The MURAVES muon telescope: a low power consumption muon tracker for muon radiography applications

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Abstract. Muon Radiography or muography is based on the measurement of the absorption or scattering of cosmic muons, as they pass through the interior of large scale bodies, In particular, absorption muography has been applied to investigate the presence of hidden cavities inside the pyramids or underground, as well as the interior of volcanoes' edifices. The MURAVES project has the challenging aim of investigating the density distribution inside the summit of Mt. Vesuvius. The information, together with that coming from gravimetric measurements, is useful as input to models, to predict how an eruption may develop. The MURAVES apparatus is a robust and low power consumption muon telescope consisting of an array of three identical and independent muon trackers, which provide in a modular way a total sensitive area of three square meters. Each tracker consists of four doublets of planes of plastic scintillator bars with orthogonal orientation, optically coupled to Silicon photomultipliers for the readout of the signal. The muon telescope has been installed on the slope of the volcano and has collected a first set of data, which are being analyzed.

1. Introduction

A new non destructive method, called *Muon Radiography* or *Muography*, was recently developed to investigate the internal structure of bodies with large dimensions and applied in various fields. This technique, analogous in principle to the usual X-ray Radiography, exploits muons produced by high energy particles - mostly protons - generated in the Cosmos and called cosmic-rays. Interacting in the upper atmosphere, cosmic rays generate showers of particles. Among them, muons reach the Earth surface thanks to their high penetrating power. The constant flux of muons hitting the Earth surface can be exploited to investigate the interior of large bodies.
Information about the mass distribution inside different kinds of targets is gathered by mapping

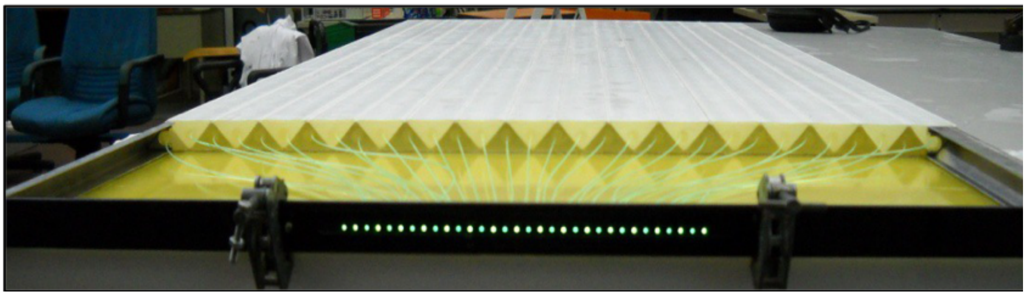

Figure 1. A module, containing 32 plastic scintillator bars with WLS fibers running inside the central hole to convey the light to the SiPMs.

the absorption or the scattering of muons that cross them. Muon Radiography has been applied in several fields: volcanology, archaeology, civil and industrial engineering, nuclear waste control, cargo inspections. For more details see [1].
The MURAVES project [2] aims at the muographic study of the summit of the Mt. Vesuvius, a very hazardous volcano in the proximity of densely populated areas. This motivates facing the challenge given by low flux of muons with enough energy to traverse a thickness of rock considerably larger than in previous applications of the technique. in addition to a sensitive area large enough to intercept a meaningful muon flux, a tight control of the backgrounds is required. The apparatus must operate as a stand-alone device remotely controlled and have a low power consumption, to be installed in locations without access to electricity supply.

2. The MURAVES muon telescope

The MURAVES apparatus consists in an array of three identical and independent muon trackers installed side by side, to cover in a modular way a total sensitive area of three square meters. Figure 2) shows one of such muon trackers. Low energy muons, carriers of background, are either absorbed by a 60 cm thick Lead wall, giving a threshold of about 940 MeV for muons with orthogonal impact on the detector, or rejected on the basis of a measurement of scattering.

2.1. Muon trackers

The basic detector module (Figure 1) consists in a robust planar array of 32 plastic scintillator bars with fast response, about 1 m long. The cross section of the bars is shaped as an isosceles triangle, 1.7 cm high and 3.3 cm wide. The bars in the array are closely glued side by side with alternating up and down orientation of the triangle. The partial superposition of two adjacent bars improves the spatial resolution to about 3 mm, through the weighted average of the coordinates given by the single bars. The expected angular resolution is 1.7 mrad for tracks reconstructed with four planes and 6 mrad for tracks reconstructed with the first three planes.The bars are made of a bulk of polystyrene with the addition of PPO and POPOP scintillation dopants emitting in the blue wavelength region, with an emission maximum at 420 nm. The scintillator bars were produced by extrusion in the Fermilab NICADD facility [3]. A 2.5 $\pm$ 0.1 mm diameter central hole is co-extruded with the plastic scintillator bar for the insertion of a 1 mm diameter wavelength shifting (WLS) fiber, which conveys the light signals to the respective photodetector.
The assembly of two modules constitutes a 1 m^2 plane. The doublet of two planes with orthogonal orientation measures the x-y coordinates of a muon hit. Muon trajectories are reconstructed by means of four plane doublets at an appropriate spacing. A 60 cm thick Lead

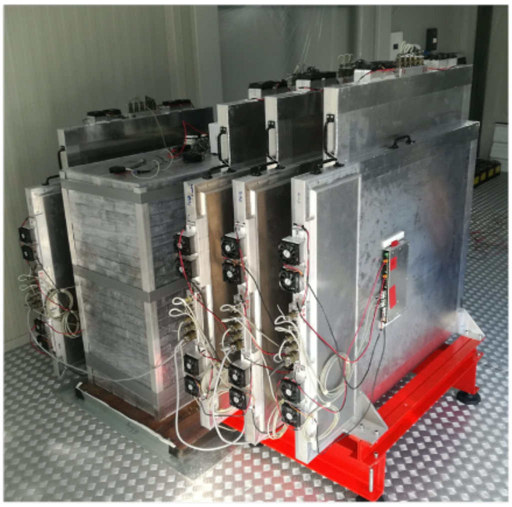

Figure 2. One of the three identical muon trackers with 1 m^2 active area

wall is interposed between the 3rd and the 4th plane doublet along the muon trajectory. Figure 2 shows one of such muon trackers. The power consumption of each muon tracker is 30 W.

2.2. Readout and data acquisition

The light signals are detected by Silicon photomultipliers (SiPMs). The 32 SiPMs of a module are hosted on a printed circuit, where they are coupled to the WLS fibers. Being solid-state devices, SiPMs do not require H.V. supply and have a minimal power consumption. This is the main motivation for their choice as photodetectors in an experimental apparatus to be operated in the absence of standard electricity supply.
However, as solid state devices the SiPMs' functioning is affected by temperature. At Mt. Vesuvius temperature and humidity have strong variations during the day, from day to day and seasonally. In MURAVES, temperature control is achieved by a system based on Peltier cells directly cooling or heating the photosensors. Two Peltier cells are allocated in each printed circuit hosting 32 SiPMs, with a copper strip to improve thermal exchanges between Peltier cells and SiPMs and with a couple of fans for ventilation.
The printed circuit with the 32 SiPMs is connected to a board containing the front end electronics for 32 channels (FEE board). Each FEE board is equipped by a dedicated ASIC, the OMEGA EASIROC chip [4], which amplifies, discriminates and ADC converts the signals. It also provides a fast signal for the trigger logic, as well as the bias voltages for the SiPMs. The FEE board also hosts a high resolution TDC for the measurement of the time-of-flight (ToF) with a resolution of the order of 0.1 ns [5], to reject those particles which mimic a muons crossing the mount but coming from to the opposite direction.
The data acquisition system is based on a Master-Slave architecture. Each muon tracker consists of 4x2x2 modules equipped by the respective FEE boards, which play the role of Slaves. A single Master board manages the 16 FEE boards of a muon tracker, defining the trigger logic in a programmable way and controlling data acquisition and storage by means of a custom-programmed FPGA coupled to a stand-alone Raspberry Pi computer.

3. *In situ* installation

The MURAVES apparatus has been installed at 600 m a.s.l. on the South-West slope of Mt. Vesuvius, which has a maximum altitude of about 1270 m a.s.l. (Figure 3). The apparatus is

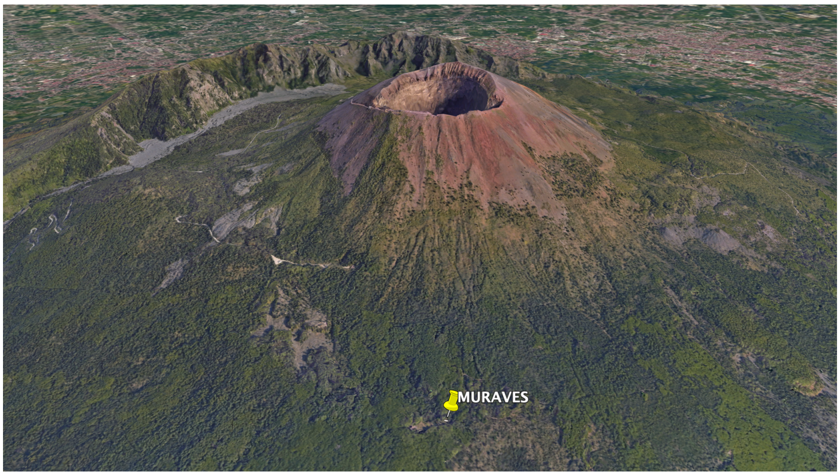

Figure 3. The South-West slope of Mt. Vesuvius, with the MURAVES location at 600 m a.s.l.

hosted by a 45 m^2 container. An array of solar panels on the roof of the container supplies power to the experimental apparatus and charges a system of batteries that intervenes during night time and in days when insufficient energy is received from the Sun.

4. Simulation and data analysis

The transmission of muons through the volcano depends above all on their energy loss in the matter which is traversed, hence on its thickness and average density. For a given direction of the line of sight, only muons above a certain energy have some chance to survive. The upper plot in figure 4 shows the angular map of the thickness of rock that is traversed by muons, as evaluated using the TURTLE tool [6], provided a Digital Elevation Model (DEM) of the volcano [7]. The extended structure of smaller thickness corresponds to the concentric ridge remaining from the edifice of a larger and higher volcano that existed before the formation of Mt. Vesuvius. The ridge, now called Mt. Somma, is visible in figure 3 behind Mt Vesuvius.
The expected muon flux through the volcano was evaluated using the PUMAS program [8], a particle transport code based on a backward Monte Carlo, which allows exclusive sampling of final states by reversing the simulation flow. The modified Gaisser's formula [9] was used to describe the muon flux at sea level.
The information about the internal structure of the volcano comes from the angular map of the muon transmission. The muon transmission is referred to calibration data, taken with muon trackers pointing to free sky in the opposite direction. The ratio, called relative transmission, is independent of detector efficiency and acceptance. Calibration data are systematically taken, using a dedicated Lead wall, installed in the container. For calibration only the active elements of the muon trackers are moved and installed in an identical, turned around configuration.
Figure 5 shows very preliminary results from a sample of data corresponding to about 50 days of analyzed data taken with one muon tracker. The plots have a $0.33° \times 0.33°$ angular binning. The measured muon flux agrees with expectation.

5. Conclusions

The MURAVES experimental apparatus has been installed at 600 a.s.l. on the South-West slope of Mt. Vesuvius and is taking data. Preliminary results from a small sample of data show a muon flux in agreement with expectation.

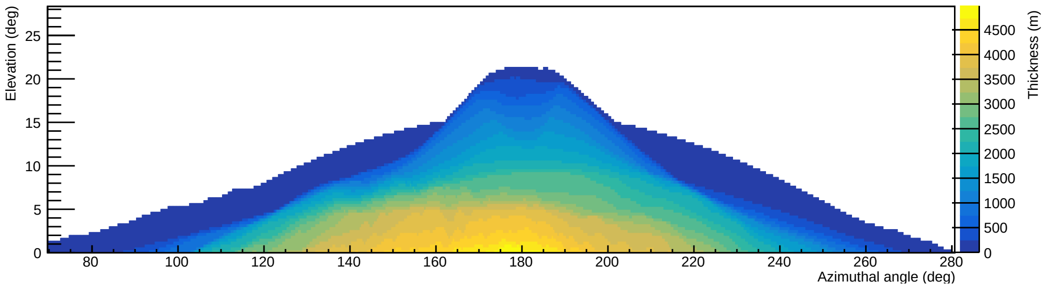

Figure 4. Thickness of rock traversed by muons, as a function of the azimuthal angle with respect to the muon telescope orientation and of the elevation angle from the location of MURAVES.

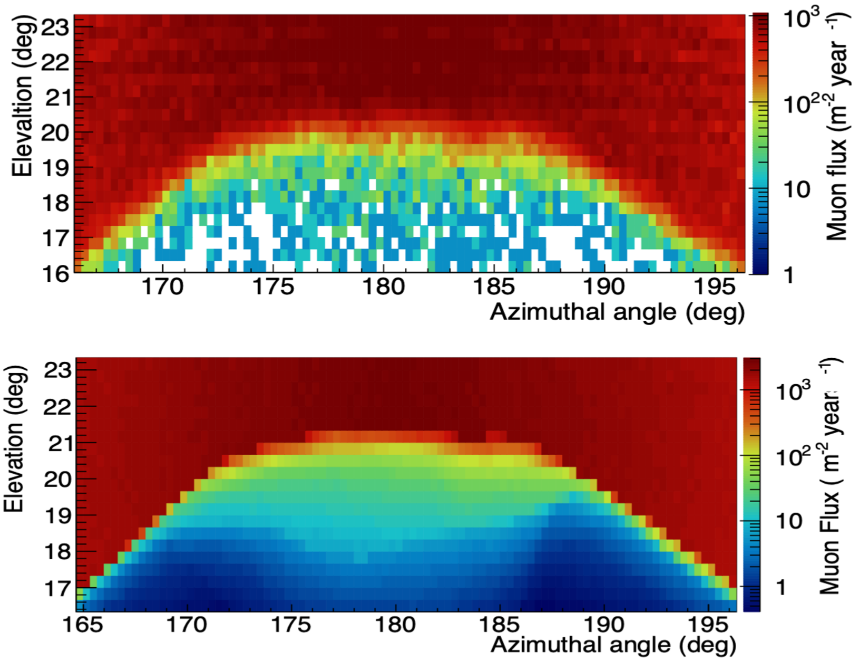

Figure 5. Measured (top) and expected (bottom) muon flux from the preliminary analysis of a sample of data corresponding to about 50 days of analyzed data from a single muon tracker.

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