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Density imaging of volcanos with atmospheric muons

Felix Fehr, for the TOMUVOL Collaboration[*]

Clermont Université, Université Blaise Pascal, CNRS/IN2P3, Laboratoire de Physique
Corpusculaire, BP 10448, 63000 Clermont-Ferrand, France, [*]http://www.tomuvol.fr

E-mail: `fehr@clermont.in2p3.fr`

Abstract. Their long range in matter renders high-energy atmospheric muons a unique probe for geophysical explorations, permitting the cartography of density distributions which can reveal spatial and possibly also temporal variations in extended geological structures. A Collaboration between volcanologists and (astro-)particle physicists, TOMUVOL, was formed in 2009 to study tomographic muon imaging of volcanos with high-resolution tracking detectors. Here we discuss preparatory work towards muon tomography as well as the first flux measurements taken at the Puy de Dôme, an inactive lava dome volcano in the Massif Central.

1. The Puy de Dôme as a reference site for muon imaging

High-energy atmospheric muons have been considered for more than half a century as a natural probe for geophysical and archaeological prospection. As early as 1955, muon imaging techniques were used to estimate the snow overburden on a mountain tunnel [1] and shortly thereafter, in the early 1960s, to search for hidden chambers in Chepren's pyramid [2].

Recent developments in particle physics have resulted in scalable tracking detectors with very fine segmentation which facilitate the application of muon imaging to larger structures. This has stimulated an interdisciplinary collaboration between volcanologists and (astro-)particle physicists on the design of a robust, portable system for *muon tomography* of volcanos with the intention of computing a three-dimensional density model by combining the results of several muon absorption measurements around a volcano. In this way, muon imaging can contribute to the understanding of volcanic structures and might possibly also help in risk prevention.

Initiated in 2009, the TOMUVOL project aims to turn the Puy de Dôme, an inactive lava dome in the *Chaîne des Puys* [3] (Massif Central, France), into a reference site where muon tomography can be compared to and combined with gravimetric and electrical resistivity measurements. In the initial phase, muon flux measurements have been performed at a site on the flank of the Puy de Dôme and the data are now analyzed for a first radiographic image. The next phase is dedicated to taking a detailed three-dimensional map of the density distribution in the lava dome and to validate the results by comparing with gravimetric and electrical resistivity measurements. In the future, after improvement of the portability of the system, the same methodology might be applied to other targets.

Here we report on preparatory work and measurements taken at the Puy de Dôme in the initial phase of the project. In Section 2, the detection site and the experimental setup are described in some detail. Preliminary results of the first months of data taking are then presented in Section 3. Based on this, we assess the prospects of muon imaging in the concluding section.

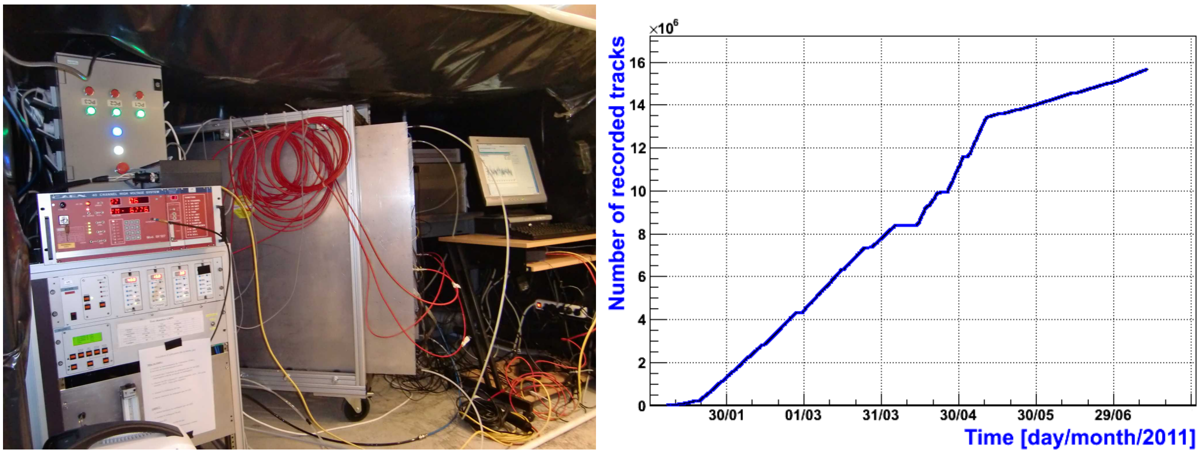

Figure 1. **a)** The detection setup at the Puy de Dôme. From left to right: (remote-)control station, HV supply and gas distribution system, GRPC detector and acquisition PC. **b)** Number of recorded muon tracks from January to July 2011 with three different detector configurations.

2. Muon detector and data taking at the Puy de Dôme

The Puy de Dôme (alt. 1464 m a.s.l.) is of volcanic origin and was formed some 11,000 years ago [4]. It has a remarkable structure with two domes originating from two subsequent eruptions, which occurred within a short time interval. For the first radiographic measurements, a muon detector (see Fig. 1a) has been installed 600 m below the summit at a distance of 2 km. The detector has been deployed underground in a basement to reduce the impact of low-energy background.

The Tomuvol Collaboration has opted for a muon detector based on (at least) three parallel planes of Glass Resistive Plate Chambers (GRPCs) [5] which afford good resolution, low noise, robustness, portability, and scalability at moderate cost. A single chamber consists of two parallel thin glass plates kept at a distance of about 1 mm using tiny ceramic balls as spacers so that gas can circulate between the plates. The outer sides of the glass plates are coated with a thin layer of highly resistive material on which high voltage, typically 7 kV, is applied. A thin Mylar layer serves as insulation between the anode and a layer of copper pads of 1 cm^2 size assembled on one face of a Printed Circuit Board (PCB) of 50.0×33.3 cm^2. On the other face of the PCB are attached the readout ASICs, named Hardroc2 [6]. In total 48 Hardroc2 ASICs are connected on one PCB, each of them handling 8×8 pads. A full square meter chamber consists then of three slabs, each with two PCBs, having in total 9142 readout channels. The chambers are embedded in steel cassettes and are vertically mounted onto a movable aluminum support framework.

A mixture of forane (93%), isobutane (5%) and SF6 (2%) is streamed at about 1 liter/h through the chambers by a gas distribution system. Charged particles, passing through the chambers, ionize the gas and produce charge cascades, which in turn induce charge signals on the copper pads. In its standard configuration, the detector is operated in avalanche mode with high voltage adapted to environmental pressure and temperature conditions.

For the data readout, Field Programmable Gate Arrays (FPGAs) implemented on the detection slabs are connected through their USB interface to a desktop computer. Three independent comparators in the readout electronics provide amplitude information. In the data-taking mode, the ASICs buffer every signal above threshold and send the recorded data upon arrival of a trigger signal generated at 10 Hz to the PC on which data acquisition and monitoring software are running. Run control and monitoring software have been customized

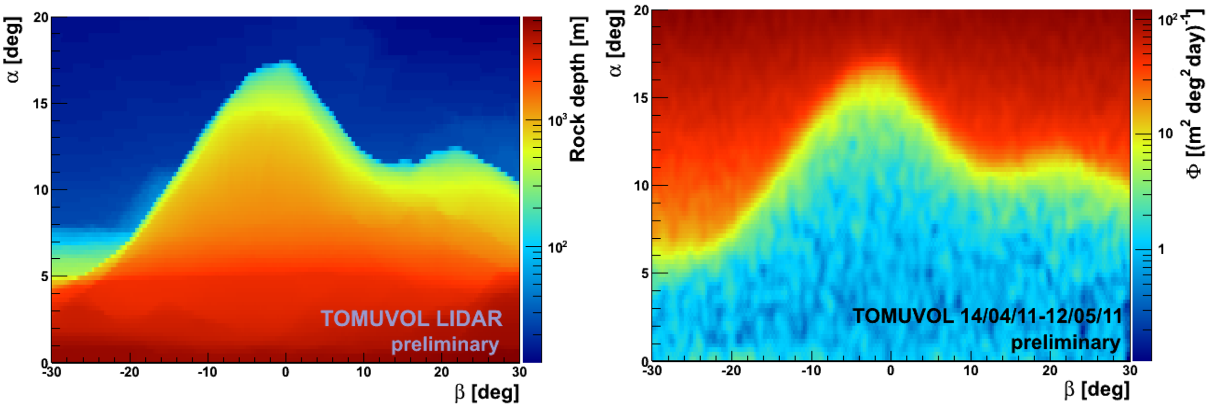

Figure 2. a) Material in front of the detector, evaluated from the LiDAR survey. **b)** The first flux measurements (here an example corresponding to 18.0 days of data taking with a 1 m^2 detector) show the shadow cast in the atmospheric muon flux by the Puy de Dôme.

for the experiment based on the cross-platform acquisition framework XDAQ. The whole setup is controlled remotely through a long-range WIFI network. This link is also used to transfer the recorded data to a central server. A video camera surveys the installation continuously.

To protect the electronics against moisture, the detector has been installed under a polyethylene foil tent. Additionally, a dehumidifier ventilates dry air under the tent. Temperature, pressure and humidity values are recorded continuously and written into a database.

From January to July 2011 about 16 million muon tracks (see Fig. 1b) from the entire sky have been recorded with three different detector configurations operated continuously with only a few short interruptions for detector maintenance and systematic tests. The initial setup consisted of two 1 m^2 chambers supplemented by a third chamber of 1/6 m^2 size (at a distance of 58 cm to the first chamber). After April 6th, the detector support framework was upgraded and a third 1 m^2 chamber replaced the small chamber until May 12th. The longitudinal extension of the detector corresponded to 85 cm (92 cm) during the second (third) data taking period.

Accurate topographical data are required to compute density images. In March 2011 the Puy de Dôme and its surroundings were therefore mapped precisely with an airborne LiDAR. In this way, a digital elevation model with an overall precision of better than 10 cm on a 0.5 m grid has been recorded. From this model, the material in front of the detector (see Fig. 2a) has been inferred. To exploit the available precision, the muon detector has been carefully aligned with respect to the volcano. For this purpose, GPS based position measurements of the local surroundings have been made. Reference points in the basement have been fixed by tachymetric measurements through the skylights of the basement. Finally the detection planes were positioned with respect to these points. Additionally, the alignment of the detection planes has been checked with the help of recorded muon tracks. To this end, the sum of the individual track χ^2s is minimized by varying the alignment parameters. Even if the procedure is limited as the track χ^2 remains invariant under global rescaling of the coordinate axes, it nevertheless provides an important crosscheck of the detector alignment.

In June 2011, first electrical resistivity profiles were measured with a multi-electrode chain deployed on the volcano. For 2012, gravimetric measurements are planned in addition. These two complementary methods will be useful for the validation of muon tomography.

3. Track reconstruction and first flux measurements

The reconstruction algorithm preselects track candidates by considering straight lines between all possible hit combinations in the outermost detection planes in a common time window of 0.4 μs. These candidates are then filtered by requiring a matching hit in the central plane within 3 cm. For each candidate, hits in a corridor of 3 cm are merged into clusters on each plane. The final track is then obtained analytically based on the method of least squares. After removal of the selected clusters, the procedure is iterated to reconstruct possible bundles of tracks passing the detector simultaneously. Overall, a position resolution of 0.4 cm and an angular resolution of 0.5 deg in both altitude α and azimuth β are achieved with the initial setup. For the extended configurations (of $85 - 92$ cm length), the angular resolution is about twice as good.

After the alignment procedure described above, the arrival directions of the recorded muon tracks are transformed into a global coordinate system whose y-axis ($\beta = 0°$) points towards the summit of the volcano. Figure 2b presents the shadow cast in the flux of atmospheric muons by the Puy de Dôme in this coordinate system. For the flux measurement the measured event rates have been divided by the detector acceptance evaluated with a ray-tracing simulation. A smoothing algorithm has been applied to the recorded map in order to reduce artificial bands (Moiré-patterns) typical of digital images. Due to the short exposure time of the dataset, the significance of the measurement is statistically limited to regions close to the surface. The observed shape of the shadow is in good agreement with the actual outline of the volcano. Also, the measured open sky flux is in qualitative agreement with a simplified simulation [7] (assuming an homogeneous density distribution), which confirms that the Puy de Dôme will be accessible for muon imaging with a 1 m^2 detector. To improve the sensitivity at greater depths, an additional detection plane might however be needed for the removal of remaining track-like background. The full statistics accumulated until July 2011 is currently being analyzed in order to extract the first radiographic density distribution.

4. Conclusions and outlook

The TOMUVOL Collaboration explores tomographic imaging of volcanos with atmospheric muons. For this purpose, a GRPC based detector was installed at the flank of the Puy de Dôme in January 2011. Preparatory work for the computation of a tomographic density map, including a precise topographical LiDAR survey of the volcano, have been performed, and the detector has been carefully positioned with respect to the volcano. Algorithms for track reconstruction, detector alignment and density analysis have been developed and are now applied to first data.

The detector is shortly going to be relocated to several more places around the volcano in order to realize a complete, three-dimensional density map. In parallel, comparisons with gravimetric and electrical resistivity tomographies will be made. Moreover, technical improvements are on the way to enhance the mobility of the detection setup; this should also facilitate future applications to possibly active volcanos under even more challenging environmental conditions.

From the first data and the performed simulation, we can conclude that muon imaging proves to be a promising technique with interesting applications in the near future.

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