Simulated Response of MuTe, a Hybrid Muon Telescope

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In this paper we present a complete and detailed computational model of the hybrid response of the Muon Telescope (MuTe), designed to perform muography volcanic studies. This instrument combines two particle detection techniques: first, a muon hodoscope based on two planes of plastic scintillator bars; and a Water Cherenkov detector located behind the rear scintillator panel acting as a third coincidence and discriminating detector.

The simulation model includes materials, geometries, dimensions, and the photo-sensitive devices of the detectors, and the detectors response to the expected muon flux at 2650 m a.s.l at Cerro Machín Volcano, Colombia. The obtained results, in agreement with several experimental setups, were used to set up the detector trigger for muon detection in terms of the expected signal for a muon depositing energy at each component of the instrument.

Keywords: Muography, Volcanic Risk, Detector simulations, Water Cherenkov Detectors,

I. INTRODUCTION

Cosmic rays (CR) are continuously impinging the Earth’s atmosphere producing cascades of secondary particles called extensive air showers (EAS), having three main components: the electromagnetic, the hadronic, and the muonic. The electromagnetic component produced by electrons, positrons, and photons, coupled through several processes. The hadronic component generated by barions and mesons produced trough QCD interactions, and the muonic component, caused mainly of muons coming from the decay of charged pions, kaons, and other charged mesons trough weak interactions processes. The energy of these muons comprises a broad spectrum, but only those muons with the highest energies (> 1 TeV) – produced during the very first interactions of the evolving particles cascade– such as the decay of charmed mesons, are collectively known as prompt muons and have enough energy to cross from hundreds to thousand meters of rock [1].

Muography is an emerging technique based on measuring the attenuation of the directional muon flux moving across geological or anthropic structures [2]. Nowadays we are witnessing several new successful academic and commercial applications such as the detection of hidden materials in containers [3], archaeological building scanning [4, 5], nuclear plant inspection [6], nuclear waste monitoring, underground cavities [7], the overburden of railway tunnels [8] and vulcanology applications (see, e.g. [9] and references therein).

The existence of more than a dozen active volcanoes in Colombia, which represents significant risks to the nearby population [10–12], motivates local research groups to explore possible applications of the muography technique [13–18].

Hodoscopes are the most common detectors designed and implemented for volcano muography. They consist of two or more panels devised to identify muon trajectories. Projects like MU-RAY [19], ToMuVol [20], and DIAPHANE [21] use hodoscopes based on different detection technologies: emulsion plates, resistive plate chambers, micromegas, multiwire proportional cameras, and scintillators, just to mention the most common ones. Each of these techniques has advantages and disadvantages: Emulsion plate detectors [4, 22] provide an excellent spatial resolution of the order of sub-microns, are passive, and easy to handle. On the other side, they have short lifetimes, and it is not possible to discriminate the time-stamp of dynamic phenomena, because the recorded events accumulate in the plates. Gas detectors, as Resistive Plate Chambers [23, 24], Micromegas [25], and Multi-Wire Proportional Cameras [26], allow obtaining short traces of the detected particles with a spatial resolution around the microns. However, for such a low muon flux, it is difficult to address the benefits of this high spatial resolution fully and, since these detectors operate outdoors, environmental temperature variability could affect the detector operation. Finally, scintillation based detectors, using segmented [6, 27, 28] or continuous scintillators [29–31] – which does not present a considerable mechanical variation caused by environmental conditions– are more robust and more affordable than gaseous and emulsion detectors. Nevertheless, their spatial resolution...
is not as good as the other detectors since the segments generally used are of the order of centimeters.

In this paper, we present a detailed computational Geant4 model of our hybrid Muon Telescope (MuTe) and the estimation of its response for an expected atmospheric muon flux at 2650 m a.s.l at Cerro Machín Volcano-Colombia. MuTe combines two detection techniques: a hodoscope with two detection planes of plastic scintillator bars, and a Water Cherenkov Detector (WCD) which acts as an absorbing element and as a third active coincidence detector. The model includes materials, detailed geometries and dimensions, and the detector’s photo-sensitive devices. In the next section, we briefly describe the rationale behind the MuTe design. Section III discussed the response from scintillator bar hodoscope to the impinging cosmic ray background. We emphasize in the bar scintillator model and the possible attenuation effects. In section III B, we compare our simulation results with data emerging from an experimental laboratory setup and study the temperature effect on breakdown voltage for the silicon photomultiplier (SiPM) used in the scintillator panels. Section IV presents the response of the WCD and also compare some of the results with recent lab measurements. Finally in section V we summarize some finals remarks and conclusions.

II. THE MUTE INSTRUMENTAL DESIGN

As we have mentioned above, our Muon Telescope (sketched in figure 1) is a hybrid detector that combines two technologies: a two-panel scintillator bar hodoscope, and a water Cherenkov detector, increasing the signal/noise separation and the backward noise [32–35]. This hybrid technique allows us to estimate not only the incoming flux directions but also the range of deposited energy of the impinging particles [13, 18].

The panels of the hodoscope consist in an array of 30 vertical × 30 horizontal scintillator bars, of 4 cm wide, 1 cm thick and 120 cm long, providing a total of 900 pixels of 4 cm × 4 cm, yielding a total detection surface of 14.400 cm². Scintillation bars are made of Styron® 665-W polystyrene doped with a mixture of liquid organic scintillators: 1% of 2,5-diphenyloxazole (PPO) and 0.03% of 1,4-bis (5-phenyloxazol-2-yl) benzene (POPOP) [36], having a photon emission peak at the wavelength of 420 nm. Each bar has a 0.25 mm highly reflective coat made of 85% Polystyrene and 15% of TiO₂. At the center, each bar has a ~3 mm diameter hole longitudinally extruded, where is placed a 1 mm, wavelength shifter (WLS) and multi-cladded optical fiber Saint Gobain BCF92. The fiber core is made of Poly-methyl methacrylate, having the first clad of Polyethylene, and the external one of Fluorinated Polyethylene [37]. Scintillation photons produced by the passage of charged particles through the bars are partially collected by the fiber, absorbed, and re-emitted in a different wave and transported along the fiber. One of the extremes of the fiber is polished at an angle of 45 degrees to increase internal reflection and to favor photon collection in the opposite extreme. Mechanically coupled to the fiber, is a silicon photomultiplier Hamatsu S13360-1350CS, which has a photosensitive surface of 1.3 mm × 1.3 mm, consisting of 2668 avalanche photodiodes [38]. This device has a spectral detection range from 270 to 900 nm, with its maximum sensitivity around 450 nm.

Casual coincidences detection and discriminations of muons signals from background noise are enhanced by using our own developed Time-of-Flight (ToF) recording system, complemented by a cubic 120 cm side water Cherenkov detector (sketched in figure 1). The WCD consists of a cubic stainless steel water container, internally coated with a reflective and diffusive material 0.4 mm Tyvek [39] and filled with 1.7 m³ of purified water, having an 8” Hamamatsu R5912 photomultiplier tube (PMT) placed at the center of the tank roof. In this way, the photosensitive PMT window is in direct contact with the water and can detect Cherenkov photons produced by relativistic charged particles moving through the detector (see figure 1).

This implemented design filters the soft-component (e±) of Extensive Air Showers and scattered/upward-coming muons. Particle deposited energy in the WCD identifies Electron/positron component, while scattered and backward muons are rejected using a pico-second ToF system.

III. HODOSCOPE RESPONSE TO COSMIC RAY BACKGROUND

The response of the hodoscope bars refers to the signal produced in the SiPM photo-sensor when a charged particle
corporate to this geometry a coating material –made of 15% fraction, 0
eallelepiped of range. especially in the Minimum Ionization Particle MIPs of the hodoscope panels to the passage of charged particles, (see section III B) and the estimation of the average response bar simulation model, the experimental setup to validate them fiber[37].

the photo-sensor device located at one of the extremes of the sorbed, re-emitted –in the green optical band– and guided to tons, conduct them through the fiber where they can be ab-

WLS by the which can be absorbed by the plastic material or collected improbable. However, as the scintillation detector volume is relatively small, these mechanisms are highly improbable.

As shown in figure 2, charged particles impinging the scintillators produce photons in the blue-violet band, which can be absorbed by the plastic material or collected by the WLS fiber. The fiber cladding helps to captured pho-

tons, conduct them through the fiber where they can be ab-
sorbed, re-emitted —in the green optical band— and guided to the photo-sensor device located at one of the extremes of the fiber[37].

In the following sections we shall discuss the Geant4 [40] bar simulation model, the experimental setup to validate them (see section III B) and the estimation of the average response of the hodoscope panels to the passage of charged particles, especially in the Minimum Ionization Particle MIPs energy range.

A. The scintillator bar model

The Geant4 geometric model of the bar consists of a par-

allelepiped of 4cm wide, 1cm high and 120cm long. We incor-

porate to this geometry a coating material —made of 15% of TiO2 and 85% of polystyrene— with a reflectivity of 1 and 0.25mm of thickness.

The scintillating bar is polystyrene, with an index of re-

fraction, n = 1.50, and a photon absorption length of 5.5cm. There is a tunnel of 119.5cm long and 1.8mm of diameter, drilled through the central axis of the bar, where we place a multi-cladding WLS fiber. This looseness of 0.5cm at the end of the tunnel —filled with air to make the model as real as possible— avoids the escape of photons. The fiber119.45cm-
tunnel119.5cm configuration leaves a space of 0.05cm to lo-
cate the SiPM inside the tunnel.

A solid cylinder of poly-methyl methacrylate, with 119.45cm long and 0.5mm radius, models the fiber. The first clad of this fiber is a cylindrical shell of polyethylene, with an internal radius of 0.5mm and an external radius of 0.515mm. The second is a shell of fluorinated polyethylene, with an in-

ternal radius of 0.515mm and an external radius of 0.530mm. Both coatings have the same fiber length.

A square surface of a side of 1.3mm, attached to one of the fiber, represents the SiPMs. The simulations allow to set the SiPM photon detection efficiency, which depends on the wavelength of the photon hitting the SiPM, where the highest probability of Photo-Electrons (pe) generation is around 470nm[38].

Figure 3 displays the simulation results of the scintillator bar response to charged particles of different energy. The histogram of the number of photo-electrons generated by 100000 electrons of 20MeV, 100MeV and 500MeV has the same profile as those corresponding to the 100000 muons of 1GeV, 10GeV and 100GeV. This similarity occurs because those particles have the same stopping power in polystyrene, i.e. \( \frac{dE}{d\rho_{\text{pol}}} \approx 2 \text{ MeV cm}^2/\text{g} \) [41], so they all deposit about 2.08MeV of energy when passing through a centimeter of polystyrene. Therefore, our detector is not able to distinguish muons from electrons, and it is necessary to use the WCD to select the muon events from noise.

The mean value of those histograms is around 40pe, which is equivalent to 2.08MeV of energy deposited in the bar since those particles pass through vertically and the distance trav-
eled is 1 cm. The following simulations are for muons with 3 GeV, which are the most frequent at the level of our observation point on the Cerro Machín volcano, thus, from now on, the MIP refers to this particular particle having this energy.

1. Attenuation of the photons in the Bar-Fiber-SiPM system

The light that propagates within the WLS fiber suffers an inevitable attenuation due to some photons escape from the optical guide, and others can be absorbed by the material while being transported to the SiPM. This attenuation depends on the length of the bar (which in this case is 120 cm), so it is necessary to study how the attenuation behaves in our Bar-Fiber-SiPM system.

From the simulations of the scintillation detector, we can count the number of pe generated in the SiPM when a MIP crosses the bar at different distances $x$, where $x$ is the distance between the point of impact and the location of the SiPM. These distances were chosen to take into account the width of the pixels of the hodoscope, i.e., 4 cm wide; therefore $x$ varies as, $x = (2 + 4p) \text{cm}$ $p = 0, 1, 2, ..., 29$.

Figure 4 shows the results of this simulation. If the particle impacts at the position closest to SiPM (i.e. $x = 2$ cm), it has the maximum photo-electron intensity and, if it impacts farther away from the SiPM, the intensity decreases. A double exponential function $F(x)$ fits the data and models this decrease

$$F(x) = 0.468e^{-0.003(2-x)} + 0.531e^{0.005(2-x)}.$$  \hspace{1cm} (1)

From this plot, we have that the attenuation in the Bar-Fiber-SiPM system is around 7%, that agrees with the experimental results, around 11%[42], given by the figure 10.

The MIP detection with scintillator bar generates a number of pe in the SiPM at a time $t$. Now we want to estimate the time needed to collect the total number of photo-electrons produced. This total is about 40 pe at $x = 2$ cm, while at $x = 118$ cm it is about 37 pe. From the top of figure 5 it can be noticed that 40% of the total photo-electrons occurred in the first 10 ns when the MIP has impacting the bar at 2 cm of the SiPM. Observe from the bottom of the figure 5 when the MIP has entered at 118 cm of the SiPM, that only 12% of the pe is produced in the same time. In both cases, the total number of pe is reached around 80 ns, that is, the average time necessary to collect the total of pe produced by the passage of a muon, at any point of impact in the bar.

2. SiPM and fiber coupling

The Geant4 model allows estimating how good is the coupling SiMP-fiber. We define the ideal SiMP-fiber when they are side by side, without any space between them. Thus, all the traveling photons at the edge of the fiber impact directly on the SiPM. As shown above, the obtained average number of photo-electrons, for an ideal coupling, is 40 pe. A non-ideal coupling has space (filled with air) of 1.15 mm between the SiPM and the fiber. The number of pe is reduced to 8, representing a loss of 80% of the signal compared to the ideal case, as shown in figure 6.

B. Experimental results from the scintillator detector

As described before, the plastic scintillators of the MuTe panels allow the indirect detection of ionizing radiation from the offline analysis of the electrical signal produced in the SiPMs. Since the SiPMs have intrinsic noise, it is essential to know the detector to define a methodology to detect particles and correctly interpret the measured data. A first study guarantees that the SiPM are working in Geiger mode at any temperature. Section III B 1 presents the results of the dependence on the breakdown voltage with the temperature.

On the other hand, given that the scintillator, the fiber, and the SiPM are not 100% efficient, there are various parameters to take into account. For example, the material of the bars is opaque to photons with an average length of 5.5 cm of attenuation. Then, to have a detector of 120 cm length, a WLS fiber is placed inside the bar. The fibers guide the photons, but they can experiment attenuation despite being multilayer, i.e., some photons can escape from the guide and even reflected in the border. This represents an additional problem when coupling different scintillators, and there will be edge effects related to the refractive index of each one. Therefore, with a controlled experiment, we must quantify the attenuation in these fibers and determine whether the coupling and the attenuation will be relevant in the case of the MuTe scintillator bars (see section III B 2).
Fig. 5. Cumulative number of photo-electrons produced when a MIP hit the bar at 2 cm from the SiPM (top) and at 118 cm (bottom). It can be noticed that 40% of the Total pe occurred in the first 10 ns when $x = 2$ cm and when $x = 118$ cm, only 12% of the pe is produced in the same time. In both cases, the total number of pe is reached around 80 ns, that is, the average time necessary to collect the total of pe produced by the passage of a muon, at any point of impact in the bar.

1. Dependence of the breakdown voltage with the temperature

To study the response of each scintillator bar, we first studied the SiPMs thermal stability. SiPMs can change their mode of operation if the input voltage ($V_{Bias}$) is less than the breakdown voltage ($V_B$), and this parameter varies with temperature. Thus we need to find this functionality to guarantee that SiPMs always works in Geiger mode.

To establish this dependence, we build a temperature-controlled box regulated by a TEC1-12706 thermoelectric Peltier cell, mounted on an aluminum frame, where we place the SiPM. The control system consists of two sensors: one to vary the temperature and the other one to measure it on the SiPM. Figure 7 displays the results for the operation of this system for different target temperatures ($10^\circ$C, $20^\circ$C, $40^\circ$C and $50^\circ$C). Note that the time required to reach the target temperature, in each case, is around $(600 \pm 50)$ s.

Next, Dark-Current [43] measurements follow in the range for 40 V to 60 V, for different temperatures and figure 8 illustrates the linear temperature dependence of $V_B$. It is clear that for each $10^\circ$C of temperature, the $V_B$ changes around 0.45 V.
Fig. 8. Dependence of the breakdown voltage with the temperature for the SiPM Hamamatsu S13360-1350CS used in the MuTe hodoscope. It can be observed that the relation is linear, that is for every 10°C of temperature the $V_B$ varies about 0.45V.

Fig. 9. Diagram of the experimental set-up to measure the bar signal attenuation. The three positions of interest are at both ends and the middle. An event is if there is a simultaneous signal in the three scintillators: the upper, the bar, and the lower one.

2. Attenuation measurements of the Bar-Fiber-SiPM system

To estimate the attenuation in the scintillator bars, we measure the signal produced by the passage of charged particles at both ends and the middle of the bar. Figure 9 illustrates the experimental set-up, which defines an event if there is a simultaneous signal in the three scintillators: the upper, the bar, and the lower one.

The trigger system, connected to a RedPitaya development card, records pulses with a frequency of 125 MHz [44]. The system was synchronized to have pulses in coincidence, producing three input signals to the card and one output signal that corresponds to each position in the scintillator test bar. The coincidence system has an angle $\theta$ for this configuration of 106.26°, as shown in Figure 9. The frequency of events per minute, measured with an oscilloscope, was $10 \pm 1$ per minute for 16cm². Thus, with this rate, it is possible to detect 0.62 particles × min × cm².

After a noise calibration, we record 10000 pulses in the three positions of interest. At the farthest end from the SiPM, the fiber was cut to 45° to maximize photon leakage and to avoid secondary pulses by reflections at the end of the fiber.

From each average pulse, we calculate the mean deposited charge at the three positions. Then, we estimate the percentage of attenuation by normalizing and comparing the values, as shown in Figure 10. In our case, the difference between the mean charge value deposited at both ends is around 11%. An exponential function fits the attenuated signal as

$$H(x) = 0.880 + 0.126e(-0.02x).$$

(2)

C. Simulated attenuation in the hodoscope

The probability of producing photo-electrons in the SiPM of horizontal and vertical bars is a crucial concept to determine the response of each panel of the hodoscope. The bar simulation generates the response of a detection panel to MIPs. Thus, independent events in a particular pixel $P_{i,j}$ is given by

$$P_{i,j}^F = P_i^F \times P_j^F,$$

(3)

where $P_i^F$ y $P_j^F$ are the probabilities obtained in the horizontal bar $i$ and in the vertical bar $j$, respectively.

Figure 11 displays the probability of photo-electrons produced by MIPs and hitting each panel pixel, obtained from equation 3.

These results are valid for both the front panel and the rear panel, and from figure 11, it clear that there is a difference between the zones. This difference around 12% can be associated with the attenuation of photons in the fiber, i.e., the pixels that are closer to the SiPM count more photo-electrons.
Fig. 11. The probability of photo-electron production in each pixel of a hodoscope panel by muons of 3 GeV of energy. Each frame represents a detection pixel and it can be seen that there is a difference between two zones of the panel. In the pixel $P_{11}$, where the SiPM of the horizontal bar and the vertical bar is only 2 cm from the point of impact of the muon, is produced the maximum number of pe while the pe decreases until 12% for pixels far from the SiPMs. This result is valid both for the front and the rear panel.

IV. THE WATER CERENKOV DETECTOR RESPONSE TO COSMIC BACKGROUND RADIATION

The WCD indirectly detects charged secondaries, by the Cerenkov photons generated by relativistic particles traveling through the contained water. The photo-multiplier tube counts photo-electrons according to its quantum efficiency, which depends on the wavelength of the impacting photon. In our case, the PMT Hamamatsu R5912 of the MuTe has a maximum detection probability value of 25% for photons with $\lambda = 400$ nm [38]. The PMT located at the top of the metal container of purified water with 120 cm side, coated with a diffusive lining of Tyvek.

The following sections will discuss some results from the detector simulation, as well as the first data recorded by the WCD.

A. The WCD model

In Geant4 the water container is a stainless steel cube of length $l_c = 1.21$m, with water inside water in a cube of $l = 1.20$m side. The water has a refractive index $n$, which varies between 1.3435 and 1.3608, and a photon absorption length ranging from 0.69m to 2.90m according to its energy. In the walls of the cube, the Tyvek is modeled as an optical surface with a reflection index $n_{Tyvek} = 1$, which diffuses the Cerenkov photons.

For the PMT, the photo-cathode was simulated as an air half-ellipsoid with semiaxes $s_x = 10.1$cm, $s_y = 10.1$cm and $s_z = 6.5$cm, located on top of the water cube. The Quantum Efficiency (QE) of this device was introduced in the code, taking into account reference Hamamatsu R5912 [38]. The QE determines whether photons reaching the outer surface of the photo-cathode will be detected or not. These photons originate photo-electrons (denoted as pe) by photoelectric effect. The WCD response is given in terms of pe generated by each particle interacting with it.

Notice that the inclusion of the QE of the PMT in the code, as a function dependent on $\lambda$, represents an improvement over the simulations of WCDs carried out previously within the research group. An unique efficiency of 25% is taken into account in [45], for the wavelength range between 330nm and 570nm. Therefore, the new code offers more precise results of the pulses produced by the passage of particles in water.

1. Estimation of the Vertical Equivalent Muon unit

The Vertical Equivalent Muon (VEM) –defined as the average charge collected in the PMT when a high-energy muon vertically crosses the entire detector – is generally adopted as the unit to calibrate the energy deposited by incident particles and is independent of the detection position. Muons can be easily identified by installing plastic scintillators above and below the WCD [46].

Geant4 code allows the injection of muons with a chosen...
energy and direction. We model injecting 100000 vertical muons with 3GeV in direction $\hat{z}$ towards the water, and the initial position given by the point $P = (80, 80, 121)$ cm, over the WCD. The portion of the number of Cherenkov photons, $N$, that reaches the external surface of the photo-cathode, is $N_{\text{PMT}}$.

The $N_{\text{PMT}}$, depending on its wavelength, produces a number of photo-electrons, $N_{\text{pe}}$. We have estimated the efficiency of the WCD with the following chain of events. One VEM of 3GeV generates around 46857 Cherenkov photons in 120cm. Next, only 1617 of those photons reach the external surface of the photo-cathode, and, due to its quantum efficiency, around an average 203.2 pe was produced. Thus, the system has a muon detection efficiency of 0.4%, that is,

$$\eta_{\text{WCD}} = \frac{N_{\text{PE}}}{N} \times 100\% = \frac{203.2}{46857} \times 100\% = 0.4\% \quad (4)$$

Figure 12 displays the comparison of the VEM simulated value ($\sim 203.2$ pe) with the measured $\sim 167.5$pe. This figure represents the pe histogram for one hour of data for a discrimination threshold of 110mV. The histogram has two prominent humps, the electromagnetic (electrons, positrons and gammas) hump at $\sim 70$pe and the muonic hump at $\sim 167.5$pe[18].

To compare the WCD response to muons and electrons at the Cerro Machín Volcano, we run simulations for 100000 vertical electrons, VE, of 20MeV at the same initial direction and point $P$. Figure 13 presents the corresponding histogram of the number of photo-electrons. The mean value of the VE is smaller than the VEM, around $16.7$pe that represents a 8% of it.

Next, in the number of pe vs time displayed in plot 14 we sketch the VEM and VE pulses. From those histogram fits, we can obtain the attenuation time $\tau$ and signal length $l_s$. Finally, the table IV A 1 summarize the comparison between both charged particles.

### 2. WCD response to the cosmic ray background radiation

The LAGO ARTI framework allows us to estimate of the WCD response to the cosmic ray background radiation flux ($\Xi$) at any site[47]. This toolkit employs a Geant4 code to estimate the number of Cherenkov photons detected by the PMT and employing its quantum efficiency. The ARTI framework uses the energy and the momentum of the particles from $\Xi$ as input and obtains the flux by using the CORSIKA code[48], with a geomagnetic correction form MAGCOS code[49]. For other examples of the precise simulation chain see [50, 51].

Figure 15 plots the histogram of the number of photo-electrons, produced at Cerro Machin. The flux $\Xi_{CM}$,

$$\Xi_{CM} = \frac{N_{\text{Sec}}}{A} \times 480 \text{m}^2,$$

is calculated over a circular area $A = 480 \text{m}^2$ placed 1cm above the detector, with a zenithal aperture of $0 \leq \theta \leq 80^\circ$, and where $N_{\text{Sec}}$ represents the number of secondaries at this particular site.

The different curves represent the contribution of various particles to the total response (empty circles). Note that this curve has two main peaks, the first one with a contribution of the electromagnetic component and the second one with the muonic component.

### V. CONCLUSIONS

As we have stated above, MuTe combines two detection techniques: a hodoscope with two detection planes of plastic scintillator bars, and a WCD, in an innovative setup which differentiates it from some previous detectors.

- **Scintillators panels**: Inspired by the experiences of other volcano muography experiments[52, 53], we...
have designed two X-Y arrays of $30 \times 30$ plastic scintillating strips ($120\text{cm} \times 4\text{cm} \times 1\text{cm}$), made with Styrion$^\text{TM}$ 665-W polystyrene doped with a mixture of liquid organic scintillators: 1% of 2,5-diphenyloxazole (PPO) and 0.03% of 1,4-bis (5-phenyloxazol-2-yl) benzene (POPOP). Each array has 900 pixels of $4\text{cm} \times 4\text{cm} = 16\text{cm}^2$, which sums up 14,400 cm$^2$ of detection surface which can be separated up to $D = 250\text{cm}$.

- **Water Cherenkov Detector:** The WCD is a purified water cube of 120 cm side, located behind the rear scintillator panel, which acts as an absorbing element and as a third active coincidence detector. Due to its dimensions and location, it filters most of the background noise (low energies electrons, protons, and muons moving backward), which could cause overestimation in the hodoscope counts [34], and it is capable of isolating the muonic component of the incident particle flux. From the charge histogram, obtained by time integration of the individual pulses measured in the WCD, it is possible to separate two components of the incident flux: electromagnetic part (photon, electron & positron) and the $\mu-$component [50].

The Colombian MuTe combines particle identification techniques to discriminate noise background from data. It filters the primary noise sources for muography, i.e., the soft-component ($e_{\pm}$) of EAS and scattered/upward-coming muons. Particle deposited energy identifies Electrons-/positrons events in the WCD, while rejects scattered and backward muons using a pico-second Time-of-Flight system.

From the Geant4 modeling of the scintillator detector, we obtain that the number of pe decreases around 7%, with respect to those produced at the end near of the SiPM. This reduction occurs due to the attenuation of the photons that travel in the fiber, since, the more distance they travel within it, the more energy they lose and lesser photons reach the SiPMS. This result is in agreement with the 11% attenuation obtained with the experimental setup described in section III.B. This attenuation seems to be insignificant in the bar, but it is more noticeable in the hodoscope panels, since, the difference between the closest corner to the SiPMs and the furthest, is around 12%.

Regarding the WCD response, the value of simulated VEM and those recorded in the laboratory measurements, are in the same order of magnitude but present a percentage difference of 18% concerning the simulated value. This difference can be related by the various components of the electronics, where part of the signal can be lost.

From the results obtained, a muon detection trigger for the MuTe is proposed in terms of the energy deposited in each of its components. That is, the muon must deposit around 2.08MeV in two scintillator bars on the front panel, then the same energy in two bars on the rear panel of the hodoscope,
to finally discriminate the signal from the noise in the WCD. Then, the muon must deposit around 240 MeV of energy in the WCD to be counted as an event.

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