Multidisciplinary applications of muon radiography using the MIMA detector

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on behalf of the MIMA team
Outline

• The MIMA detector
• A multidisciplinary team
• Field activities
  • Activities in the archaeo-mining field
    • The Bourbon tunnel (Naples)
    • The Temperino mine (Livorno)
  • Civil engineering / territorial protection / hydrogeological instability
    • Riverbanks (Florence and Pistoia)
    • The Dome of Florence (idea)
• Summary and perspectives
The MIMA detector - Muon Imaging for Mining and Archaeology

Purpose: rugged, light, low power tracking detector to be used for the application of muon radiography in multidisciplinary contexts.

Main requirements: ease of installation in inhospitable sites (mining and archaeological sites, riverbanks etc.)

MIMA: lab. test

MIMA: data taking

- Devel.: 2016–2017
- Tecnology: plastic scintillator
- Electronics: inherited from MURAVES (with small modifications)
- Power consumption: $\sim 30$ W.
- Size: 50 cm x 50 cm x 50 cm
- Weight: $\sim 50$ kg
- Ang. Res.: $\sim 14$ mrad ($0.8^\circ$)
- Acceptance: $\sim 1000$ cm$^2$ sr (3 xy planes)
- Altazimuth mount
**The MIMA detector - Muon Imaging for Mining and Archaeology**

**Tracking planes**: fast plastic scintillator
- 3 pairs of planes: $X_1 Y_1 + X_2 Y_2 + X_3 Y_3$
  - Outer pairs made of 40 cm long bars with triangular section
  - Middle pair made of 40 cm long bars with rectangular section (test)

\[ \sigma \approx 3.3 \text{ mm} \]
Development of multidisciplinary applications of muon transmission radiography

Team involved in the different activities

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The «physics group» in Florence

PHYSICS
GEOLOGY
ENGINEERING & GEOPHYSICS
ARCHAEOLOGY
Activity in the **Archaeology** field

- Multiple measurements with Mu-Ray and MIMA inside the **Bourbon Tunnel** (Naples, Italy)
  - 2\textsuperscript{nd} half 2017
  - It is the 1\textsuperscript{st} measurements with MIMA in its full config.
  - Target measurement: 50 d, rate 0.55 Hz, $N_T = 2.36M$
  - Free-sky measurement: Florence, $N_{FS} = 21 M$

(ref. 2, 3)
Angular transmission map measured by MIMA

(x=azimut, y=elevation, 
z=transmission: (target/free-sky) ratio

- Empty volumes reconstructed by Mu-Ray in two measurements are shown in yellow
- Angular regions detected by MIMA are shown as green cones
Activity in the **archaeo-mining** field

- **Temperino mine** in Campiglia Marittima (Livorno, Italy)

- Five measurements completed in different positions between the 2018 and 2019
  - Mapping of **known and unknown cavities**
  - Reconstruction of **2D density maps**
  - Study of ancient pits of Etruscan age
  - Development of **3D imaging**

- **First results**: ref. 4

- **New updates**: on-going work by G.Baccani, S.Gonzi and D.Borselli
The Temperino mine (Livorno, Italy)
Exploited since the Etruscan age – abandoned in ‘900 – now touristic site

3D laser scan (plan view)

The «Gran Cava» seen from inside
3D laser-scanner reconstruction of the Temperino mine

Gran Cava

Temperino mine

Surface of the hill

MIMA detector - pos 1

26.557 m

~26.6 m
The Temperino mine (Livorno, Italy)

Description of the reference frame:
- center = vertical direction
- distance from center = zenith angle
- angle around center = azimuth angle

Muon angular distributions

Underground (target) flux \( N_T \)
- 2 M events
- 53 days data

Free sky (reference) flux \( N_{FS} \)
- 35 M events
- 17 days data

Gran cava
The Temperino mine (Livorno, Italy)

Description of the reference frame:
- center = vertical direction
- distance from center = zenith angle
- angle around center = azimuth angle

Simulation details:
- realistic muon flux based on experimental data (ref. 5)
- updated DTM of the hill with a 1 m spatial definition
- Uniform density $d=2.65 \text{ g/cm}^3$

Muon transmission

$\mu$ transmission

$$\mu_{\text{TRANSMISSION}}$$

$\mu_{\text{TRANSMISSION}}$

$\mu_{\text{TRANSMISSION}}$

$$t = \frac{N_T}{N_{\text{FS}}} \frac{t_{\text{FS}}}{t_T} \frac{\varepsilon_{\text{FS}}}{\varepsilon_T}$$

$t =$ DAQ durations
$\varepsilon =$ efficiencies
The Temperino mine (Livorno, Italy)

Description of the reference frame:
- center = vertical direction
- distance from center = zenith angle
- angle around center = azimuth angle

Comparison with a single simulation assuming uniform rock density

Comparison with N simulations with different densities

Transmission ratio and 2D density map

Under development:
- Localization in 3D of the observed «unknown» cavities and dense bodies (ref. 6)
- 3D muon absorption tomography using ART techniques
The Temperino mine (Livorno, Italy)

The other two measurements performed in different positions below the Gran Cava.

MEASURED $\mu$ TRANSMISSION – pos 3

MEASURED $\mu$ TRANSMISSION: pos. 5
Environment – civil protection and hydrogeological instability

- Measurement at the Arno riverbank in Mantignano (Firenze, Italy, June 2017)
- Measurement at the Bure stream embankment (Pistoia, Italy, July 2018)

PURPOSE:
- Conservation status of embankments
- Comparison with other survey methodologies
Muon transmission radiography of arginal bodies

Time variation of DAQ rate

23 day data taking - TARGET
18 days data taking - FREE SKY

Power supply: photovoltaic solar panels
Reference measurement: detector on top of the riverbank
Muon transmission radiography of arginal bodies

MEASURED $\mu$ TRANSMISSION – Bure stream (Pistoia)

Upper limit of the embankment as seen from MIMA

Problem not yet understood in data

Very low elevation: low muon flux, possibility of mountains on the background
Results of the muon radiography at the Bure stream

The direction «T» identified in the transmission map agrees with the direction of the tree.
The directions of the signals identified as possible cavities in the transmission map point to the holes observed by visual inspection.
Preliminary comparison of muon radiography with a geoelectric measurement

Upper image: muon radiography $\rightarrow$ 2D projection of all the identified signals
Lower image: slice of the 3D geoelectric tomography
Muon radiography and geoelectric measurements shows a general agreement

Roots: missing in the muon radiography
An interesting case being evaluated

Brunelleschi’s Dome, located in the Cathedral of Santa Maria del Fiore in Florence

Radial forces are determining a deformation of the dome that has been growing for centuries.

The wood belt originally installed between the two shells of the dome to contrast the radial forces.
An interesting case being evaluated

Result: visible cracks on the frescoed dome walls. Continuous monitoring with sensors. Cracks are increasing in size since centuries.
Dedicated test: study of cracks and metal bars inside a concrete wall

**Concrete cubes**
- cube size: 50 cm
- density: \( d = (2.37 \pm 0.08) \text{ g/cm}^3 \)

**Iron bars**
- Size \((15 \times 4 \times 200) \text{ cm}^3\)
- density: \( d = 7.8 \text{ g/cm}^3 \)

**Measurements**
Free sky: 29 d  Target: 58 d

**Simulation**
- Current: simplified, based on CAD
- Next: 3D laser scan
Preliminary test: imaging of small metal volumes

Course of «Particles and applications»
Undergraduate program in Physics and Astrophysics

2018-2019
Backprojections and focusing effect

Strong focusing effect is observed in the backprojection maps
- due to the fact that the metal blocks were quite close to the detector
- It allows finding the distance of the objects from the detector.

~ 6.5 d data acquisition
Backprojections and focusing effect

Image reconstruction @ d=60 cm

Estimation of the size

\[ \sigma_y \approx 2 - 2.5 \text{ cm} \]
GSRM2018
Giornata di Studio sulla Radiografia Muonica in ambito multidisciplinare

29-30 Ottobre 2018
Auditorium dell’Ente Cassa di Risparmio di Firenze
(Via Folco Portinari 5, Firenze)

L’evento è dedicato alla discussione, in un’ottica multidisciplinare, dello stato di avanzamento e delle attività in corso nell’ambito della radiografia muonica in Italia. L’incontro ha come scopo principale quello di mettere in contatto le comunità di fisici, archeologi e geologi per mettere in luce le potenzialità di questa tecnica radiografica, le reali necessità nei possibili campi di applicazione e i limiti delle tecniche standard, attualmente in uso, stimolando una discussione costruttiva tra i vari soggetti. 

Comitato organizzativo
Guglielmo Baccani
Lorenzo Bonechi
Chiara Dei Ventriglia
Sandro Gonzi
Elisabetta Greco
Stefano Saracino

Comitato consultivo
Lorenzo Bonechi
Nicola Casagli
Raffaele D’Alessandro
Paolo Stronin

Web page
http://agenda.infn.it/event/GSRM2018

Registered: 43
Participants: 38 of whom
- 13 physicists (FI-NA-PD-PV-TO)
- 13 geologists (FI-NA-PI-LI)
- 8 archaeologists (FI-SI-PI)
- 3 engineers (FI)
- 1 architect (FI)

Presentations: 19 of which
- 4 methodologies
- 4 archaeology
- 4 geologic/minerary
- 4 civil / environment

https://agenda.infn.it/event/GSRM2018/
Conclusions and perspectives

- The MIMA detector
  - Angular resolution: 14 mrad
  - Weigth: 50kg
  - Size: 50x50x50 cm$^3$
  - Power consumption: 30 W
  - Geometrical factor: $\sim 1000 \text{ cm}^2 \text{ sr}$
  - Altazimuth mount

- Measurements with MIMA in different fields since 2017:
  - Archeology
  - Mining
  - Hydrogeological instability: riverbanks
  - Metal detection

- Next
  - New fields of application
    - E.g.: the Brunelleschi’s Dome in Florence
  - 3D algorithms for muon transmission tomography
    - MITO: Muon Imaging Tomography
References

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The MIMA project. Design, construction and performances of a compact hodoscope for muon radiography applications in the context of Archaeology and geophysical prospections.  
2018 JINST 13 P11001 |
|---|
| 2) G. Saracino et al.  
Imaging of underground cavities with cosmic-ray muons from observations at Mt. Echia (Naples)  
| 3) L. Cimmino et al.  
3D Muography for the Search of Hidden Cavities  
| 4) G. Baccani et al.  
Muon Radiography of Ancient Mines: The San Silvestro Archaeo-Mining Park (Campiglia Marittima, Tuscany)  
Universe 2019, 5, 34 |
| 5) L. Bonechi et al.  
Development of the ADAMO detector: test with cosmic rays at different zenith angles  
29th International Cosmic Ray Conference, Pune (2005) 9, 283286 |
| 6) L. Bonechi et al.  
A projective reconstruction method of underground or hidden structures using atmospheric muon absorption data  
2015 JINST 10 P02003 |
BACKUP
Preliminary studies of the application of the muon absorption imaging technique to the «Sellafield case»

- Simulation code
  - Generic simulation code developed in Florence, based on Geant4
  - Only tracks in acceptance are simulated

- Realistic muon generator
  - Based on a measurements campaign carried out in 2004 using the ADAMO magnetic spectrometer (ref 5)
  - Zenith angle $0 < \theta < 80^\circ$
  - Momentum $100 \text{ MeV}/c < p < 130 \text{ GeV}/c$

- Realistic detector implementation
  - 2 xy tracking planes

- Reconstruction and analysis
  - # of simulated events → acquisition time
Preliminary results using a back-projection method at the Bourbon tunnel

Example: projection to the x-axis and measurement of the width of the selected peak

\[ \sigma = (22 \pm 2) \text{ cm} \]
Check of sensibility on the density map (Temperino mine)

5x5 bin region in the center of the Gran Cava signal

14 October 2019
L. Bonechi - IPRD 2019 - Siena
Materials collected at the Temperino mine

1. Porfido acido
2. Porfido mafico
3. SKARN
4. marmo

\[ \rho_1 = (2.41 \pm 0.07) \text{ g/cm}^3 \]
\[ \rho_2 = (2.62 \pm 0.08) \text{ g/cm}^3 \]
\[ \rho_3 = (3.08 \pm 0.07) \text{ g/cm}^3 \]
\[ \rho_4 = (2.70 \pm 0.06) \text{ g/cm}^3 \]
The backprojection method
A projective reconstruction method of underground or hidden structures using atmospheric muon absorption data

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VOLUME SEEN AS AN "ANOMALY" IN THE DENSITY MAP (CAVITY OR DEPOSIT OF DENSE MATERIAL)

UNDERGROUND MUON TRACKER
**HYPOTHESIS**: the size of the object and the distance from the detector are comparable to the size of the detector or anyway no too large wrt it

VOLUME SEEN AS AN "ANOMALY" IN THE DENSITY MAP (CAVITY OR DEPOSIT OF DENSE MATERIAL)

UNDERGROUND MUON TRACKER
STEREOSCOPIC VIEW: different parts of the detector look to the target from different directions
IDENTIFICATION OF THE ANGULAR REGION WHERE AN ANOMALY IN THE MUON DENSITY MAP IS EXPECTED
IDENTIFICATION OF THE ANGULAR REGION WHERE AN ANOMALY IN THE MUON DENSITY MAP IS EXPECTED

INCOMING MUON TRACKS
PARALLEL PLANES AT INCREASING DISTANCE FROM DETECTOR
BACK-PROJECTION OF TRACKS TO PARALLEL PLANES OR CONCENTRIC SPHERICAL SURFACES
BACK-PROJECTION OF TRACKS TO PARALLEL PLANES OR CONCENTRIC SPHERICAL SURFACES
STUDY OF THE ANGULAR WIDTH OF THE ANOMALOUS REGION AS SEEN FROM THE DETECTOR’S POSITION

Z₀  Z₁  Z₂  Z₃  Z₄  Z₅  Z₆  Z₇  Z₈
STUDY OF THE ANGULAR WIDTH OF THE ANOMALOUS REGION AS SEEN FROM THE DETECTOR’S POSITION

Angular width:

\[ \lambda(z) = 2 \tan^{-1} \left( \frac{w(z)}{2z} \right) \]
THE MINIMUM ANGULAR WIDTH OF THE OBSERVED «ANOMALY» (AS SEEN FROM THE DETECTOR) IS FOUND WHEN PROJECTING TRACKS TO A SURFACE PASSING THROUGH THE ANOMALY ITSELF.

\[ \lambda(z) = 2 \tan^{-1} \left( \frac{w(z)}{2z} \right) \]
DEPENDENCE OF THE ANGULAR WIDTH FROM THE Z-COORDINATE FOR 1m LARGE TARGET PLACED AT DIFFERENT DISTANCES FROM THE DETECTOR
Casi d’interesse in ambiti molto diversi (I)
Simplified CAD reconstruction

3D laser scan (August 2019)