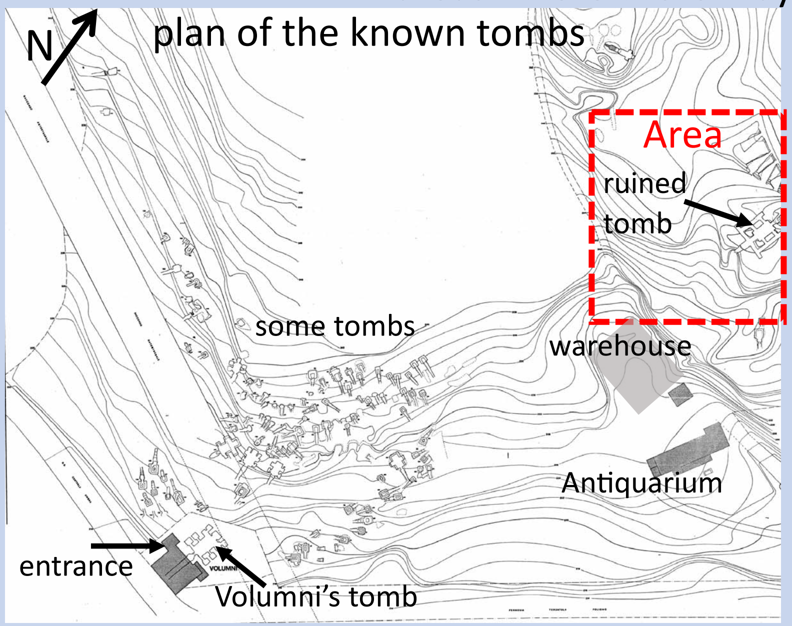
Report of the PhD project activity (first year)

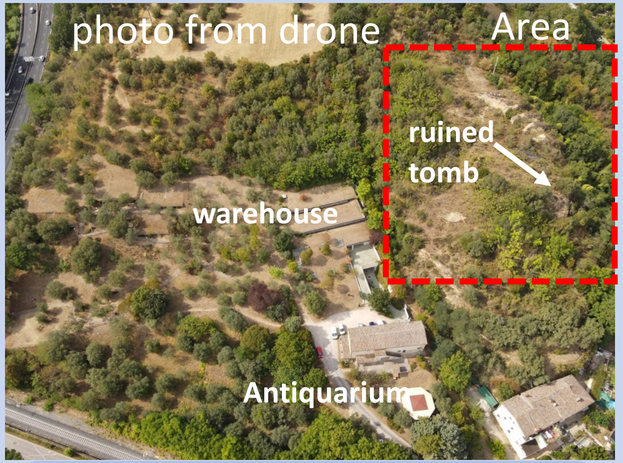
Palazzone Necropolis inspection and choice of the installation point

On 25th August 2021 an inspection was carried out in the archaeological site to define the area to be studied and possible installation points of the detector.
Participation of physicists, archaeologists and geologists.

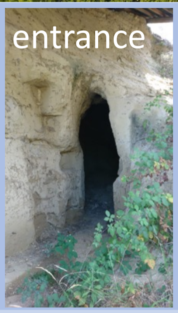
Definition of the measurement area:

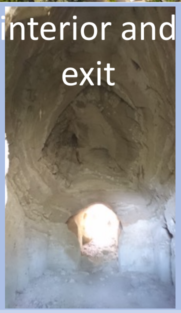
areas where there may be unknown tomb



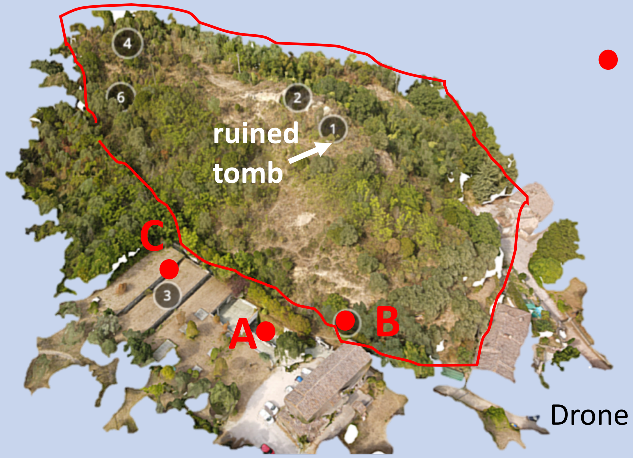


Ruined Tomb





Search for installation points in the area



Main requirements related to the flux of cosmic rays:

- the installation point must be lower in altitude than the area to be observed
- the elevation angles under which the area of interest is viewed must be as high as possible

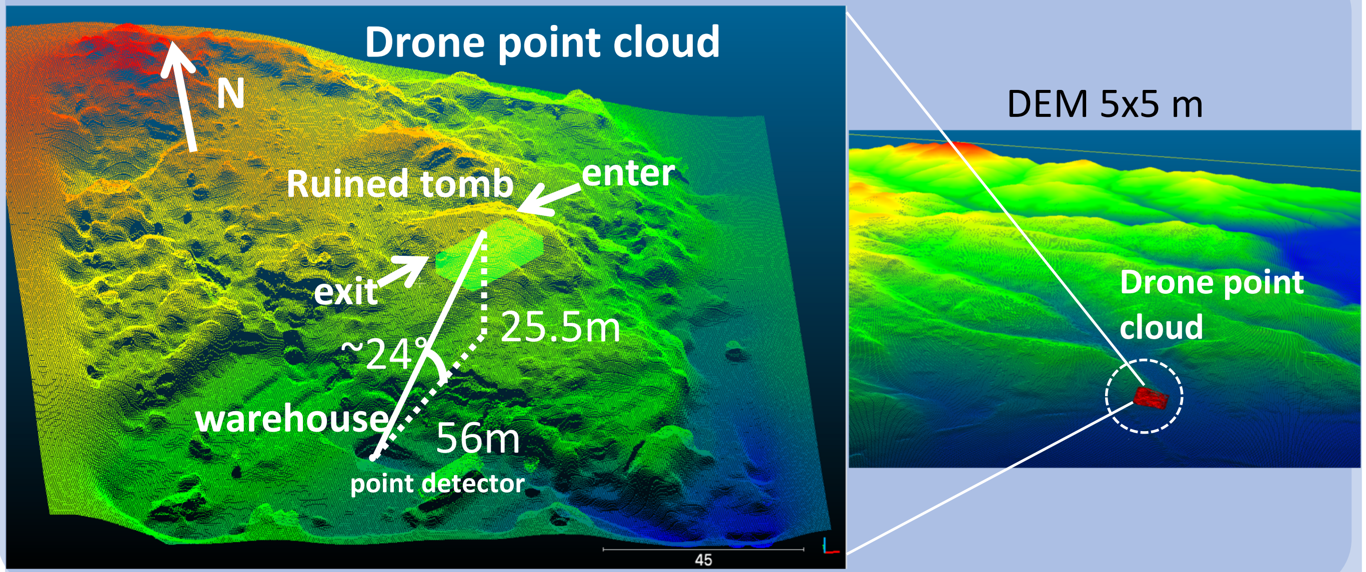
Report of the PhD project activity (first year)

Preliminary simulation- geometry

To study the feasibility of the measures, the signal of the ruined tomb observed from the installation point of the warehouse was sought.

Geometry of the simulation

A fictitious volume (12x24x4 m) that reproduces the dimensions of the «ruined tomb» has been inserted.



the top of the tomb is at ~24 ° of elevation

*trees have been partially cleared from the point cloud

Steps of the simulation

Fixed the position of the detector within the geometry, the simulation predicts:

1. the calculation of **opacity** $X(\theta,\phi) = \int \rho(l,\theta,\phi) \cdot dl$ where (θ,ϕ) polar angles, $\rho(l,\theta,\phi)$ is the average density along depth l,

2. the **minimum energy** that a muon must have to reach the detector assuming a uniform density $E_{min}(X)$,

3. the **integral flux of muons** arriving at the detector based on the differential flux model of cosmic rays to earth obtained with data from the ADAMO magnetic spectrometer (INFN-FI)

$$\Phi_{simu}(\theta,\phi,\rho) = \int_{E_{min}(X)}^{\infty} \varphi_{ADAMO}\big((\theta,\phi,E)\big)dE$$

4. The **simulated transmission** of muons

$$T_{simu}(\theta,\phi,\rho) = \frac{\Phi_{simu\_target}(\theta,\phi,\rho)}{\Phi_{simu\_freesky}(\theta,\phi,\rho)}$$

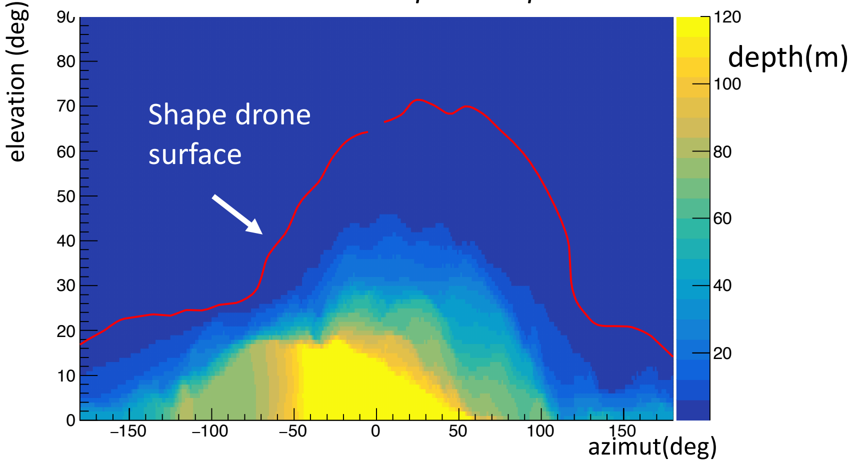
Simulation output with point detector

Interpretation of the maps:

- each bin is a direction:
  (azimut[deg], elevation[deg])
- North direction→azimut=0°
- the detector points North

Evaluation of depth and opacity

2D material thickness map-Drone point Cloud

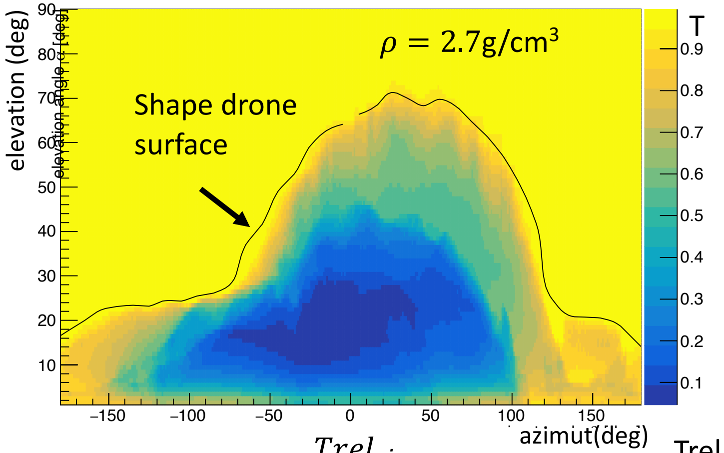


It is evaluated both in the case of the absence of a tomb (uniform case) and in the case in which there is the ruined tomb.

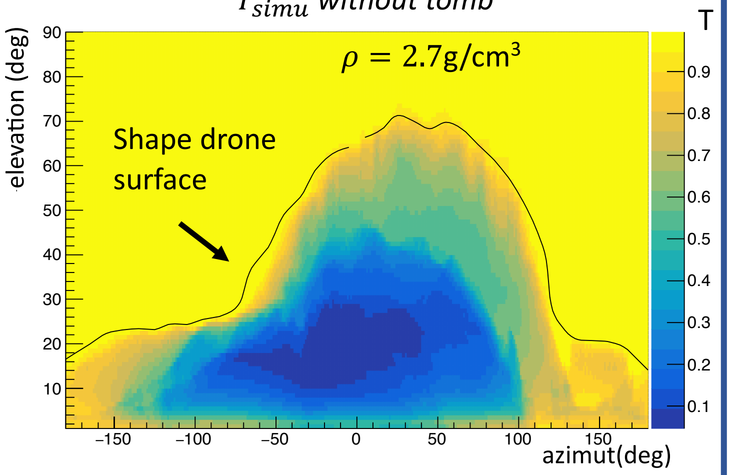
Opacity is calculated by taking a density of 2.7g/cm³

Evaluation of the transmission through the target

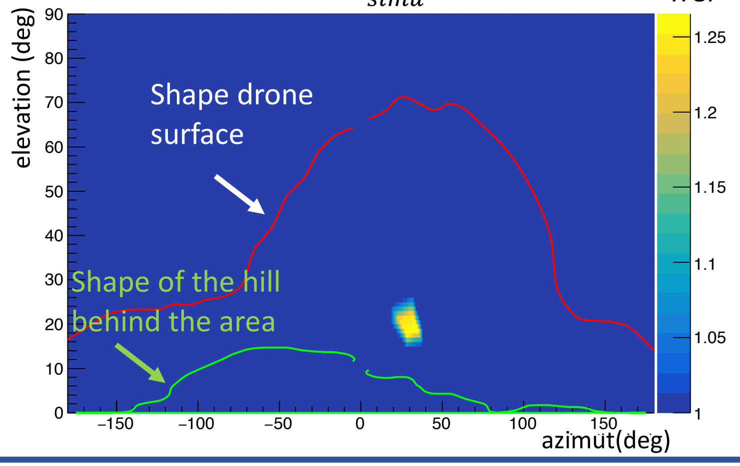
T_{simu} with tomb



T_{simu} without tomb



$Trel_{simu}$



$$Trel_{simu} = \frac{T_{simu\ withTOMB}}{T_{simu\ withoutTOMB}}$$

Transmission with tomb is greater than ~25%.

More detailed simulation is required by including the hills behind (new more detailed DEM), in order to be able to locate any lower tombs.

Report of the PhD project activity (first year)

Preliminary simulation- results

Simulations scaled with a real freesky measure
to evaluate Transmission with statistical errors

Input:

- T_{simu} with tomb and witout tomb
- Two freesky sets, $t_{acq1,2}$~14days

Evaluation of expected Transmission after 14 days

$$T_{target} = \frac{\phi_{target}}{\phi_{freesky2}} = \frac{T_{target\_simu}\frac{N_{freesky1}}{t_{acq1}}}{\frac{N_{freesky2}}{t_{acq2}}} \quad \begin{cases} \text{With tomb} \\ \text{Without tomb} \end{cases}$$

Errors:

$$\delta\phi_{target} = \frac{T_{target\_simu}}{t_{acq1}}\sqrt{N_{freesky1}}$$, but,

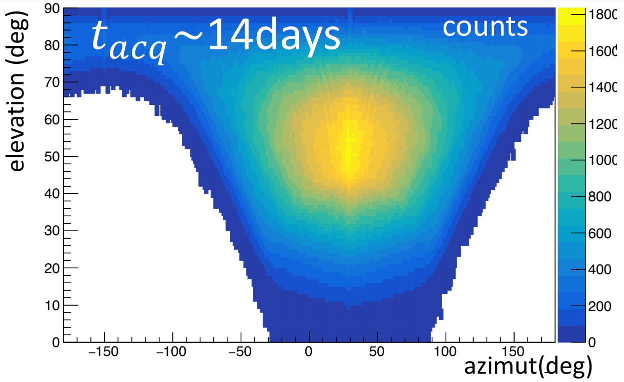
$$\delta\phi_{target} < \sqrt{N_{target}} \,/\, t_{acq1} = \sqrt{T_{target\_simu\_}N_{freesky1}} \,/\, t_{acq1}$$

an uncertainty Δ is added tc: $(\delta\phi_{target})^2 + \Delta^2 = \sqrt{N_{target}} \,/\, t_{acq1}$

Evaluation of Relative Transmission after 14 days

$$T_{rel} = \frac{T_{target}}{T_{simu\_without\_tomb}} \quad \begin{cases} \text{With tomb} \\ \text{Without tomb} \end{cases}$$

With tomb ⟶ **after 14 days the tomb is visible**

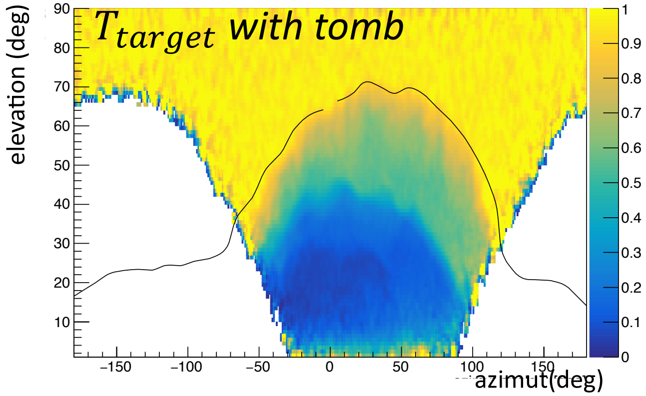


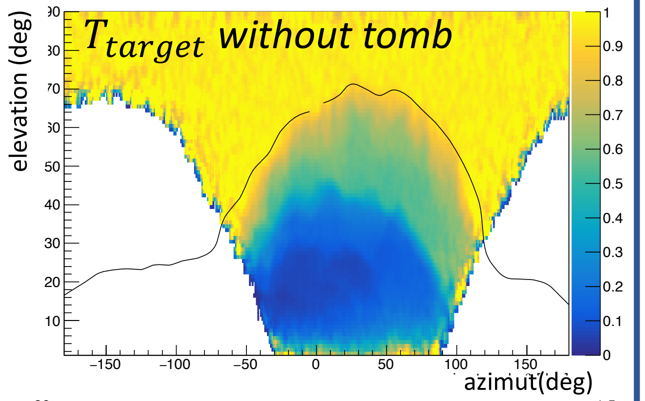
Freesky real measure –muon counts (from MIMA detector)

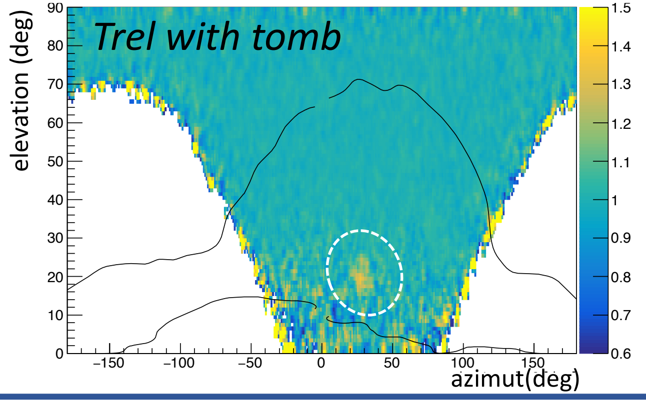
Elevation detector 45°

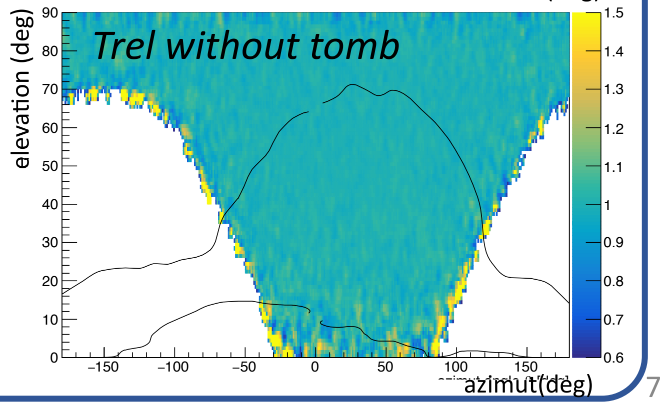
Azimut detector 30°

Each bin contains the counts of muons in a direction (azimut[deg],elevation[deg])









Report of the PhD project activity (first year)

Future PhD perspectives

Installation of the detector at the archaeological site
(March 2022) in the position A

More detailed simulations
- 1x1 m dem of the Umbria region
- drone point cloud without trees

Optimization of software for the 3d reconstruction of anomalies

Data analysis

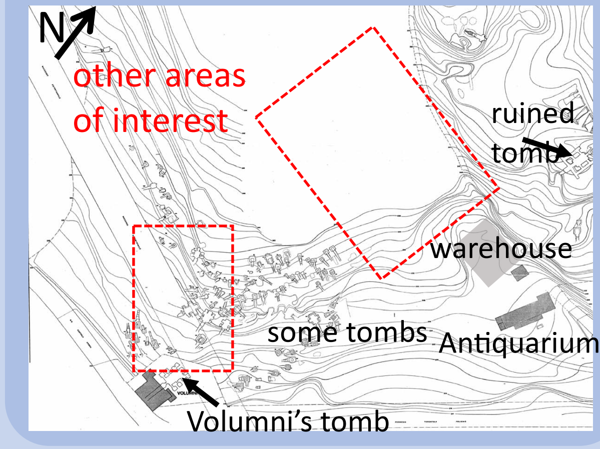
identification of ruined tomb
(reference anomaly)

- application backprojection technique,
- comparison with the real position

identification of new cavities

- application of backprojection technique,
- installing the detector at another location

redefinition of the area of interest



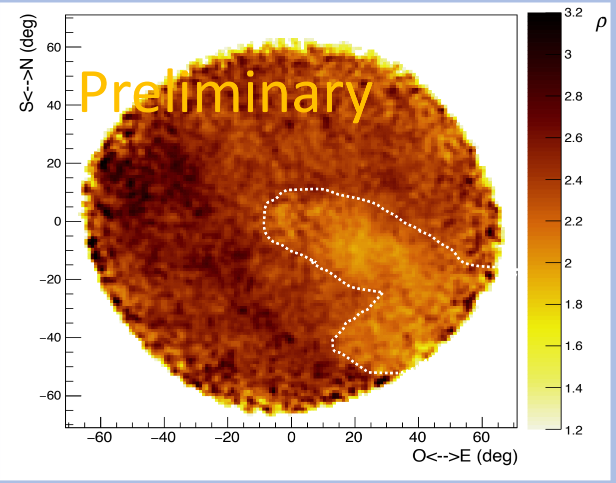
three-dimensional reconstruction using the triangulation technique

Optimization of three-dimensional reconstruction software for anomalies

Application to data acquired in 2019 at the Temperino mine (Tuscany), from **a single point of view** (data are acquired with MIMA)

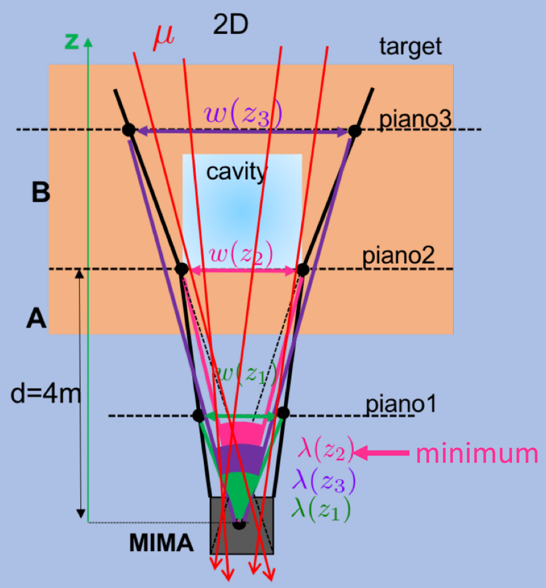
Search of cavites

2D Density map

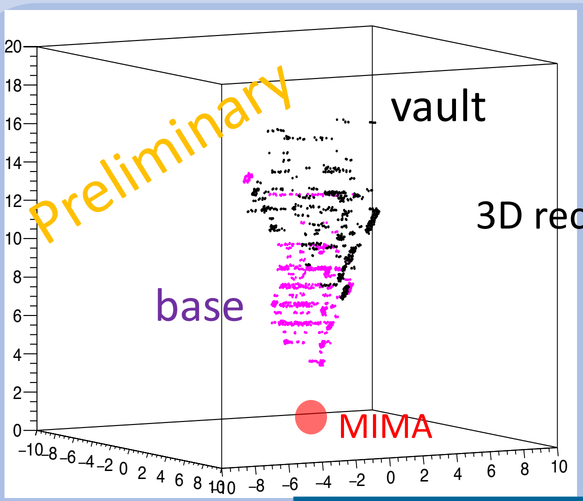


a cavity: an anomaly that has a density lower than that expected on the basis of the rock and ground conformation of installation site $\rho < 2.4$ g/cm^3

using **backprojection technique (image focusing technique)**

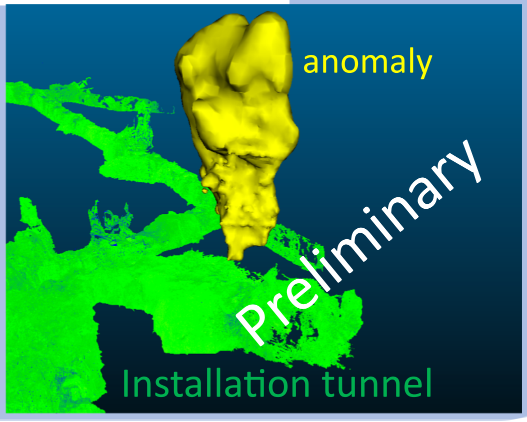


the distance z at which the signal has the minimum angular width $\lambda(z)$ is the detector-anomaly distance



3D reconstruction

the shape of the anomaly is compatible with that of an Etruscan well



Report of the PhD project activity (first year)

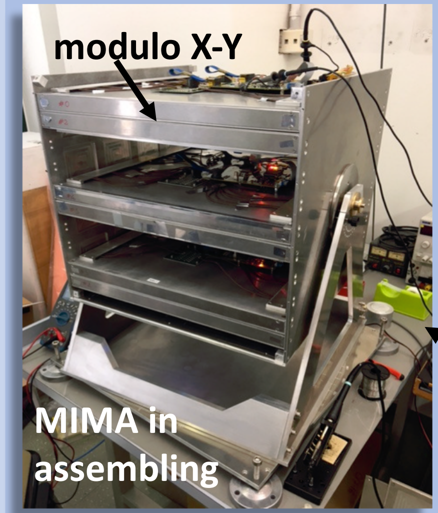
Activities related to the phd project - Hardware

MIMA tracker

(**M**uon **I**maging for **M**ining and **A**rchaeolog)

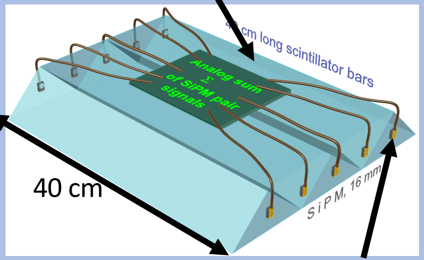
- I became familiar with the MIMA muon tracker acquisition system, and with "low level" data analysis

<u>MIMA</u>



<u>Single module:</u>
22 scintillators bar

triangular section (2x4 cm) scintillator



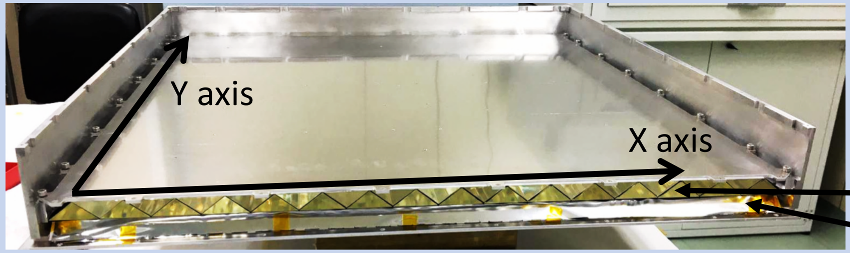
40 cm

SiPM (Silicon Photomultiplier)

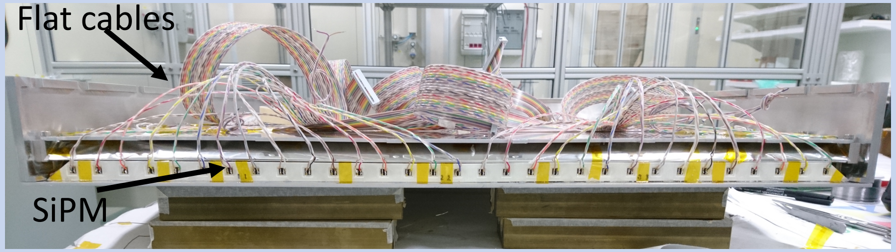
- **spatial resolution 1.5mm**
- **angular resolution 0.3 °;**
- **cube (50 x 50 x 50) cm^3;**

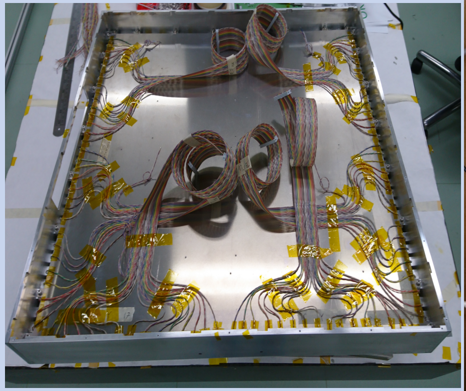
Assembly of a new tracker

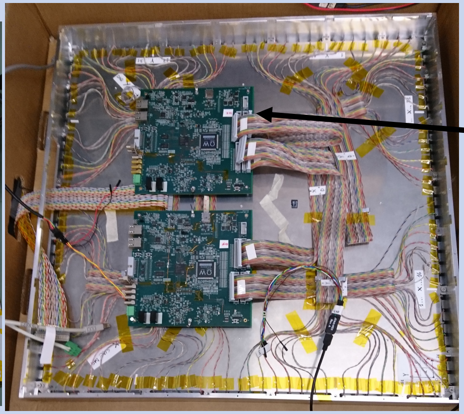
MIMONE consisting of 3 modules XY of 32 bars (2x4x60 cm) of triangular scintillator for each plane.



X plane
Y plane







electronic boards (being tested)

Report of the PhD project activity (first year)

Educational Activities - List

Courses and exams taken

I semester:

- Introduction to Effective Field Theory (EFT I), Prof. Buttazzo
- Effective Gauge Theory in Spintronics (EFT II), Prof Tatara – Exam
- Effective Field Theory studies at LHC (EFT III), Prof. Govoni
- Probability and uncertainties of measurement, Prof. D'Agostini –Exam
- Nanosystems and advanced material I, Prof. Postorino
- Nanosystem and advanced material II, Prof.ssa Pedio – Exam
- Nanosystem and advanced material III, Prof. Garlatti/Chiesa

II semester:

- Teaching and Learning Physics at University, Prof. Organtini – Exam
- Introduction to Atmospheric Physics, Climate and Copernicus Data Store, Prof.ssa Cerlini –Exam
- Multimessanger Astrophysics, Prof. Padovani/Punturo/Greco
- Physics at LHC, Prof. Gallinaro - Exam

Seminars followed

- PerAPS2021- A fast pre-clinical PET insert, Prof. Gunther Dissertori
- PerAPS2021 – A new force to understand the origin of particle masses: searching for clues on how to go beyond the Standard Model, Prof. Gino Isidori
- PerAPS2021 - Neutrons for Magnetism in Spin Chain Materials, Prof.ssa Béatrice Grenier
- PerAPS2021 -The black hole guide to the quantum theories of gravity, Prof. Roberto Emparan
- Le acque della Luna: immaginazione, realtà e scienza (webinar)
- Upgrade of the CMS tracker for LHC at CERN, Prof. Duccio Abbaneo
- INFN- A new paradigm for muon collider based on electron-photon collisions, Dr. Luca Serafini
- PHP2021: Misura di raggi cosmici nello spazio: progetti, prospettive future e attività in corso, Dr. Matteo Duranti
- PHP2021: Nuove prospettive per l'astrofisica gamma al TeV, Stefano Germani

Report of the PhD project activity (first year)

Educational Activities - List

Other Activities followed:

- Formazione trasversale per dottorandi Edizione dicembre 2020 (19 ore) – UNIPG
- Laboratorio di astrofisica multimessaggera, Prof. Greco
- Workshop: First MODE Workshop on Differentiable Programming (6-8 September 2021)

Conference participation:

- Communication at SIF National Congress 2021

  Title: *The **BLEMAB** European Project: muon radiography as an imaging tool in the industrial field*

Collaboration meetings:

- I actively contribute to the meetings of the INFN FI muography group (monthly)

Publications:

- G.Baccani et al., *The MIMA project. Design, construction and performances of a compact hodoscope for muon radiography applications in the context of archaeology and geophysical prospections*, JINST volume 13 (2018), P11001
- Bonechi et al. *Blemab European project: muon imaging technique applied to blast fournace, (*available on arXiv, Submitted to JINST 22/10/2021)

Papers in preparation

- *Muographic study of the Temperino mine: application of an innovative algorithm for identification and reconstruction of cavities in three dimensions*

  (topic of my master's thesis)

Thanks for the attention