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Use of horizontal cosmic muons to study density distribution variations in the Popocatepetl volcano

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Abstract: The use of muon-attenuation imaging, coupled with geophysical information, is proposed to investigate the internal density distribution of the Popocatepetl, an active volcano located some 70 Km south-east of Mexico City. This, and other active volcanoes such as the Colima, are currently being studied using conventional geophysical techniques. Our aim is to add important new information, including the volcano chimney's dimensions and structure, as well as monitoring possible changes in the dome and magmatic conduit system. Hopefully, this would become part of the Mexican long-term volcanic hazard-monitoring system. Muon radiography, as the technique is colloquially termed, is an innovative method which is still in its development stage. It can be used to determine the average density along the muon tracks, as well as the density distribution of large volumes by identifying patterns in the muonic flux attenuation distribution. Concerning the detection system, here we show how the muon-telescope dimensions are mostly depend on the volume size to be investigated, as well as on the image-taking frequency required to detect given dynamic density variations. Based on simulations, a detector prototype design is proposed, which includes data processing systems (acquisition, transfer, analysis, etc.) .

Keywords: cosmic rays, muon radiography.

1 Introduction

The Popocatepetl is an active, 5452 m a.s.l. height, andesitic stratovolcano, which is part of the Trans-Mexican volcanic arc. Its current activity phase (initiated in December 1994) included the emplacement of a series of dacitic lava domes, which were destroyed by frequent explosions involving pyroclastic flow eruptions with scoria and ash emissions. Its proximity to Mexico City, one of the more densely populated areas worldwide, represents a risk deserving careful study and monitoring. The most active Mexican volcano, the Colima, is also a threat to a number of surrounding urban areas, including the city of Colima itself, a state capital. The Popocatepetl and the Colima activities are monitored by a multi-parametric observation system with continuous recording of seismicity, ground deformation, gas emission, etc.. The detailed scientific studies performed over the years allowed to establish a model for the volcano, down to depths of several Km with precision of several hundred meters. More trustful model of the volcano, based on muon radiography, should help in understanding the dynamics of the next eruptions. A more precise assessment about the internal structures of Mexican volcanoes should have an important impact in reducing eruption risks to the corresponding nearby population. The methodology, established and successfully applied to several volcanoes in Japan[?, ?], relies on measuring the attenuation of quasi-horizontal muons occurring in the volcanic volume. The recent addition of combining muon tomography with gravimetric information provides new means to determine more precisely the internal density distribution of large volumes, using the attenuation of cosmic muon flux crossing the geological body of interest [?]. As an example, the mass ejection rate during an eruption depends strongly on the diameter of the lava conduit. A diameter change, from 50 m to 100 m would produce a one order of magnitude in-

Fig. 1: Detector location at the Popocatepetl volcano used in simulation.

crease in the mass ejection rate during an eruption. As in the Mu-Ray[?] project, our primary goal here is to generate muon-radiographies having the highest possible resolution for both, the Popocatepetl and the Colima volcanoes.

2 Location experimental implications

Conventional geological methods (seismological, gravimetric and electromagnetic) provide spatial resolutions of the order of hundreds of meters[?], while the detection of density variations in lava conduits in 50-100m size range, requires resolutions better than 20m. This can be achieved using muon radiography, when the detector is located at a distance from the lava conduit of less than 2km. This limitation is due to (angular) muon multiple scattering inside the volume of the volcano, which is estimated to be of order of 10 mrad, representing one of the most restringing limitations to the detector design. Often the ideal detector location, when considering acceptance, is less desirable when evaluating environmental parameters. A preliminary choice of detector location, before a detailed environmental study, is shown in Fig 1. The matter thickness angular distribution for this detector location is shown in Fig. 2. There, the volcanic thicknesses, in the lava-conduit region, is greater than 2000m. Taking as a reference what is reported by muon radiographies in Japan using a $1 m^2$ detector, where thicknesses are of the order of 400-500m [?], the muon flux in Popocatepetl is expected to drop faster. So, to get the comparative rates, we need a detector with the active area of the order of 10 m^2 , or more. Lower rates and larger surfaces

Fig. 2: Angular distribution of volcano thickness in the detector acceptance

Fig. 3: Difference distributions between the initial(generated) and the reconstructed(measured by the detector) angles.

will increase the contributions from accidentals, especially in the simplest configuration such as a two-plane position-sensitive detector (PS). The increase in the number of P-S planes [**?**] improves the situation, while increasing the detector cost. In volcano applications, angular resolution requirements are more important in the horizontal plane, where the lava conduct size is 50m to 100m. The vertical resolution is less critical, what would reduce the weight and the cost.

3 Detector design considerations

3.1 Liquid scintillation

Among the available detector technologies, scintillation stands out as the most convenient, based on the above mentioned location requirements. Discussions on this subject may be found in [**?**], and references therein. Plastic scintillation is a widely used particle physics technique, which is the subject of constant development. Uniform response from large surfaces is best achieved when coupling plastic scintillators with wavelength-shifters (WLS) fibers having large absorption lengths and an emission spectrum which is better fit for the sensitivity window of photo multiplier tubes (PMT). Among the disadvantages of using WLS is the deterioration of their time characteristics, and their added cost. Still, successful muon radiographies of volcanoes have been obtained by means of plastic scintillator telescopes, covering a total area of approximately $1m^2$, and providing angular resolutions down to 40 mrad [**?**, **?**]. An alternative we consider here is based on liquid scintillation, which is less common in muon tracking applications. The general concept contemplates the use of square-section plastic pipes, having good internal light transmission properties, which are filled with a liquid scintillator, and are optically coupled to fast light detectors on each end. The principal advantages are: reduced cost, and the fact that this technique provides an easy way to renew the scintillator material, without having to dismount the detector. This is an important consideration for long-term (several years) monitoring applications. Also, detector transportation is simplified, as the scintillator liquid can be transported separately, reducing the weight of detector modules. Furthermore, we propose to use the time difference between the signals at each end of the scintillaror-filled pipe, to define the position. This cuts in half the scintillator volume required to determine (x,y) coordinate pairs, what has an important impact in cost and detector weight.

3.2 The Silicon Photo-Multiplier option

Silicon Photo-Multipliers (SiPM) are semiconductor photo-detectors operated in limited-Geiger mode [**?**]. They are operated at 25 - 50 V and require small electricity consumption. The typical SiPM pixel gain is $\approx 2 - 3 \times 10^6$ for a 10 to 20 ns pulse length. SiPM have sub-nanosecond time resolution and their quantum efficiency and the geometrical fill factor together are order of $30 - 70\%$, to be compared with a typical value of 15% for multi-anode PMTs. Nowadays SiPM costs are becoming competitive when compared with PMTs. The use of SiPM would bring several advantages.

One of them is the simplification of the optical system by mounting the single channel SiPM directly on the scintillator surface, thus avoiding complex fiber systems, which would represent environmental and cost advantages in volcano monitoring applications.

3.3 Detector Baseline Design

In our baseline proposal, each module has 2 or 3 scintillator planes and each plane has 16 strips, with 3.2m length, 20cm wide and a thickness depending the scintillator properties. As already mentioned, the readout would be on both sides by two PMT or SiPM. We are planning to shield each scintillator plane with iron plates up to 1 cm thick (to be optimized), to reduce the electromagnetic background. The number of scintillator planes, 2 or 3, shall depend on the measured accidental rate [**?**]. On a first prototype we estimate to have a one degree angular resolution on the horizontal plane, using 6m as the distance between scintillator planes. Vertical angular resolution depends on the time resolution. Assuming a 0.5ns time resolution, which is not hard to achieve, we should have close to two-degree resolution for vertical angle, what corresponds to about 40m at a distance of 1Km.The estimated weight of each plane would be approximately 250 kg, when using 2.5cm thick plastic scintillators. In case of a liquid scintillator, there would be a slight weight increase in the integrated detector, but separate transportation reduces the logistics problem.

4 Data Management

As mentioned before, volcano monitoring likely contemplates an independent form of electricity generation, such as solar. Hence, energy consumption deserves a serious consideration. Here we consider using a data acquisition (DAQ) system based on VME-standard commercial electronics. The development of specific, ragged, reliable, in-house electronics is currently beyond our possibilities. We estimate that two 1.5KW solar stations, at an estimated price of 5-6 thousand Dollars each, can maintain our DAQ electronics setup. Another important energy need is related to data transmission and communications. Detector module will have 64(96) channels (96 in case of 3-planes) and the readout of timing information should be done using a CAEN fast sampling TDC(VX1190A-2eSST-128ch, or VX1190B-2eSST-64ch) [**?**]. The expected single rate for the $10m^2$ 3-plane detector module (assuming single rate proportional to surface) is about 3.0kHz [**?**]. This single rate would allow a readout based on the VME SBC (Single Board Computer). The software trigger will significantly reduce the volume of information acquired; to make feasible a wireless system with less than 1kBs transmission speed.

5 Monte Carlo simulation

Monte-Carlo simulations have been performed to study the stochastic behavior of very high energy muons traversing large depths of rock. A number of simulation packages can be used for this purpose [**?**, **?**]. Here, a preliminary simula-

Fig. 4: Angular distribution of detected events corrected by the detector acceptance.

Fig. 5: 1D projections of 2D histogram from the Fig 4 for the θ_y values between 0 and 15 degrees.

tion has been done using the GEANT4 tracking program [**?**]. The elevation map ("SRTM Worldwide Elevation Data 3-arc-second Resolution")[**?**] of Mt. Popocatepetl, which was digitized with a 10 m precision, has been used to extract the geometry of the absorber. This information has been used to introduce the geometry of Mt. Popocatepetl in the simulation program. The main goals of the preliminary simulations are to estimate:
- The angular resolution of the proposed detector, and optimize the angular binning.
- The expected muon count-rates, including an approximate muon survival probability. Unfortunately the transport model [**?**] is not yet validated for the muons traversing large thicknesses.
- The required statistics necessary to detect structures (i.e., the lava conduct) of a given size. This depends on the multiple scattering, detector resolution, volume thickness variations along the muon track within one angular bin. The thickness variation in the simulation, in turn, depends on the precision of the digitization of the Mountain geometry as well as the angular bin size. The tuning and final validation of the Monte Carlo simulations will be obtained by comparison to the data taken at Mt. Popocatepetl. Simulation results are presented in Fig 3-5. Figure 3 shows the difference distributions (between initial and reconstructed angle) for two projection angles. For the vertical coordinate measurement precision is chosen to be 10cm, which corresponds to a time resolution of 0.5ns. As can be seen from the figure, the angular resolutions in the horizontal and vertical planes are 0.8 and 1.4 degrees, respectively. The results of a simulation having hypothetical lava conduct of $100m \times 100m$ cross section, while the height from the top of Popocatepetl to its crater's bottom is shown in Fig 4. There we represent the muon-rate angular distribution corrected by the detector geometry efficiency. The chosen bin-size 2 degrees is approximately $2.8 \times resolution$, which is optimal for this object detection task [**?**]. The simulation image statistics is for a one hundred day collection time assuming 100% detector efficiency. As it can be seen from the figure in $2D$ plot the lava-conduct is difficult to note, but in the projection histogram it is better observed, see arrow in Fig 5. So within this statistics the empty lava-conduct having 15 degree angular size in vertical angle(with the length of 600m) can be detected.

6 Muon rate estimation

To estimate the muon count rate, a knowledge of the muon flux at energies larger than 500GeV for zenith angles $\theta \geq 60°$, is required. For this energy, and angular, region there are very few experimental measurements (the existing data are for zenith angle 88° and for the energies 0.1 to 22 TeV) [**?**]. Thus, the data has been extrapolated using a parameterization that includes two sources of muon production: pions and charged kaons, see Fig. 6. Also

Fig. 6: Energy dependence of different muon flux models. Lines are from: PDG - (Particle Data Group); Bugaev 98 - [**?**]; Hebeker -[**?**]; LAng flux and exp. data - [**?**]

included in this figure are the different muon vertical flux models. As can be seen, the energy dependence of different models for energies larger than 0.2TeV can be approximated by the power low spectrum ($E^{-\gamma}$) with a constant γ (within a 50% accuracy, and the variation in γ value is about 0.2). The contributions from energies larger than 20TeV is less than 1% , while one should not expect a strong angular dependence from the low energy region dependence. Hence, using this muon flux model [**?**] in our simulation we estimate a muon rate of ≈ 20 per hour. To obtain the statistics demonstrated in Fig 4 we need to collect data during the 100 days, assuming 100% detector efficiency.

7 Conclusions

Muon radiography is proposed to monitor Mexican active Volcanos. The proposed detector design here differs from others already used for this purpose, as it uses a one-layer scintillator plane to measure both coordinates, making it cheaper while reducing its weight. A liquid scintillator option is also under consideration, which we find it preferable for long time monitoring tasks. The final choice will be done after the completion of prototype and environmental studies. The 10 m^2 surface detector allows to locate a 100m(this is equivalent to density variation of 5%) diameter empty cavity during 3 months of data taking. Smaller density differences would, of course, require more time to be detected.

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