



Volcano radiography with GRPCs

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The Tomuvol collaboration aims to develop a high resolution, robust and low power consumption muon tracker in order to perform density imaging of volcanoes using atmospheric muons. The technology used originates from the R&D of the Calice collaboration, which is developing imaging calorimeters for ILC. Here we present the design of the Tomuvol detector as well as the encouraging results of the preliminary measurement campaigns.

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1. Introduction

Thanks to their long range in matter and their broad energy spectrum, atmospheric muons are well suited to probe the density structure of massive objects with size ranging from tens to thousands of meters. The idea to apply this technique, which is very similar to medical radiography, on volcanoes emerged in 1995[1]. 3D "tomographic" reconstructions are also possible whenever images from different viewpoints are available. The outreach is rather large, with applications from pure geophysical studies to hazard reduction through eruptions prediction.

The principle of this method is to install near the mountain a device capable of tracking muons and to count them as a function of their direction. A comparison of the flux measured behind the volcano with the open-sky flux then provides the integral density of rock that the muons encountered. A difficult step at this point is the inversion procedure, to go from flux attenuation to a density map. Ancillary geophysical measurements of the volcano topology are needed in order to constrain the problem. In the case of the monitoring of an active volcano, muography aims to help predicting eruptions patterns. Indeed, the volcano internal structure is known to undergo important modifications before an eruption, which should be visible in density measurements.

In this article, we will first expose the requirements for a detector used in volcano "muography", and we will focus afterwards on the design and the performances of the Tomuvol telescope. Then, the results obtained from one of the preliminary measurement campaigns held in 2011 and 2012 on the Puy de Dôme (a French dormant volcano) will be reported. These preliminary results, compatible with geophysical density measurements performed in parallel on the Puy de Dôme, are confirming the potential of the method.

2. Detector requirements for muon imaging of volcanoes

When operated in-situ, the telescope will typically be installed at a distance of the order of one kilometer from the volcano. To achieve a resolution on the target of the order of 10 m, the angular resolution of the detector must not exceed 10 mrad. Also, in order to be able to monitor volcanoes almost in real-time, a notable change in their structure should be detectable within a few days. This requires an important detection surface, since the flux of muons crossing the volcano decreases rapidly as we get closer to the horizontal. For example, the expected time-scales to observe one muon crossing the Puy de Dôme in a 1 deg^2 pixel and using an ideal 1 m^3 tracker are shown in figure 1. Furthermore, aside from real-time monitoring purposes, obtaining an accurate image of the base of the volcano, where it gets wider and the muon flux weaker, can take an impractically long time. But those deep zones are very interesting, since they are unattainable with other techniques used by geophysicists such as resistivity and gravimetry. The required observation time is inversely proportional to the active area of the detector, thus technologies offering a low price per unit surface are favored. In addition, for the same reasons as above, the efficiency should be kept high, and the detection dead time low.

On the other hand, to facilitate field deployment, in sometimes difficult environmental conditions, the detector has to be robust and autonomous, since it is likely that there will be little or no infrastructures close to active volcanoes. Thus, the power consumption should be kept as low as possible, so that the energy produced by few solar panels would suffice, and completely

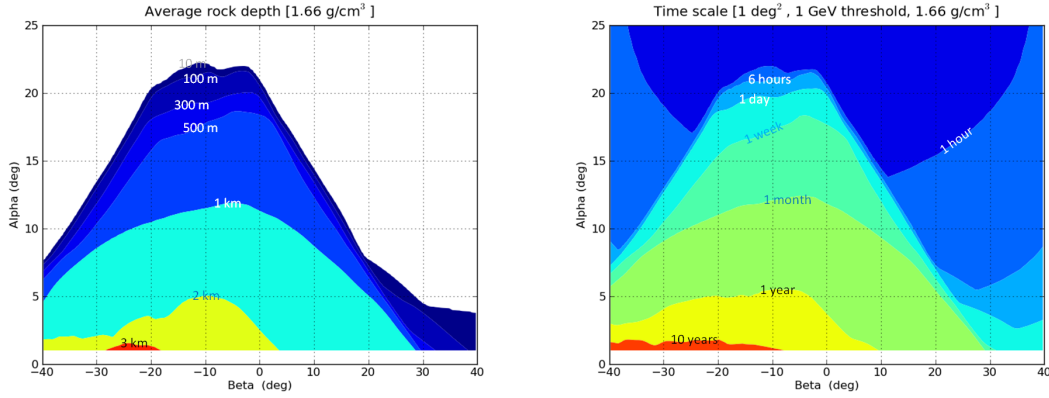


Figure 1: (left) Thickness of rock, as a function of the direction, of the Puy de Dôme. (right) Corresponding average time in order to observe one muon with a 1 m^2 detector in a 1 deg^2 pixel.

controllable from a remote location. Finally, reduced weight and easy assembly are appreciable, since, as it has been emphasized before, images from different sides of the volcano are needed for a three-dimensional imaging.

3. The Tomuvol detector design

The Tomuvol detector is made of four layers of Glass Resistive Plate Chambers (GRPC), 1 m^2 each, equally spaced apart with a 35 cm step. Each layer is divided into six smaller chambers of $50 \times 33 \text{ cm}^2$, which are mounted on an aluminium crate with 24 slots, as shown in figure 2. This allows for easy chamber maintenance and transportation, and accurate alignment features. These $1/6 \text{ m}^2$ GRPCs are an adaptation of the 1 m^2 chambers developed by the Calice collaboration for the semi-digital hadronic calorimeter of ILC[2, 3]. They are operated in avalanche mode, with a high voltage applied of $\sim 7 \text{ kV}$ at working point. The gas mixture used is 93% TFE, 5% isobutane, 2% SF₆, with a flux set for full renewal in each chamber every two hours. The charge avalanches created by ionizing particles in the 1.2 mm gas gap induce signals on a grid of 1 cm^2 copper pads on the anode. This makes a total of 1536 channels per chamber, that is nearly 40000 for the whole detector.

Each section of 8×8 pads is read by a "HARDROC2" ASIC [4]. These chips amplify the signal and can store up to 128 hits with charges above a configurable threshold. A "hit" contains the pad position, and a three-fold digital output corresponding to two additional and adjustable charge thresholds. The GRPCs themselves having a $\sim \text{ns}$ time resolution, the overall time resolution is given by the frequency of the clock, 5MHz, and a time stamp is associated with each hit accordingly. In each chamber, the twenty-four ASICs are read by a front-end board (DIF), developed by the LAPP/Annecy, which ensures the transmission of the data to the DAQ computer. All the DIFs receive the clock trigger signals from dedicated boards designed at LLR. When an ASIC has registered 128 hits, a signal is sent which triggers the reading of the whole detector, and during this period no data is registered : this constitutes the main source of dead-time.

Thirty $1/6 \text{ m}^2$ chambers have been produced in the beginning of 2013. For all of these chambers, the plateau value of the efficiency measured in the conditions specified above is better than 95%. The average median noise level is of the order of 1 Hz/cm^2 which, combined with our 5 MHz clock, allows for a negligible contamination of noise-induced fake tracks. In fact, the principal motivation for a low noise rate is the minimization of the dead-time. Thus, the optimal ASIC settings for the charge thresholds and the pads individual amplification gains are under investigation, and the noise level can be expected to improve.

Once the calibration and optimisation of the detector is finished, it will be deployed on the Puy de Dôme, and the first data taking are expected during autumn 2013. In the next sections, we will focus on the results of the preliminary measurement campaigns that were held using prototype GRPCs borrowed from the Calice collaboration.

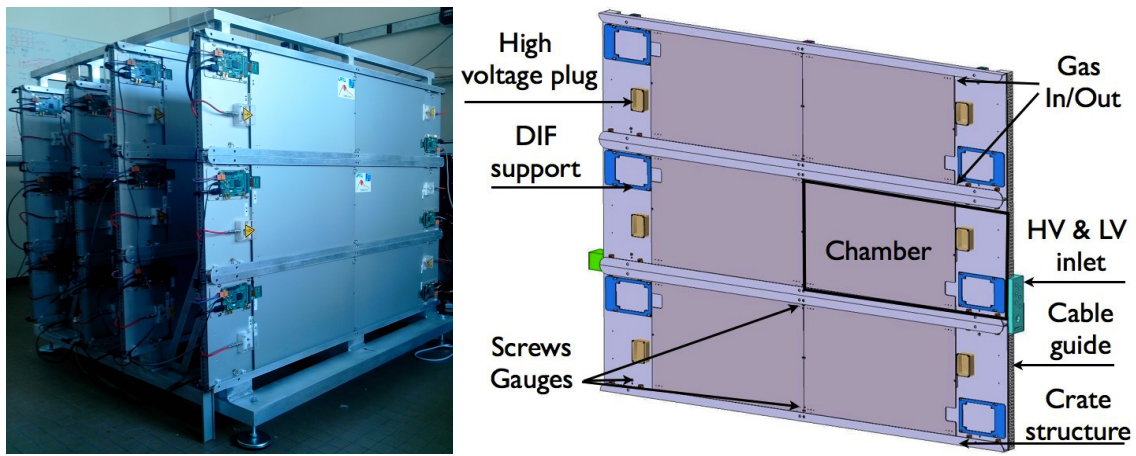


Figure 2: (left) Picture of the crate with twenty-four $1/6 \text{ m}^2$ chambers, fully wired, mounted on it. (right) Schematic view of a single 1 m^2 layer.

4. Preliminary measurement campaigns

Two measurement campaigns were held on Jan-Jul 2011 and Feb-Mar 2012 respectively. The first location, called "La Taillerie" is 2 km away from the summit, at the east of the volcano. The second one, namely "Col de Ceyssat" is located 1.2 km at the south, making a 107° angle with La Taillerie relative to the Puy de Dôme axis. The Col de Ceyssat offered relatively comfortable premises, the detector being hosted in an inn, with internet connection. On the other hand, La Taillerie campaign gave a foretaste of the harsher conditions that are expected on some experimental sites. In particular, the detector, stored in a cave, had to be protected against high ambient humidity.

5. Analysis of the Taillerie data

Overall, 16M tracks were recorded during the Taillerie campaign, despite the instability caused by the ad-hoc setup, made of prototype, borrowed equipment. The calculation of the misalignment (shifts and rotations) of the chambers and the determination of each chamber efficiency has been

performed at regular time intervals, using the tracks themselves. In particular, the alignment parameters were determined by minimizing the sum of all of the tracks chi-square values with respect to each degree of freedom. This procedure allowed to determine the relative positions of the chambers to a mm precision.

Once the misalignment effects are properly corrected, the first step in the analysis is to count the tracks as a function of their direction, which leads to the left part of figure 3. This raw counting is then corrected for the efficiencies of the chambers and the acceptance of the detector. This can be converted to a track rate map once the dead-time is accounted for. Then, after normalizing to the open sky flux and correcting for the rock depth for each line of sight, a density map is obtained. These last steps are the most critical, since they require a reliable model for the atmospheric muon flux at the experimental site as well as for the muons interaction in the volcano, and are still subject to investigations in our collaboration. Also, various sources of background such as backward nearly-horizontal muons, low-energy particles scattering near the detector, etc., must be understood and properly rejected in the analysis. Indeed, we observed that when looking at regions near the base of the mountain, where the rate of through-going muons is weak, an apparently uniform background becomes the dominant source of signal. Therefore, the plot shown in the right part of figure 3 is labeled with the arbitrary unit "opacity coefficient" instead of "density", to stress the fact that these results are not to be considered as reliable absolute density values, and in the bottom part the values indicated are biased by the dominant background tracks. On the other hand, the value of "opacity coefficient" at the zone near the summit, relative to the rest of the upper part of the volcano, clearly indicates a denser core in this region.

In parallel with the muon measurement, gravimetry measurements were performed on the Puy de Dôme. In [5], the results obtained with this standard, well-established geophysical method, are compared with the muon results presented here. It appears that the two methods are in agreement with the presence of this dense core near the top. Furthermore, it can be seen that the muon technique yields an image with a far better resolution, and, provided that the background can be well rejected, can image the volcano at deeper levels toward its base.

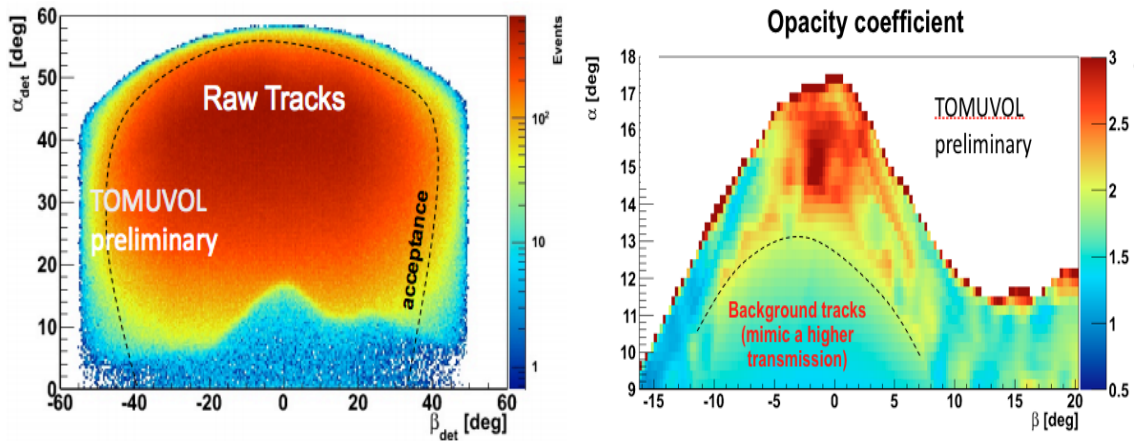


Figure 3: (left) Raw counting of the tracks, as a function of the vertical and horizontal angles, recorded at La Taillirie. (right) "Opacity coefficient map", as obtained with the data from the Taillirie campaign.

6. Conclusion

The results obtained during the preliminary campaigns have confirmed the potential of the muon radiography of volcanoes, and allowed us to define a good muon telescope, adapting the GRPCs developed by Calice to our purposes. The first data taking with this new apparatus is scheduled soon, and, with the knowledge acquired during the preliminary campaigns and an optimized detector, an accurate image of the Puy de Dôme inner structure is expected within one year.

Acknowledgments

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