MiniMuTe: A muon telescope prototype for studying volcanic structures with cosmic ray flux

MiniMuTe: un prototipo de telescopio de muones para el estudio de estructuras volcánicas con flujos de rayos cósmicos

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***Abstract*—The Universidad Industrial de Santander develops the Muon Telescope (MuTe) project in collaboration with the Universidad del Tolima, the Servicio Geológico Colombiano and supported by Colciencias. The MuTe will record the muonic component of the flux of Cosmic Ray atmospheric secondary particles crossing Cerro Machin Volcano located in South-West of Colombia. This recorded flux can be associated with the density distribution inside the geological structure, producing images of their inner structure. As a proof of concept to test the readout electronics, we develop a prototype of 9 pixels hodoscope (miniMuTe). In this paper, we describe the characteristic of this electronics and discuss some preliminary measurement of the background flux of cosmic rays at Cerro Machin Volcanoes.**

***Index Terms*—detector prototype, cosmic rays, muon tomography.**

***Resumen*— La Universidad Industrial de Santander desarrolla el proyecto Telescopio Muon (MuTe) en colaboración con la Universidad del Tolima, el Servicio Geológico Colombiano y el apoyo de Colciencias. El MuTe registrará la componente muónica del flujo de partículas secundarias atmosféricas de rayos cósmicos que cruzan el volcán Cerro Machin ubicado en el suroeste de Colombia. Este flujo registrado puede asociarse con la distribución de densidad dentro de la estructura geológica, produciendo imágenes de su estructura interna. Como prueba de concepto para probar el diseño electrónico, desarrollamos un prototipo de hodoscopio de 9 píxeles (miniMuTe). En este artículo, describimos las características de esta electrónica y discutimos algunas mediciones preliminares del flujo de fondo de los rayos cósmicos en los volcanes de Cerro Machin.**

***Palabras claves*— Prototipo detector, rayos cósmicos, tomigrafía de muones.**

I. INTRODUCTION

Muography or muon tomography is a technique which uses atmospheric muons to study geological and/or anthropic structures. Applications of muography range from archeology to civil engineering, however, geology is presently the field with more ongoing experiments because no-invasiveness, high spatial resolution, and penetration introduce it as an excellent method to study volcanoes. The most common tools for studying volcanoes as gravimetry and electrical tomography lack the spatial resolution [1], penetration and offers a complex inversion problem due to data interpretation. Another issue is their invasive nature, which is a hazardous task considering that the information must be recorded over volcano domes [2].

Several experiments based on muography have been developed, L. Alvarez and collaborators made the earliest on the Chephren pyramid looking for hidden cavities. They did not find any cavity but advertise the technique [3]. More recently, Tanaka et al. [4], [5] and Lesparre et al. [6], [7],

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[8] mark the landmark in the muography field with several studies about the feasibility of muon imaging. Today the most representative muon telescopes to study volcano structure (that we shall describe in the present work) are Muon Radiography (MuRay), ToMuVol and Diaphane.

The MuRay detector [9] was designed to perform muography on the Mount Vesuvius. It has 3 XY planes of 128 triangular plastic scintillators, 64 vertical and 64 horizontal. The planes have a separation distance of 1 m. The newest feature in MuRay is the capability to measure the Time-of-Flight to filter "albedo muons" (muons incoming from the detector back) and other false positive events. Each scintillator bar couples to a Silicon Photomultiplier for converting the scintillation light-beam into an electrical signal. Muon flux information coming from panels are processed by the EASIROC ASIC and an FPGA Xilinx Spartan III [10].

ToMuVol -located in the south of France in the Puy de Dôme- has four layers about 1 m of single Resistive Plate Chambers (RPCs). The readout system is a 64 channels Hardroc2 ASIC which efficiently discriminates events from noise. Moreover, the detector needs a Programming Logic Controller (PLC) to monitor gas, high voltages, and environmental conditions. The RPCs need a high voltage (7.5 kV) to operate, this fact is a drawback concerning the power consumption of the telescope. Another issue is about the mechanical robustness of the detector and its limits to operate in harsh environments. It achieves an angular resolution of 1 deg in 1000 days [11].

The DIAPHANE is an ongoing experiment at the Soufrière of Guadeloupe, an active volcano. These detectors have two matrices of 16x16 pixels of scintillators where the light signals from each scintillator are collected through of a wavelength shifting (WLS) optical fiber and converted to electrical signals using a 64 channel Multi-Anode Photomultiplier (MAPM). Each MAPM is readout by a multichannel frontend electronics for discrimination and trigger generation. DIAPHANE has an angular resolution of 0.1 rad and low power consumption about 36 W [8]. The principal disadvantage of DIAPHANE is that a fraction of fibers length is out of the scintillation bars and this exposes them to external light noise sources, and a decrease in the signal-to-noise ratio (SNR) could occur.

In this paper, we shall briefly discuss the concept of a hybrid muon telescope which solves some of the main drawbacks of the detectors mentioned above. MuTe (for Colombian Muon Telescope) combine two detection techniques: a hodoscope formed by two planes of plastic scintillator bars, and a WCD which allows us to isolate the muon from the electromagnetic component and to estimate the energy of this component. MuTe project aims to study Colombian active volcanoes [12, 13] and in this note, we report the first test of the hodoscope electronic system and measurements of the background flux at Cerro Machin Volcano made through the miniMuTe prototype.

II. METHODS

A. The Detector

MuTe is a hybrid detector composed of two sub-detectors: a hodoscope and a Water Cherenkov Detector (WCD), see Fig. 1. The hodoscope consists of two scintillation panels each of 30x30 strips of 120 cm x 4 cm x 1 cm forming an array of 900 pixels. When muons pass through the scintillation bars generate light pulses, then optical fibers collect and drive these signals to coupled Silicon Photomultipliers (SiPMs) which convert these them into electrical pulses, see Fig. 2. These events are then discriminated by the 64 channels MAROC3 ASIC using a programmable threshold per channel. On the other hand, the ASIC allows setting an optimum gain per channel which is essential for the calibration stage of the hodoscope, where Cyclone III Field Programmable Gate Array (FPGA) manage the control parameters.

The hodoscope electronics has a Time-to-Digital Converter (TDC) which measures the Time of Flight of particles coming from the volcano. The ToF is useful to filter "albedo" muons, to increase the SNR of the MuTe, and to be a second flag in the MuTe trigger system. Each event information is managed and stored by a Raspberry Pi 2 Single Computer Board.

The WCD is a cubic water tank with a Tyvek inner covering, a photomultiplier tube as a sensitive element and a discrimination electronics. This sub-detector provides a shield for the "albedo" muons and acts also as a calorimeter to estimate the energy loss of arrival muons which decays inner the WCD.

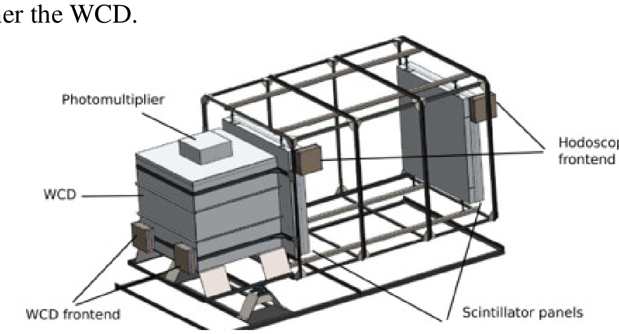

Fig. 1. Structure of the MuTe hybrid detector. This is composed by two scintillator panel hodoscope with their respective electronic frontend and a WCD which performs the energy loss estimation of the events coming from the volcano.

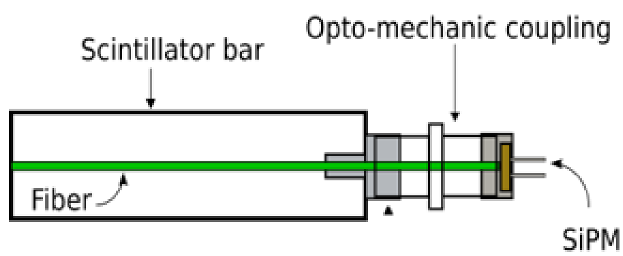

Fig. 2. Scintillator-fiber-SiPM system. The opto-mechanic coupling allows fibers to be connected correctly on the SiPM surface.

B. A Prototype: miniMuTe

We present hodoscope a prototype of 9 pixels per panel designed for testing the electronics system of the MuTe. Fig. 3. Our electronics consists in a MAROC3 board which

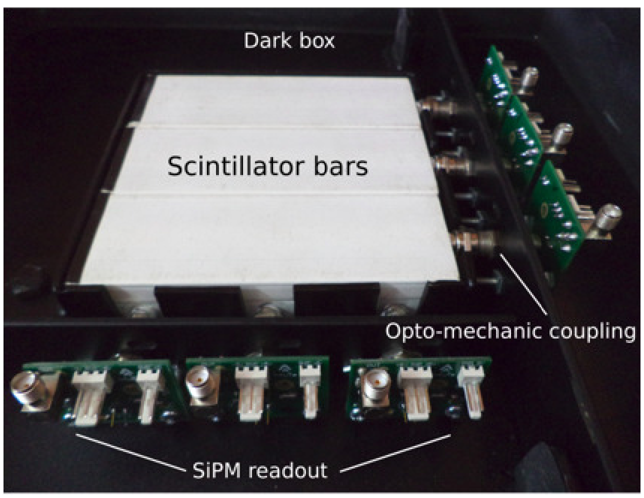

Fig. 3. Structure of a miniMuTe 9 pixel panel. Each panel of miniMuTe prototype is formed by, 6 scintillator strips of 12 cm x 4 cm x 1 cm, 6 SiPM readouts and 6 opto-mechanic couplings, all contained inside of a dark box.

manages the 12 signals from both panels, and there is no TDC system implemented Fig. 4.

Two voltage sources power minimute. A dual voltage source (-5v/+5v) for the panels readout, and a high voltage (56V) DC-DC converter (Hamamatsu C11204). The first one and second.

C. First Measurements

The miniMuTe prototype measures the background flux at the Cerro Machin Volcano. The coincidence between events at both scintillator panels validates them. i.e., four high signals in the recorded channels during a temporal window of 15 ns, Fig. 5.

The number of possible trajectories nT is defined as

$$nT = (2n-1)^2 \quad (1)$$

where n is the number of rows of one scintillator panel. In this case, $n = 3$ then $nT = 25$. The trajectories are expressed in terms of the angles $\theta_x$and θ_y.

Our prototype registers vertical (a 0° zenith angle) one-day cosmic ray background flux, with a panel size is 12 cm x 12 cm, and 13cm between them, generating 68° aperture angle, as Fig. 6. sketches.

CORSIKA background simulations are crucial to

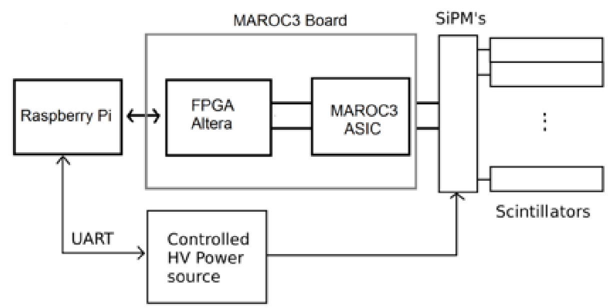

Fig. 4. miniMuTe electronic system. The 12 signals provided by the hodoscope are amplified and discriminated by the MAROC3 ASIC whose slow control parameters are fitted by the FPGA Cyclone III of Altera, then the data are managed and stored in a SD card through the Raspberry Pi 2 which also controls the high voltage source for powering SiPMs.

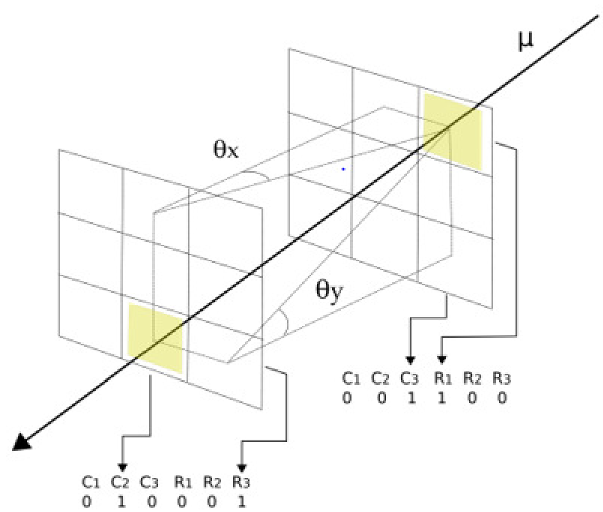

Fig. 5. A valid coincidence event schema. The yellow squares indicate the activation of two scintillator strips in a panel for forming a pixel. When a muon hits in both panels 4 valid signals are obtained, and then the incidence trajectory of the muon is expressed by the angles $\theta_x$and θ_y.

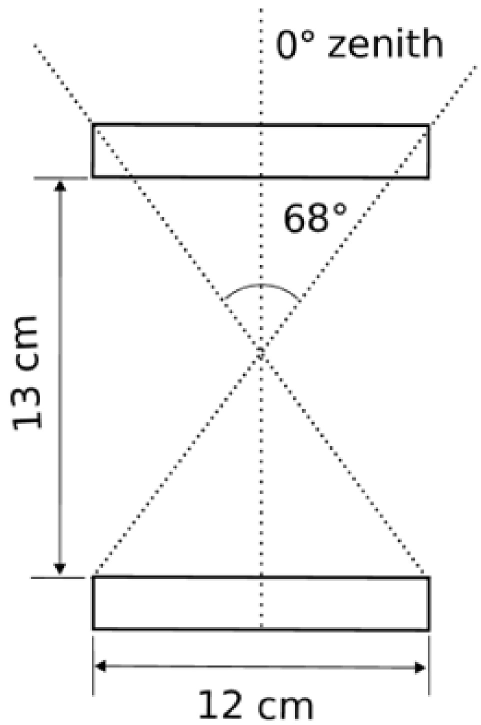

Fig. 6. Positioning of the miniMuTe detector for measuring the background flux at Cerro Machin Volcano.

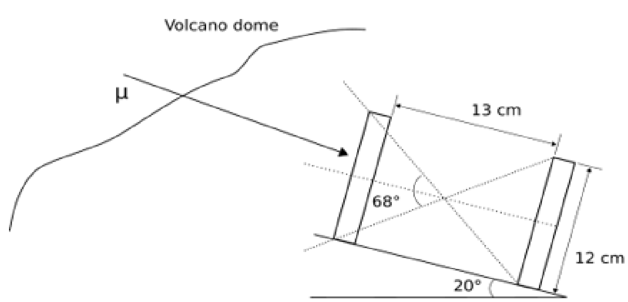

Fig. 7. Positioning of the miniMuTe detector for measuring the flux coming from a fraction of the sky and a fraction of the volcano dome.

estimates time exposure of the detector to collect enough information for imaging inside the structure of the volcano dome.

Our prototype, with an elevation angle of 20°, measures a muon flux crossing the Cerro Machin volcano dome during one-day and from the selected position, it covers both: a fraction of clear sky and part of the volcano dome.

III. Results

The first test made at Cerro Machin was to measure the temporal evolution of the background flux. The panels were placed one next to the other attaining a sensitive area of 288 cm² and registered an average flux of 0.6 hits/min-cm at an altitude of 2.650 m.a.s.l, during 7.5 hours with an aperture angle of 68°. Fig. 8. shows the number of hits per minute.

The second test, --displayed in Fig. 6. and performed having the two panels one over the other-- records 25 trajectories in a 2-dimensional histogram which has a maximum in $\theta_x = 0$and $\theta_y = 0$ due to flux variation from 0° to 90° zenith modulates by a square cosine factor.

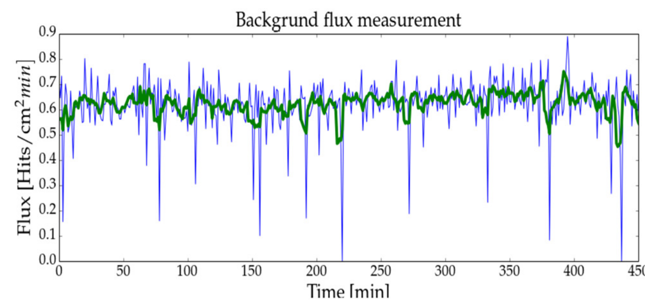

Fig. 8. Background flux at Cerro Machin Volcano. Flux raw rate (blue line). Average flux rate with a temporal sliding window of 60 minutes (green line).

However, the 2D-histogram obtained shows a maximum value near the right-bottom corner, see Fig. 9. This phenomenon occurs due to the position of SiPMs; light produced by muons crossing in the opposite direction to the SiPMs location have less probability of reaching the photo-sensors; therefore, a bias appears in the acceptance of the hodoscope. This bias in the acceptance maximum is corrected by applying a variable gain mask on the MAROC3 amplification stage, that is, to find the maximum gain per each channel.

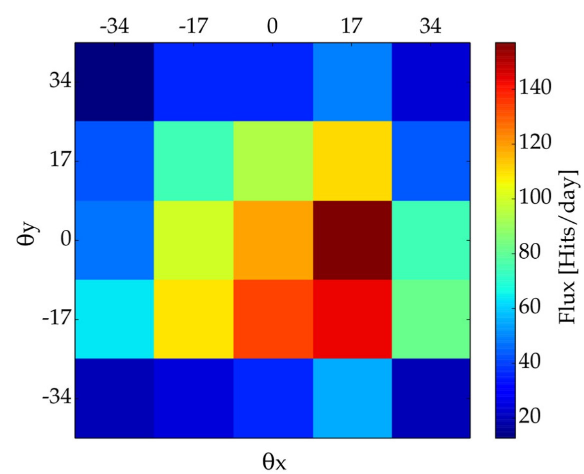

Fig. 9. Background flux histogram depending on the muon incident trajectory. The color bar shows the flux in hits per day.

Finally, the last test was pointing the miniMuTe to a section of the volcano dome, for recording data from a fraction of clear sky and, at the same time, from a fraction of the dome during 24 hours.

Fig. 10. illustrates the resulting 2D-histogram. In this case, the histogram per day has decreased in comparison with the background measurement due to the flux is small for angles near to 90° zenith. However, a clear contrast between clear sky and dome section appears.

IV. Conclusion

The angle of the incident muons crossing the volcano dome is an important issue to determine the time of exposure of the instrument to collect enough information to do a muography of the Cerro Machin volcano.

The background flux histogram provides information on the acceptance of the detector and how to carry out the calibration process to get a fair distribution of hits rate.

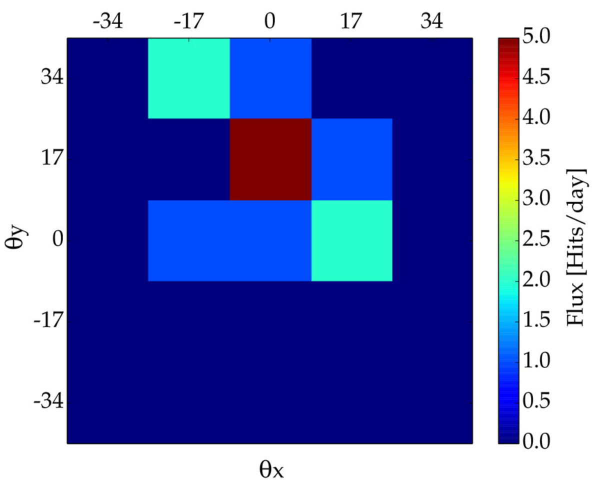

Fig. 10. 2D flux histogram depending on the muon trajectories as result of pointing the miniMuTe to a fraction of the Cerro Machin volcano dome.

With this fist evaluation of the hodoscope electronic system, we have checked the stability of its performance, particularly of the data acquisition system through the SiPM and the reliability of the operation in recording the data. We have also tested the field response SiPM with the variation of the temperature, which was of 10°C --between 5 °C and 15 °C. This behavior affects the breakdown voltage point for the SiPMs and, in this way, the acceptance of the detector; To correct this effect we implement a high voltage corrector depending on temperature on the Raspberry Pi SCB.

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