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Volcanoes in Italy and the role of muon radiography

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Cosmic-ray muon radiography (muography), an imaging technique that can provide measurements of rock densities within the top few 100 m of a volcanic cone, has now achieved a spatial resolution of the order of 10 m in optimal detection conditions. Muography provides images of the top region of a volcano edifice with a resolution that is considerably better than that typically achieved with other conventional methods (i.e. gravimetric). We expect such precise measurements, to provide us with information on anomalies in the rock density distribution, which can be affected by dense lava conduits, low-density magma supply paths or the compression with the depth of the overlying soil. The MUon RAdiography of VESuvius (MURAVES) project is now in its final phase of construction and deployment. Up to four muon hodoscopes, each with a surface of roughly 1 m², will be installed on the

slope of Vesuvius and take data for at least 12 months. We will use the muographic profiles, combined with data from gravimetric and seismic measurement campaigns, to determine the stratigraphy of the lava plug at the bottom of the Vesuvius crater, in order to infer potential eruption pathways. While the MURAVES project unfolds, others are using emulsion detectors on Stromboli to study the lava conduits at the top of the volcano. These measurements are ongoing: they have completed two measurement campaigns and are now performing the first data analysis.

This article is part of the Theo Murphy meeting issue 'Cosmic-ray muography'.

1. Introduction

Italy is one of the most active volcanic regions of Europe. The peninsula sits on top of the point where the Eurasian Plate meets the African Plate and suffers from considerable seismic and volcanic activity. There are four very active volcanoes in Italy (Etna, Stromboli, Vulcano and Vesuvius). We plan to use muography to glean further insights into the workings of two of these volcanoes, namely Vesuvius and Stromboli. The former is famous for the destruction of Pompeii and Herculaneum in the eruption in 79 AD and is now in the middle of the sprawling urban development that has characterized the city of Naples in the past 100 years.

It is, in fact, impossible to underestimate the disaster potential of this situation. Vesuvius has erupted many times since and is the only volcano on the European mainland to have erupted within the last 100 years. Today, it is regarded as one of the most dangerous volcanoes in the world because of the population of 3000 000 people living nearby (figure 1), making it the most densely populated volcanic region in the world, and its tendency towards violent, explosive eruptions of the Plinian type.

The specific areas actually affected by the ash cloud depend upon the particular circumstances surrounding the eruption and, probably, the volcanic plug conformation. The evacuation plan (http://www.protezionecivile.gov.it/jcms/it/view_pde.wp?contentId=PDE12771) put in place by the Italian 'Protezione Civile' assumes between two weeks and 20 days notice of an eruption and foresees the emergency evacuation of 600 000 people, almost entirely comprising all those living in the 'zona rossa' (red zone), i.e. at greatest risk from pyroclastic flows.

In 2012, we submitted to the Italian Ministry of Research a proposal for a muographic and gravimetric measurements campaign on Vesuvius with the purpose of better defining the volcanic plug at the bottom of the crater that is currently sealing the magma ducts from the caldera below. The Ministry approved the proposal, named the MUon RAdiography of VESuvius (MURAVES), and allocated funds (of approximately 800 KEuros) in 2015 (Progetto Premiale decreto MIUR n. 949/ric del 19.12.2012, CUP D54G14000110001).

MURAVES involves physics researchers, geologists and volcanologists from Istituto Nazionale di Geofisica e Vulcanologia (INGV), Istituto Nazionale di Fisica Nucleare (INFN), the University of Florence and the University of Naples. The project is now in its final installation phase and should start taking the first muographic data at the end of 2018. These data, used in combination with the planned gravimetric and seismic measurements, should allow our team to obtain a high-resolution image (10 m voxels or better) of the Vesuvius crater and surrounding rocks.

The seed for the MURAVES [1] project was the development, with funding received from INFN, of an innovative plastic scintillator detector (MU-RAY [2,3]) with a 1 m² surface that has been used as a prototype for technology assessment and also as a muography instrument in short data taking campaigns (i.e. Vesuvius and Mt. Echia (Naples)).

Colleagues from Naples University have also maintained an emulsion plate computer controlled optical scanner, first used for the OPERA [4] experiment, which is now used to analyse emulsions stacks placed on the slopes of Stromboli (figure 2) [5]. The first results of the data analysis will probably be available before the end of the year.

Figure 1. Vesuvius volcano seen from the sea, surrounded by the metropolitan area of Naples. Image courtesy of Massimo Finizio (from Wikimedia Commons, the free media repository). (Online version in colour.)

Figure 2. (a) An emulsion stack placed on the slope of Stromboli, during one of the frequent eruptions (b). (Online version in colour.)

In the following sections we will provide a description of and status update on the MURAVES project, with a look at muon flux expectations and the imaging capabilities versus the length of the data-taking period.

2. The MURAVES detector

The MURAVES project consists of three 1 m^2 muon hodoscopes that will be housed in containers on the slope of Vesuvius. Each hodoscope (figure 3) consists of four XY layers, with the central

Figure 3. Conceptual schematic of one of three MURAVES hodoscopes. There are four XY tracking layers (1 m^2 surface area) with a 60 cm thick lead block between the third and fourth layers. The lead block is used for muon energy discrimination, necessary to reduce background (see §3).

Figure 4. (a) Each scintillator bar has a triangular shape and a white oxide outer coating. A wave length shifting (WLS) fibre is run through the middle of each scintillator. (b) The 32 bars are glued together in a half-plane section roughly 50 cm wide. (c) A centre-of-mass algorithm is used to reconstruct the muon coordinate from the amount of light collected by two contiguous scintillators. (Online version in colour.)

axis aligned towards the middle of the crater, and with an angular coverage extending from 100 m below the bottom of the crater up to the topmost rim.

The MURAVES detector is based on a design developed for the MU-RAY prototype. The MU-RAY hodoscope consists of three pairs of tracking planes measuring XY coordinates. Each plane (for MURAVES as for MU-RAY) is assembled using triangular scintillating bars (figure 4) with 1 mm diameter optical fibres running inside along their axis. With this design, we have achieved a spatial resolution of about 3 mm (with 33 mm wide bars), using a weighted average of the signal given by two adjacent bars (figure 4c).

The optical fibres are read-out by Silicon Photo-Multipliers (SiPMs) housed on dedicated circuits (figure 5). The device used is a 1.2 mm diameter device (1.13 mm^2 active area) circular SiPM in a plastic chip scale package, with relatively large cells ($40\text{ }\mu\text{m}$) optimized for the visible spectrum (ASD-RGB1C-P). The device is completely covered with a transparent epoxy layer and is sold by AdvanSiD (previously FBK).

The SiPMs are glued on a custom flex PCB hybrid (figure 5b). Each hybrid hosts 32 SiPMs, two temperature probes and one humidity sensor. The SiPMs are precision-aligned and exactly match the 32 wave length shifting (WLS) fibres belonging to the optical connector from a half plane. The hybrids also provide an air and light tight seal for the half plane.

Figure 5. (a) The circular-shaped SiPM used in the MU-RAY prototype. The first versions were wire-bonded. Current devices are glued with conducting glue to the hybrids shown in (b). Each hybrid houses 32 SiPMs and reads out the fibres from a half-plane section. The hybrid lower section houses connectors, temperature and humidity probes. (Online version in colour.)

Figure 6. (a) Two MURAVES half-planes that are having the WLS glued inside. (b(i)) A stack of half-planes ready for assembly into complete layers. (b(ii)) Final checks on a fully assembled layer. The read-out electronics are placed just at the outside, on top of the scintillator assembly. (c) One complete hodoscope undergoing tests in Naples. (Online version in colour.)

Two half-planes are glued together to form a complete hodoscope layer (figure 6). A complete layer provides only one coordinate read-out, so two of them are coupled in a self-supporting structure that only weighs ~ 35 kg, including floor pads and reinforcement braces.

The electronic read-out uses a Master-Slave architecture (figure 7) consisting of two Slave boards for each layer (64 SiPM channels) and one Master board capable of handling up to 32 Slaves, and which provides data formatting and storage, data transmission and the particle trigger to the hodoscope.

The Slaves are built around an ESIROC [6] chip developed by LAL specifically for use with SiPMs, while the Master uses a custom-programmed FPGA coupled to a stand-alone RASBERRY micro-controller. The power budget of the whole system is roughly 3 W per Slave and 5 W for the Master.

Each SiPM hybrid is serviced by one Slave and the electrical connections between the two are made with micro-ribbon coaxial cables. Each Slave provides biasing of the SiPMs, amplification, discrimination and ADC conversion of the signals. The slaves are daisy-chained and read-out by the Master. The maximum sustainable trigger frequency is ~ 1 KHz. This set-up was developed specifically for our first prototype (MU-RAY), and apart from minor improvements, has not been changed for the MURAVES project. In fact, we have already produced and tested 48 Slave boards (plus spares) for the Vesuvius hodoscopes and the Master boards.

In addition, there is a Slow Control Unit that takes care of temperature and humidity readings. This unit also drives a highly efficient Peltier cooling system developed by us (figure 8) that allows us to operate the hodoscopes even during the hottest days by keeping the SiPM temperatures at manageable levels. For this purpose, our SiPM hybrid has many thermal vias that connect

Figure 7. (a) A MURAVES slave board while under debugging. The Master board in (b) has individual connectors for trigger purposes, while data are shifted in through a daisy-chain connection to the slaves. (Online version in colour.)

Figure 8. The MURAVES Peltier cooling system. (a) The SiPM hybrid is held against a copper diffuser to which two Peltier cells are attached. The hot sides are cooled with standard aluminium CPU cooler. The controller (b) can either cool or heat the hybrid while monitoring temperature and humidity. (Online version in colour.)

the electrical top (where the SiPMs are laced) to a gold-plated bottom copper pad. A copper diffuser (figure 8a) further ensures an optimal heat exchange between the SiPMs and the Peltier elements. The various elements are kept together thanks to a three-dimensional printed plastic holder, which is fixed to the scintillator plane.

The Peltier elements are controlled through a custom circuit developed by us that uses Pulse Width Modulation drivers to pilot the Thermal Electric Coolers with maximum efficiency. The board connects to the outside world with USB and CAN Bus; temperature regulation uses NTC elements soldered on the SiPM hybrids. We have achieved up to 20°C temperature differences with the outside world, with 0.1°C stability.

We estimate that at full cooling power, our Peltier system will use only an additional 15–20 W (including heat exchanger ventilation) per layer, and much less or nothing at all at other times. Figure 9 shows the hybrid's thermal vias and a complete cooling assembly mounted on a layer mock-up.

The hodoscope structure, consisting of various XY layers, is shown in figure 10. Each of these layers is self-supporting and is completely free from the others. This allows a great freedom in the setting up of the muon hodoscope. At the time of press, all X(Y) layers are ready in our laboratories in Naples waiting for deployment on Vesuvius. In the following sections we will describe the installation and expected performances.

Figure 9. (a) Drawing of a section of the SiPM hybrid showing the great number of thermal vias connecting the top and bottom layers. (b) The cooling unit assembled on a mock-up of a scintillator layer. (Online version in colour.)

Figure 10. (a) Drawing of a three XY layer hodoscope. Each XY layer is an independent self-supporting unit allowing great flexibility in the hodoscope configuration. (b) One of the scintillator planes with its cover removed showing the slave boards attached to the hybrids. (c) An XY layer standing on the floor with its support pads/feet. (Online version in colour.)

3. The Vesuvius setting

The initial aim of the MURAVES project was to install the hodoscopes in one of four possible locations. A lot of effort has gone into determining the best possible site given the logistics, ease of access, and achievable imaging performance.

There were only a few initial locations with a sufficiently low enough altitude to allow the imaging of the bottom of the crater (albeit with a long data-taking period), and one of these was Casina di Amelia (posizione Nord 600 m in figure 11). Although there is no electricity available, in the end we chose this site for deployment because of the nice gated road leading to the site that can only be accessed by the authorities of the Ente Parco Nazionale del Vesuvio, and also because this site has the most favourable signal-to-background ratio. This background derives from low-energy scattered muons [7] which have lost their original direction. They are scattered mainly in the topmost soil and arrive in massive numbers on the detector.

The lead walls used in the MURAVES hodoscopes will act as ‘minimum muon energy’ selectors, with a turn-on point of ~ 1 GeV. In fact, our final deployment will consist of four (not three) XY layers, with the fourth layer sitting behind a 60 cm thick lead wall (figure 12) used as an antiveto counter. We plan to install three 1 m^2 muon hodoscopes inside the containers (figure 13). A fourth slot (with its accompanying lead block) will be used for special calibration runs with the hodoscopes pointing away from Vesuvius towards the open sky.

As there are no electrical mains available on site, we are installing solar panels on the container roofs with back-up batteries to ensure 24 h continuous operation.

The first engineering work finally started in June this year with the placing of the concrete supports for the five ton lead walls. Once this work is finished, the containers will be placed in

Figure 11. Aerial view of Vesuvius with markers indicating possible observation sites. (Online version in colour.)

Figure 12. Installation plan for a single hodoscope consisting of four XY layers (green rectangles) and one 60 cm thick lead block (grey). Distances between the various elements are detailed in the table on the right. The detection layers will be offset from each other to point at 9.2° above the horizon. In this way, the angular coverage will extend up to 1300 m in altitude, above the crater rim. (Online version in colour.)

the designated positions, after which the solar panel installation will begin (figure 14). In October, we should have the first data from the three hodoscopes relayed to us by the INGV radio bridges. In the meantime, we are continuing simulations to estimate data-taking rates and sensitivity (see the next section).

Figure 13. Technical drawing of the containers that will be deployed around the lead walls. In one of the containers (second from left) the lead wall is placed at the opposite end for the calibration runs (see text).

Figure 14. Technical rendering of the containers superimposed on the photo of the Casina di Amelia site. The solar panels will be installed on the roofs of the containers. (Online version in colour.)

Figure 15. (a) Aerial view of Vesuvius with Mt. Somma in the background. In (b), the elevation map in metres corresponding to the photo. (Online version in colour.)

Figure 16. Expected muon transmission as a function of elevation and azimuth. White regions are where the transmission falls below 10^{-4} as the traversed rock thickness increases. The crater region extends to 15° in elevation. (Online version in colour.)

4. Expected performance

When considering the muography of Vesuvius one cannot ignore the backdrop of Mt. Somma, which was the original volcano in whose caldera Vesuvius developed (figure 15).

This effectively constitutes an additional rock shield that further decreases the muon flux penalizing data-taking. From the digital terrain models, we have produced a map of the various traversed thicknesses as a function of elevation and azimuth angles (figure 16). The muon energy spectrum used for this estimate was taken from the paper by Tanaka *et al.* [8], but we have developed our own muon spectrum generator (with flux dependence on energy and angle) using data collected by the ADAMO experiment [9].

We have also derived sensitivity estimates to density variations as a function of years of data-taking (figure 17). For a given density variation, the indicator gives the significance of the eventual signal expressed as a number of sigmas (using Poisson statistics).

The plots show the level of significance we can reach in terms of a minimal density variation of only 5%. We expect much greater density variations in the crater region, due to not only the empty space inside the crater, but also to the solid rock plug. In fact, recent gravimetric measurements seem to indicate the presence of a high-density layer of rock at the bottom of the crater.

Figure 17. Significance (coloured scale) of the observed muon count variation (Poisson statistics) for a 5% density variation as a function of the observation angle, after (a) two-year and (b) four-year data-taking. Below a certain elevation, due to the huge rock overburden, no discernible signal can be extracted. In the crater region (above 15°), the significant increases and more detail can be extracted in the imaging process. (Online version in colour.)

5. Conclusion

The MURAVES project is now nearing final installation, with data-taking to begin in October 2018. For the first time, a muographic imaging of the Vesuvius crater and its underlying solid plug will be performed. Our data will be combined with gravimetric and seismic measurements taken by our INGV colleagues. After one year, we should already be capable of obtaining the first detailed images of the crater. The project has required advanced detector development with respect to detector maintenance, reliability and power consumption. The project was awarded special funding from the Italian Ministry (MIUR) in recognition of its importance to volcanology, and the soundness and quality of its science.

Data accessibility. This article has no additional data.

Authors' contributions. R.D.'A., G.S., G.M. and L.B. are the main proponents and coordinators of the MURAVES project. F.A., G.B., L.B., M.B., V.C., M.D.'E., S.G., N.M., P.N. and L.V. are involved in the simulations and development of data analysis algorithms. R.C., L.C., R.D.'A., V.M., B.M., P.P., G.S. and L.S. are all involved in the design, development, construction and testing of the muon hodoscopes for the MURAVES project. A.C., F.G., G.M., M.O., R.P. and E.V. of the Osservatorio Vesuviano are responsible for site installation, infrastructure, and for the future gravimetric/seismic measurement campaigns and geophysical data analysis. P.S. is our main science consultant with infinite experience in particle physics and muon radiography. All authors read and approved the manuscript.

Competing interests. The authors declare that they have no competing interests.

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