The MURAVES Experiment: A Study of the Vesuvius Great Cone with Muon Radiography

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Abstract

The MURAVES experiment aims at the muographic imaging of the internal structure of the summit of Mt. Vesuvius, exploiting muons produced by cosmic rays. Though presently quiescent, the volcano carries a dramatic hazard in its highly populated surroundings. The challenging measurement of the rock density distribution in its summit by muography, in conjunction with data from other geophysical techniques, can help the modeling of possible eruptive dynamics. The MURAVES apparatus consists of an array of three independent and identical muon trackers, with a total sensitive area of 3 square meters. In each tracker, a sequence of 4 XY tracking planes made of plastic scintillators is complemented by a 60 cm thick lead wall inserted between the two downstream planes to improve rejection of background from low-energy muons. The apparatus is currently acquiring data. Preliminary results from the analysis of the first data sample are presented.

Keywords: muography, cosmic rays, volcanology
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1. INTRODUCTION

Mt. Vesuvius is an explosive volcano, still active though quiescent for about 80 years and located near the city of Naples. Possible eruptions would be particularly dangerous due to the dense urbanization even in its close surroundings. The history of Vesuvius is characterized by several violent eruptions. The best known is the Plinian eruption of 79 BC that destroyed the city of Pompeii and other settlements around it.

In the course of millennia, the morphology of the volcano strongly changed due to its activity. In particular, several explosive eruptions in the last period of activity caused the collapse of the caldera and the formation of the present crater. The interior of the cone is thought to be composed of materials having different densities, probably distributed in a layered structure [1].

So far muon radiography (or "muography") was applied to volcanoes requiring muon penetration through a rock thickness below 1 km [2, 3, 4]. However, exploring the mass distribution inside the summit of Vesuvius' cone roughly requires doubling the extent of the muon range, which implies coping with very low muon rates and inexperienced backgrounds. This is the challenge of the MURAVES (MUon RAdiography of VESuvius) project [5] that is described in the following, concluding with the presentation of some preliminary results.

2. TECHNOLOGY AND INFRASTRUCTURE

The MURAVES muon telescope has a total sensitive cross-sectional area of 3 m^2, provided by an array of three identical muon trackers. Each muon tracker is formed by a sequence of four tracking stations distributed over a length of 2 meters, with a 60 cm thick lead wall inserted between the two downstream tracking stations for the purpose of background reduction, in particular

FIGURE 1: One of the three independent muon trackers.

tagging and rejecting low-energy muons. The tracking stations, realized on the basis of the *Mu-Ray* technology [6, 7, 8], consist of two adjacent planar arrays of plastic scintillator bars, orthogonally oriented to provide the horizontal and vertical coordinates of the muon impact point. Figure 1 shows one of the three muon trackers. The bars have a cross-section shaped as an isosceles triangle with a 1.7 cm height and 3.3 cm basis (Figure 2) and are assembled with an alternate up-down orientation of the triangle. The spatial resolution of the corresponding coordinate is improved through the weighted average of the signal in adjacent bars. The plastic scintillator bars were extruded at the FERMILAB-NICADD facility from a bulk of polystyrene with the addition of PPO and POPOP scintillating dopants, emitting in a blue wavelength spectrum centered on a 420 nm wavelength. They are of the same type as those used in the D0 [9] and Minerva [10] experiments. Multiclad Kuraray Y11 S-35 wavelength shifting (WLS) fibers with a 1.2 mm diameter run in a coextruded central hole of 1.5 ± 0.1 mm diameter. Their absorption and emission spectra are in the blue wavelength range of 400–470 nm and in the green range of 470–550 nm, respectively. The WLS fibers are read out by ASD-RGB1C-P Silicon Photo-Multipliers (SiPM), produced by the AdvanSiD company [11].

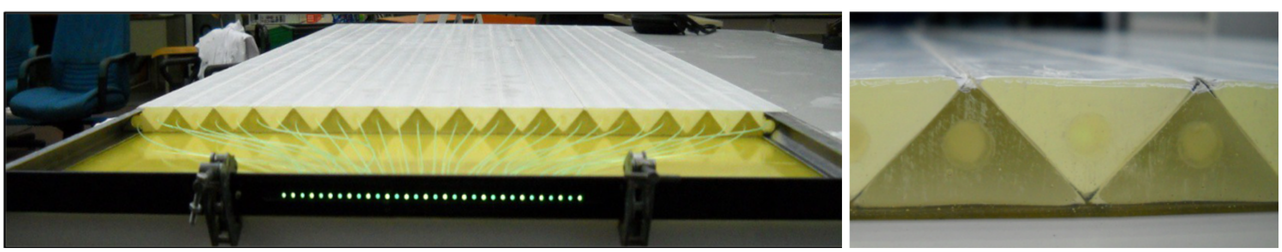

FIGURE 2: Left: the 32 scintillator bars and WLS fibers assembled in half of a planar array. Right: triangular section of the scintillator bars.

Each muon tracker has 8 planar arrays of plastic scintillator bars. The 32 SiPMs of each half array (16 half-arrays for each muon tracker) are hosted on a hybrid circuit and are connected to a 32-channel front-end electronics (FEE) based on the ASIC chip EASIROC [12]. The setting of the trigger and the data acquisition of each muon tracker is provided by 16 slave boards managed by a master board. The readout and data acquisition system is described in [13]. The experimental apparatus and the data transfer are remotely controlled.

As they are solid state devices, the SiPMs operation is affected by temperature variations. A custom-designed temperature control system based on Peltier cells cools or heats the photosensors according to the requirement. For each group of 32 SiPMs, it consists of two Peltier cells, a copper strip providing uniform thermal conduction and a couple of fans for heat dissipation. A custom circuit controls the cells through Pulse Width Modulation drivers. The temperature can be set within a 5–7°C maximum difference with respect to the ambient temperature. The bias voltage and the temperature determine the working point of the SiPMs. The stability of the SiPMs performance is thus obtained by changing the bias voltage according to the temperature, so as to maintain a constant overvoltage. The temperature control system is shown in Figure 3. Anyhow, the SiPMs must be operated at a temperature resulting in sufficiently low power consumption and far enough from the dew point, to prevent damage from condensation.

FIGURE 3: The temperature control system: the components (left); the system installed on the detector (right).

The MURAVES telescope is housed inside a container, installed on the southwest slope of Mt. Vesuvius at 600 m a.s.l. and 1500 m distance from the summit. The electric power is supplied by a solar panel system located on the roof of the container and connected to an array of batteries, which ensures continuity at night or on cloudy days. Four concrete platforms inside the container rest directly on the ground and can support lead walls of up to 90 cm thickness (at present 60 cm). One of the platforms is intended to take calibration data with trackers, in turn, pointing to the free sky opposite to the mountain. Figure 4 shows the container and a scheme of the muon trackers' arrangement inside the container.

FIGURE 4: Left: the container installed at Mt. Vesuvius. Right: the scheme of the arrangement of the muon trackers inside the container: the not-colored tracker indicates the position of a muon tracker while taking calibration data.

3. MEASUREMENT AND SENSITIVITY

The experiment aims at mapping the mean density of the matter crossed by muons in the traversal of the volcano, through the measurement of the muon flux that reaches the detector. Its ratio with the muon flux measured in calibration runs with the muon tracker pointing to the open sky in the opposite direction (Figure 5) gives the *muon transmission*:

$$T(\theta,\phi) = \frac{N_\mu^v(\theta,\phi)/\Delta t^v}{N_\mu^{fs}(\theta,\phi)/\Delta t^{fs}} = \frac{\epsilon^v \cdot S_{\text{eff}}(\theta,\phi) \int_{E_{\text{min}(\rho)}}^{\infty} \Phi(\theta,\phi;E)dE}{\epsilon^{fs} \cdot S_{\text{eff}}(\theta,\phi) \int_{E_0}^{\infty} \Phi(\theta,\phi;E)dE}, \tag{1}$$

where $\Phi(\theta,\phi;E)$ is the differential muon flux, and $N_\mu^v(\theta,\phi)$ and $N_\mu^{fs}(\theta,\phi$ are the muons observed in a time interval Δt^v and Δt^{fs} respectively, with the apices v and fs indicating *volcano* and *free-sky* data. $E_{\text{min}(\rho)}$ is the energy needed to survive the rock and to be seen by the detector; E_0 is the minimum energy needed to not be absorbed in the detector itself. The measured fluxes can be factorized as indicated on the r.h.s. so that with a sufficiently good approximation the efficiency ϵ and the effective sensitive area S_{eff} of the muon tracker cancel out, isolating the ratio of the muon fluxes $\Phi(\theta,\phi;E)$ as a function of the elevation and azimuthal angles θ and ϕ.

Figure 6 shows the rock thickness to be traversed by muons, as evaluated exploiting a Digital Elevation Model (DEM) of Mt. Vesuvius [14]. The rock thickness ranges from some hundreds of meters at the uppermost part of the cone to almost 5000 meters at its basis. The sensitivity of the experiment depends on the statistics which can be accumulated and on the background which is left in spite of the hardware and algorithmic means for its reduction.

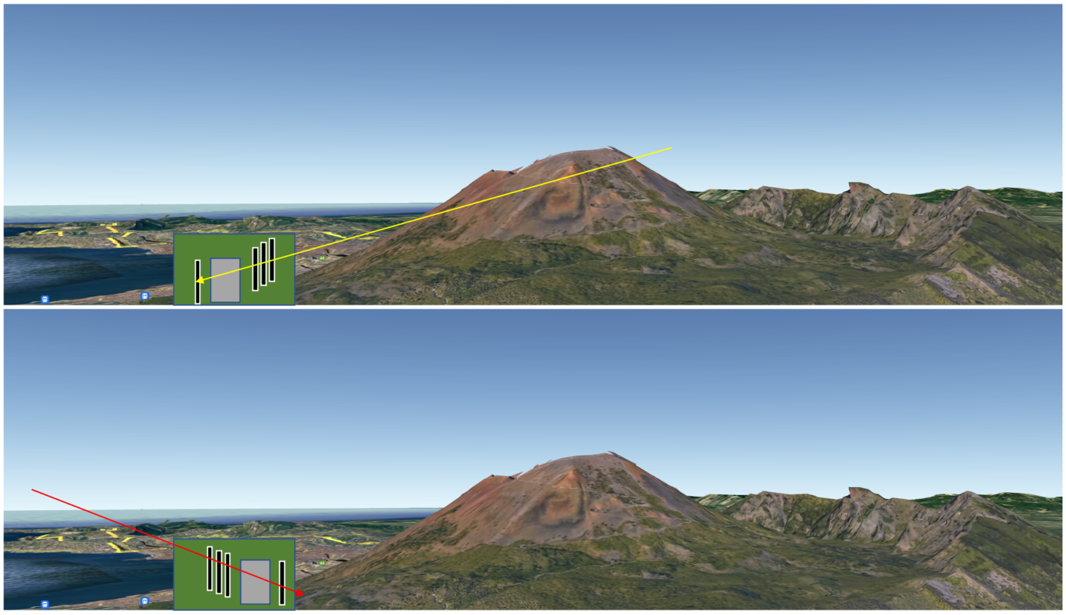

FIGURE 5: A scheme of the configuration for the measurement of the muon flux transmitted through the volcano (top figure) and of the free-sky calibration flux (bottom figure). Detector not in scale.

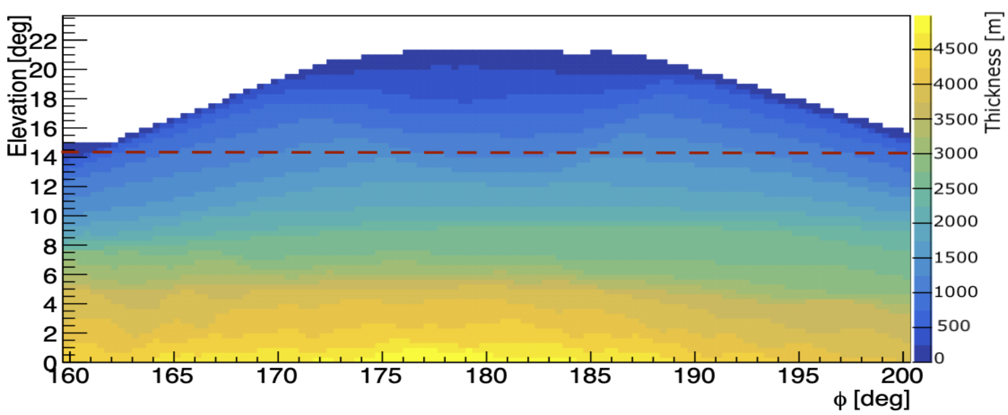

FIGURE 6: A map of the rock thickness to be traversed by muons through Mt. Vesuvius as a function of the elevation and horizontal angles. The horizontal range reflects the detector's geometrical acceptance.

The expected muon flux through the volcano was evaluated using simulations. Table 1 gives estimates of the exposure times required to measure the mean rock density ρ with a statistical uncertainty $\Delta\rho/\rho = 10\%$, for a set of volumes defined by Δx and Δy and the rock thicknesses L, averaged to $\bar{L}$. The required exposure times have been obtained as described in [15]. The nominal density has been taken to be $\rho = 2.65\,\mathrm{g\,cm^{-3}}$. In a first approximation, data are assumed to be background free and, presumably of lesser importance, the detector efficiency was not taken into account. Looking at the thickness map of Mt. Vesuvius in Figure 6 in light of Table 1, one can deduce that a detector of a few m^2 area like MURAVES can face the challenge of exploring the summit of the cone of Mt. Vesuvius. A larger area is required for a path length in the 3 km range.

4. DATASETS AND DATA ANALYSIS

Data adequate for a preliminary analysis was acquired by two of the three muon trackers of the MURAVES telescope, named NERO and ROSSO. Because of the variations in the environmental conditions, the SiPMs were operated at two different working points corresponding to temperatures 15°C and 20°C. Correspondingly, data is subdivided into the four groups shown in Table 2. The table gives the respective effective exposures. The exposures pointing to the volcano quoted in the table have an order of magnitude of 1-2 months, to be compared to a few years of data taking foreseen for MURAVES, with the full muon telescope. The

Δy	Δx	$\bar{L} = 500\,\mathrm{m}$	$\bar{L} = 1000\,\mathrm{m}$	$\bar{L} = 3000\,\mathrm{m}$
9 m	9 m	8 months	3 years	100 years
9 m	26 m	3 months	1 year	33 years
9 m	130 m	15 days	2.5 months	6 years
26 m	130 m	5 days	1 month	2 years
52 m	260 m	2 days	6 days	16 months

TABLE 1: Exposure times expected to be required to measure the mean density with a 10% statistical uncertainty for a set of values of the muon path length in the rock and of horizontal and vertical space resolutions Δx and Δy.

Dataset	Vesuvius	Free-sky
ROSSO wp 15°C	51 days	9.5 days
ROSSO wp 20°C	40 days	14.3 days
NERO wp 15°C	43 days	10 days
NERO wp 20°C	26 days	17 days

TABLE 2: Exposure times of the four datasets with the two muon trackers pointing to Mt. Vesuvius or to free sky for calibration.

table gives also the effective exposure already available for each free-sky calibration of the datasets. The free-sky exposures are shorter, but thanks to the high muon flux, they give a comparable or even lower statistical uncertainty.

A preliminary analysis was performed separately for the four datasets. After a selection of the good muon events, the data analysis proceeded by dividing the angular range corresponding to the upper part of the cone into regions large enough to contain reasonable statistics, as shown in Figure 7. These regions were chosen to be larger in azimuthal angle than in elevation, so as to obtain better visibility of a possible stratification of materials of different densities. For a better balance of the rates, the layers cover an increasing range of elevation angles going down from the top of the volcano. The three layers were further subdivided into the left and right parts as shown in the figure (west and east sides, respectively) in order to show possible asymmetries in principle visible from the detector location.

The number of events registered in each of the six chosen angular regions is listed in Table 3 separately for each of the four datasets. The statistical uncertainty is maintained below 10% in most cases; in a few cases, is larger but not exceeding 20%.

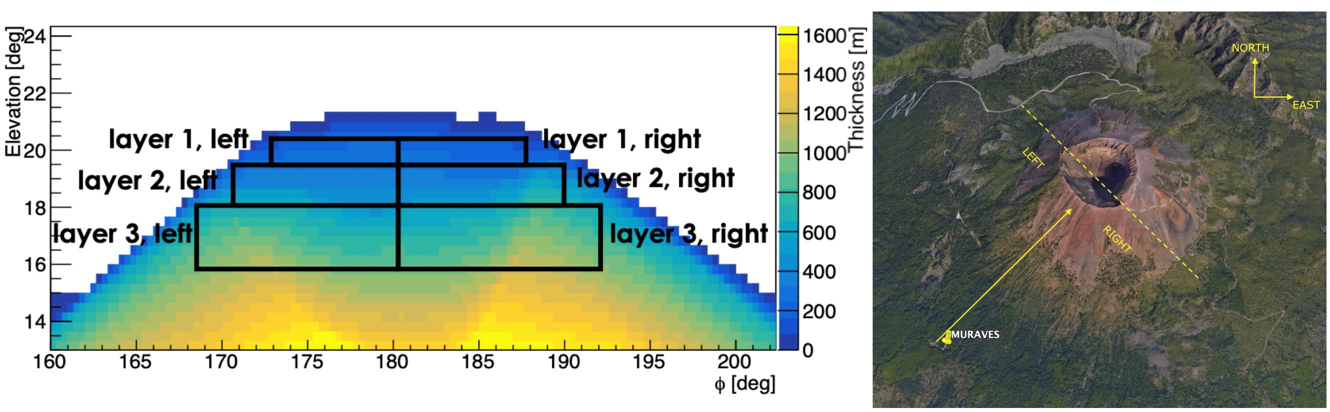

FIGURE 7: Left: a map of the muon path length through the volcano, with an indication of the angular regions where the average density is at present in the process to be evaluated. Right: a map of the Vesuvius area with the indication of the detector orientation.

The expected muon flux through the volcano was evaluated using the PUMAS software [16], a backward Montecarlo simulation program especially optimized for muography applications. The muon absorption in the volcano and the lead wall energy threshold were taken into account. Figure 8 compares the expected muon flux to the measured flux given by one of the datasets, to be taken as an example. Within uncertainties, there is agreement. The simulation chain is still under development, and a higher level of details is being included, in particular, the detector responses and the effects of analysis cuts for background reduction, such as those on the scattering in the detector and on the muon time-of-flight for forward/backward discrimination. The expected transmission will be evaluated with a dedicated software chain, which is currently under construction. Finally, the density will be measured in each angular region by comparing the measured transmission to the expected transmission.

	N events		Stat. unc. (%)	
Dataset	left	right	left	right
Layer 1				
ROSSO wp 15°C	428	439	0.05	0.05
ROSSO wp 20°C	346	323	0.05	0.05
NERO wp 15°C	231	258	0.05	0.05
NERO wp 20°C	128	258	0.07	0.06
Layer 2				
ROSSO wp 15°C	164	140	0.08	0.08
ROSSO wp 20°C	106	109	0.10	0.10
NERO wp 15°C	78	79	0.11	0.11
NERO wp 20°C	61	63	0.13	0.13
Layer 3				
ROSSO wp 15°C	61	76	0.12	0.11
ROSSO wp 20°C	58	63	0.13	0.13
NERO wp 15°C	47	47	0.14	0.15
NERO wp 20°C	27	30	0.19	0.18

TABLE 3: Events and statistical uncertainties in the six angular regions, separately for the four datasets.

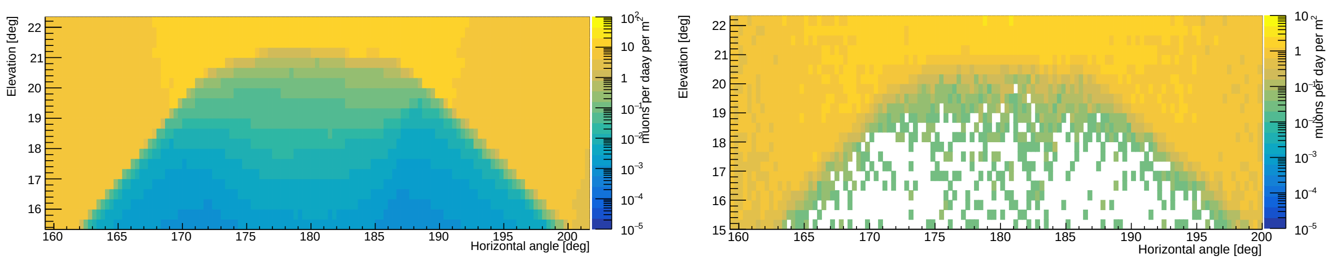

FIGURE 8: Expected flux, evaluated with PUMAS (left); measured flux obtained from one of the datasets in Table 2.

5. CONCLUSIONS

The MURAVES experiment exploits muography to investigate, in combination with other techniques, the rock density distribution inside the summit of Mt. Vesuvius, a very dangerous active volcano in Southern Italy. A muon telescope of $3\,\text{m}^2$ total sensitive area, subdivided into three identical and independent muon trackers, was installed on the south-west slope of the volcano inside a container. Four initial datasets are being analyzed, each corresponding to exposures ranging from 26 to 51 days by single muon trackers. Within uncertainties, the measured muon agrees with the muon flux expected from a simulation that accounts for the muon absorption in the path through the volcano and for the energy threshold set by the detector. Calibration datasets, taken in the same conditions, exist for each of the four datasets. A first measurement of the mean density of the rock in six angular regions projected on the volcano is under way. Data taking is foreseen to continue for a few years.

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