Muography: Fundamental Aspects of the Technique and Reconstruction of CRC Data

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ABSTRACT

Muography is an image reconstruction technique based on the interaction between cosmic muons and matter, aimed at producing a muogram—an internal image of the object under investigation. This article outlines the basic operating principles of the method, describing its historical applications through to the most recent studies, with a particular focus on scintillation detectors. A dataset from the portable muon telescope CRC (Cosmic Ray Cube), which is based on scintillation technology, will be analyzed to reconstruct a muon’s trajectory. The collected data will then be processed using Excel spreadsheets, ultimately allowing for the calculation of the particle’s incidence angles.

INTRODUCTION

1.1 DEFINITION Muography, or muon radiography, is an imaging technique that involves analyzing the interaction between a flux of cosmic muons and a target object to reconstruct its internal structure, identifying potential density variations and anomalies. This method exploits the high penetrating power of muons (μ), elementary particles with a mass 200 times greater than that of electrons, which allows them to travel undisturbed through the Earth's atmosphere and into the upper layers of the subsurface.

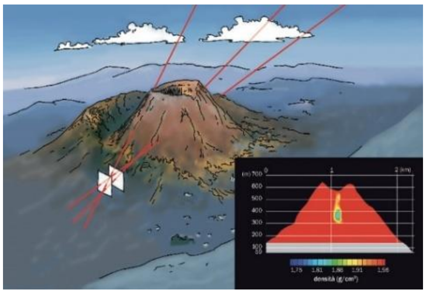


Fig.1 muography of Satsuma-Iwojima volcano, Japan

1.2 HISTORY Over time, muography has been applied in a variety of fields, contributing to both Earth sciences and archaeology. The first publicized application of the technique dates back to 1968, when American physicist Luis Walter Alvarez obtained the first muogram of the Pyramid of Khafre **[1]**, placing muon detectors inside the structure. He concluded that the pyramid was structurally solid and lacked hidden chambers. The experiment, as no cavities were detected, made it possible to avoid invasive, irreversible exploration methods.
Subsequent experiments include:

- 2007: A research group from the University of Tokyo and Nagoya University discovered a dense lava mass beneath the crater floor of Mount Asama **[2]**, with a low-density area below it—interpreted as a porous conduit through which magma flowed downward.

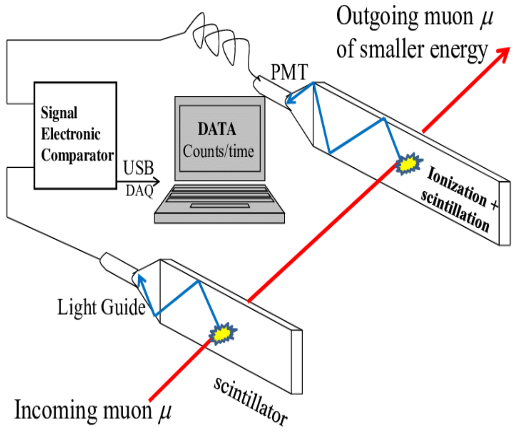
- 2015: The MURAVES (MUon RAdiography of VESuvius) project was launched to perform muography of the summit area of Mount Vesuvius, allowing INGV volcanologists (National Institute of Geophysics and Volcanology) to predict potential future eruptions. The data collection system includes three scintillator-based telescopes with a total sensitive area of 3 m². The system is currently collecting data for future analysis **[3]**.

- 2017: Nature published the discovery of a Grand Gallery over 30 meters long inside the Great Pyramid of Giza **[4]**, detected using three different muon detection techniques.

- 2019: The first muon radiography of Stromboli volcano was carried out through a collaboration between INFN (National Institute for Nuclear Physics) and INGV. Published on Nature on April 30 **[5]**, the results revealed a low-density area at the summit, linked to a pyroclastic residue from the 2007 eruption.

- Researchers from the University of Naples Federico II, INFN, and Nagoya University used muon radiography to study the subsoil of the Rione Sanità district in Naples, discovering a hidden funerary chamber **[6]**. Two emulsion detectors were placed 18 meters underground and collected over 10 million muons in about a month.

Fig.2 schematic diagram of a scintillation muon detector



1.3 SCINTILLATION MUON DETECTORS

At the core of muographic reconstruction techniques is the operation of muon detectors **[7]**. The simplest method to isolate the muon component of cosmic showers is to make muons interact with specific materials that emit light (scintillation), which is then converted into an electrical signal.

Scintillation detectors work based on this principle and are made of the following key components:

1. ***Scintillator*****:** it is a plastic material that emits light (photons) when traversed.

2. ***Wavelength-shifters (WLS)*****:** these are used to collect the light emitted by the scintillator, and transport it to the detection apparatus. They absorb light at a certain wavelength and re-emit it at a longer wavelength to ensure compatibility with the detection device.

3. ***Photomultipliers (PMT)***: these detect and amplify the signals, converting them into electrical signals using the photoelectric effect. Among new generation photomultipliers, there are those based on silicon (SiPMs)

Individual detectors may also register events unrelated to the cosmic ray flux, such as natural radioactivity and electronic noise; thus, it is crucial to discriminate between the particles of interest and unwanted signals. The method used to reduce random events and accurately detect the passage of muons is the coincidence technique: a coincidence is a signal simultaneously detected by multiple aligned detectors.

The interpretation of a certain number of data collected by detectors is essential for muographic reconstruction, as it allows for the determination of the angular distribution of the particles. Through the transmission map, which shows the directional variation in muon flux intensity, it becomes possible to determine the internal density of the object being examined. Areas with greater attenuation correspond to regions of higher density, while those registering less attenuated flux correspond to hollow or low-density zones.

The transmission function T(θ,φ) measures the ratio between the number of muons detected by the sensor after passing through the material in the direction defined by angles θ and φ, and the number of muons expected in the absence of obstacles:

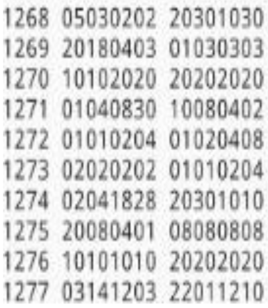
$$T(\theta,\varphi)=\frac{N_{detected}}{N_{expected}}$$

If the value of T is approximately equal to 1, the material traversed does not attenuate the expected flux, indicating the presence of a cavity. Conversely, if the measured T value is significantly less than 1, it suggests the presence of particularly dense material obstructing the particles. If the transmission value is 0, this means that the material between the flux and the detector has acted as a total barrier.

1.4 SCINTILLATION APPLIED TO MUOGRAPHY

Among the muon telescopes that use scintillation is the CRC (Cosmic Ray Cube), designed and built by the Gran Sasso National Laboratory (LNGS) for educational purposes **[8]**. In the following part of the article, starting from a dataset collected by the CRC, the measurement of a cosmic muon's trajectory will be illustrated and the angles of incidence with respect to the z-axis (azimuthal angle) and the x-axis (azimuth angle) will be determined.

Fig. 3 CRC data set



```
1268  05030202  20301030
1269  20180403  01030303
1270  10102020  20202020
1271  01040830  10080402
1272  01010204  01020408
1273  02020202  01010204
1274  02041828  20301010
1275  20080401  08080808
1276  10101010  20202020
1277  03141203  22011210
```

METHODS: 1.1 CRC: The Cosmic Ray Cube is a cube-shaped muon telescope, measuring 30 cm per side, composed of 4 planes of scintillators arranged vertically with 7 cm spacing. Each plane is made up of two layers, consisting of 6 scintillating rods, each containing a special optical fiber (WLS) that collects the light produced by the passing particle. This light signal is sent to a small silicon photomultiplier (SiPM) that converts it into a measurable electrical signal. Finally, the CRC's electronic component activates LEDs that visually indicate the muon's passage.

1.2 DATA COLLECTION AND RECONSTRUCTION: From the “Cosmic Rays Live” app **[9]**, by navigating to “File Manager,” then the “Download” folder, and finally the “CRC” folder, one can view a dataset collected by CRC. In the first column is the event number (e.g., **1272**), while the second and third columns contain two hexadecimal strings that, once decoded, provide the coordinates of the triggered pixels on the two faces of the cube. It is possible to decode CRC data and reconstruct a muon's trajectory by following these steps:

1) For example, event **1272** is chosen and the two numeric strings are converted from hexadecimal to binary:
Evento 1272: 01010204 01020408

-First string (XZ plane): ***01 01 02 04***, in binary: ***01*** → 000001, ***01*** → 000001, ***02*** → 000010, ***04*** → 000100

-Second string (YZ plane): ***01 02 04 08***, in binary: ***01*** → 000001, ***02*** → 000010, ***04*** → 000100, ***08*** → 001000

The binary numbers are entered into a 4.row, 6-column table in Microsoft Excel, highlighting the particle’s passage in yellow, knowing that the “**1**” represents the scintillator rod hit by the muon, while the “0” indicates the rod not hit.

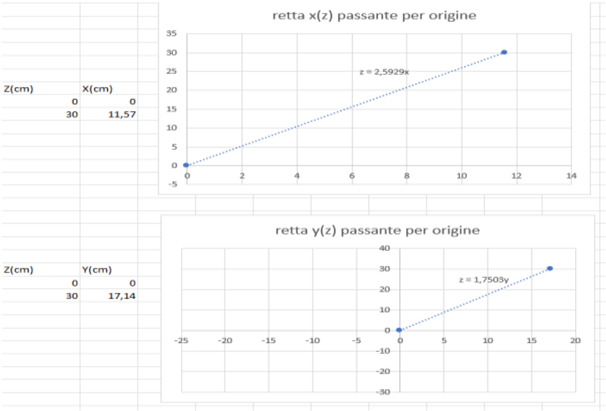
2) Knowing the width of the strips (4 cm) and the spacing between planes (7 cm), a table can be filled in with Z (cube height), X, and Y values. On the same page, the trend lines of the points are determined, assuming a linear dependence between Z and X, and Z and Y.

3) The obtained lines are drawn on two coordinate planes (with axes swapped to place Z on the x-axis) to define two points for each plane:

P1: [x(0);0], **P2 : [x(h);h]**, with h=30cm (total cube height)

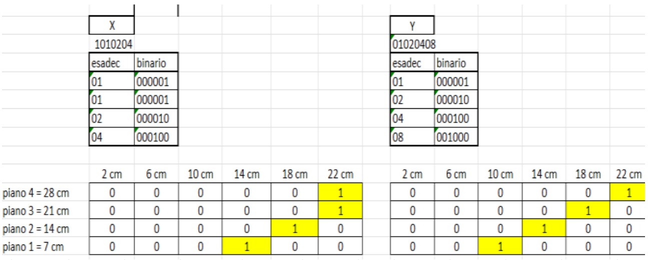
P3 :[y(0);0], **P4 : [y(h);h]**

The trend lines represent the projections of the muon trajectory onto the ZX and ZY planes.



Z(cm)	X(cm)
0	0
30	11,57

Z(cm)	Y(cm)
0	0
30	17,14

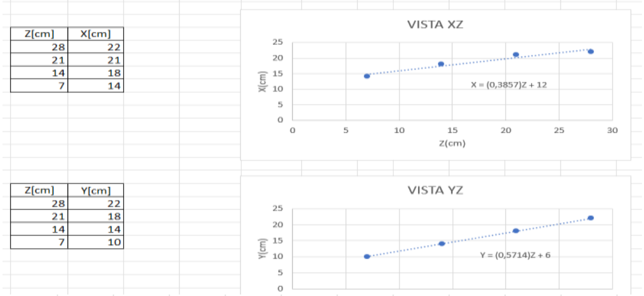


X	
1010204	
esadec	binario
01	000001
01	000001
02	000010
04	000100

Y	
01020408	
esadec	binario
01	000001
02	000010
04	000100
08	001000

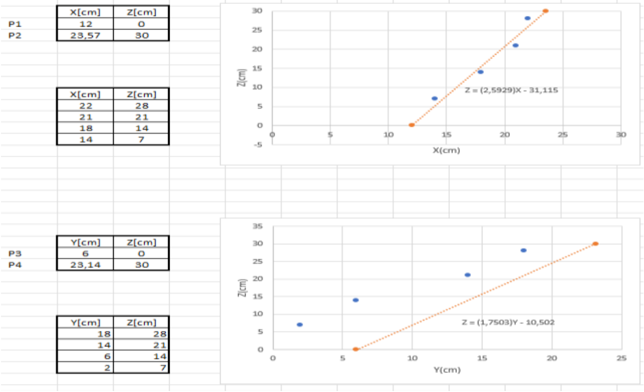
	2 cm	6 cm	10 cm	14 cm	18 cm	22 cm
piano 4 = 28 cm	0	0	0	0	0	1
piano 3 = 21 cm	0	0	0	0	0	1
piano 2 = 14 cm	0	0	0	0	1	0
piano 1 = 7 cm	0	0	0	1	0	0

	2 cm	6 cm	10 cm	14 cm	18 cm	22 cm
piano 4 = 28 cm	0	0	0	0	0	1
piano 3 = 21 cm	0	0	0	0	1	0
piano 2 = 14 cm	0	0	0	1	0	0
piano 1 = 7 cm	0	0	1	0	0	0



Z[cm]	X[cm]
28	22
21	21
14	18
7	14

Z[cm]	Y[cm]
28	22
21	18
14	14
7	10



	X[cm]	Z[cm]
P1	12	0
P2	23,57	30

X[cm]	Z[cm]
22	28
21	21
18	14
14	7

	Y[cm]	Z[cm]
P3	6	0
P4	23,14	30

Y[cm]	Z[cm]
18	28
14	21
6	14
2	7

4) To reconstruct the particle’s 3D trajectory, the **direction vector** “v” is calculated, from which the angles **θ** and **φ** can be derived. To do this, we set the intercept **q** to 0 and draw the lines obtained in step 2 with inverted axes. The resulting trend lines are of the form: $\mathbf{X = m_xZ}$ and $\mathbf{Y = m_yZ}$

These lines are parallel to those previously found: $\mathbf{X = m_xZ + q_x}$ and $\mathbf{Y = m_yZ + q_y}$

RESULTS

The direction vector has components v = (v_x, v_γ, v_z). To simplify calculations, the vector is normalized by setting v_z = Thus, the vector becomes: **v = (m_x, m_γ, 1).** To obtain the angles θ (inclination with respect to the x-axis) and φ (azimuthal angle in the xy-plane), spherical coordinates are used and the slope coefficients of the lines are inputed into Excel to get angle values in degrees and radians using the following formulas:

$\theta=\arccos(v_z/v)$ and $\varphi=\arctan2(v_y, v_x)$

with $v_z=1$ $\quad v=\sqrt{v_x^2+v_y^2+v_z^2}$ $\quad v_x=m_x=0{,}386$ $\quad v_y=m_y=0{,}57$

$\theta = 34{,}58°$ $\quad \varphi = 34{,}01°$

By repeating the process for multiple events and positioning one or more detectors downstream of the object under study (such as a volcano or pyramid), it is possible to map the particle distribution and obtain a complete muogram.

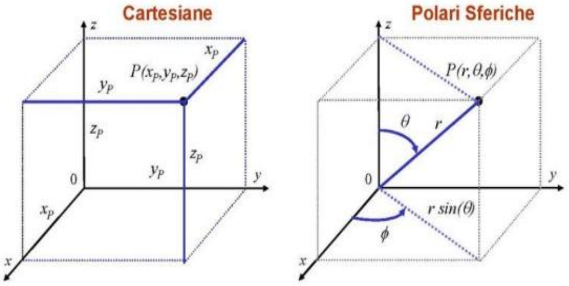


Fig. 4 Cartesian and spherical polar coordinate systems in three dimensions

CONCLUSIONS

This study presented an introductory paragraph on muography, including its definition, possible applications, and some of the most significant results achieved over time. Subsequently, detection techniques were introduced, focusing on scintillation detectors. As an example, CRC, a portable muon telescope with publicly accessible data, was introduced as a study case. Starting from a hexadecimal numerical string, the trajectory of a muon passing through CRC was reconstructed, allowing the zenith angle (with the vertical) and the angle with the x-axis to be determined. These angles describe the direction of the muon relative to the reference system. In general, this data allows us to locate the trajectories of different fluxes and, through the transmission map, study muon flux attenuation and consequently analyze the internal density of the object of study. Despite the successful application of muography in various fields, the technique still presents limitations, mainly related to detector scale and data processing methods.

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[9] *https://web.infn.it/OCRA/misura-della-rate-di-muoni-cosmici/*