Astroparticle projects at the Eastern Colombia region: facilities and instrumentation

Proyectos en Astropartículas en la región Este de Colombia: iniciativas e instrumentación

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***Abstract*— We describe some projects and initiatives for astroparticles physics from basic and application level. Three specialized instruments have been designed, built and put into operation for the study of various characteristics and phenomena of cosmic rays. One detector based on Cherenkov effect consists of three Water Cherenkov Detectors calibrated spatially and temporally, that allow the characterization of secondary cascades of cosmic ray particles. These devices allow studying the original composition and parameters of primary cosmic rays from the secondary particles detected on the ground. The second type of detectors based on scintillation effect and used for specific applications in the characterization of materials and geological structures inferring inner composition and density profiles.**

***Index Terms*— Astroparticle techniques, cosmic rays, high energy physics instrumentation.**

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***Resumen*— Describimos algunos proyectos e iniciativas para la física de astropartículas a nivel básico y de aplicación. Se han diseñado, construido y puesto en funcionamiento tres instrumentos especializados para el estudio de diversas características y fenómenos de los rayos cósmicos. Uno de los detectores basados en el efecto Cherenkov consiste en tres detectores de agua Cherenkov calibrados espacial y temporalmente, que permiten la caracterización de cascadas secundarias de partículas de rayos cósmicos. Estos dispositivos permiten estudiar la composición original y los parámetros principales de los rayos cósmicos primarios así como también de las partículas secundarias detectadas en superficie. Un segundo tipo de detectores basados en el efecto de centelleo se utilizan para aplicaciones específicas en la caracterización de materiales y estructuras montañosas. Estos detectores permiten el conteo de partículas secundarias incidentes (principalmente muones) mediante la determinación de su dirección de llegada. Al estudiar su atenuación en el medio material podemos inferir perfiles de composición y densidad.**

***Palabras claves*— Técnicas en Astropartículas, rayos cósmicos, instrumentación en física de altas energías.**

I. INTRODUCTION

COSMIC rays (CR) are particles (hadrons, atomic nuclei, or photons) generated outside the Earth's atmosphere which provides evidence about the nature of high-energy astrophysical phenomena and, at the same time, helps the understanding of high-energy physical processes in elementary particles physics.

The study of Astroparticle Physics is an interesting topic with great openness and upswing in recent years throughout the Latin American continent with significant efforts dedicated in the design, construction, and start-up advanced and specialized measuring instruments for the study of the cosmic rays and their applications. Some of these include the study of physics of Gamma-Ray Burst, Forbush decreases, space weather, characterization of the atmosphere and interstellar medium, modulation, and cyclicity of solar activity and a growing technique called muon tomography.

In this work, we present some of the ongoing projects Bucaramanga Colombia, oriented to study cosmic rays applied to the physics of terrestrial phenomena and estimate density distribution from the interior of volcanic structures.

II. Guane Array

One of the methods existing for the measuring of cosmic rays is the use of WCD, which detects secondaries particles produced by the Extended Atmospheric Showers (EAS) [1], [2], [3], [4]. This type of detectors captures the radiation generated by the passage of charged particles moving faster than the speed of light in the dielectric medium (water). One of the benefits of this type of instruments is low cost and high efficiency.

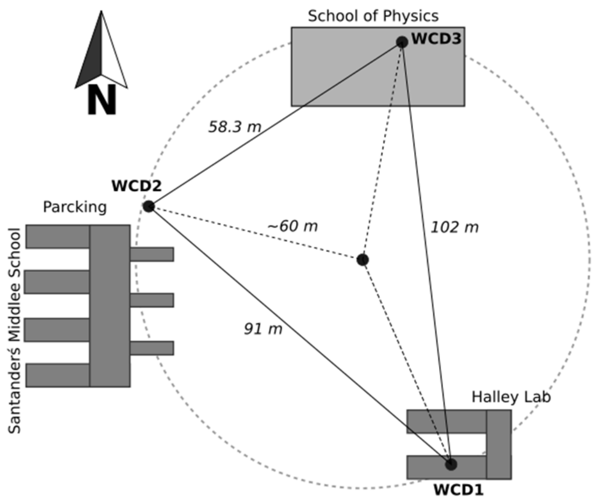

Fig. 1. Array of three WCDs in Industrial University of Santander. In the triangle array is showed the distances between each detector

The Universidad Industrial de Santander in Bucaramanga-Colombia --at 992 m.a.s.l., and magnetic rigidity in the subequatorial zone-- has three WCDs at the vertices an equilateral triangular array (100m side). Each WCDs consists of cylindrical plastic tanks with a base diameter of 210 cm and 130 cm in height, covered internally with Tyvek material. The water into the tank requires purification treatment; we use LAGO standard electronics consisting on DAQ (amplification and discrimination, base-line correction), FPGA NexysIII, GPS Motorola on-core, temperature and pressure sensor HP03, a cubie-board AII, a hard disc for storage, and a Photomultiplier Tube (PMT) is reference R5912 Hamamatsu.

We use detailed CORSIKA simulations to estimate the secondaries particles observed at ground level by the EAS produced during the interaction with the atmosphere of the complete flux of primaries parametrized by the geographical location of Bucaramanga city, altitude, and magnetic fields components (B_x=26.89 μT, B_z=16.62 μT, Data obtained from the National Oceanic and Atmospheric Administration (NOAA) https://www.ngdc.noaa.gov/geomag-web/#igrfwmm). We assume a range $1 \leq Z \leq 26$ for injected primary nuclei considering a single power law for the energy of each primary nucleus. As the rigidity cut depends on the arrival direction of each primary, the total number of primaries N is strongly angular dependent. The objective of these simulations is to find which are the secondary particles predominant in EAS, as well their associated energy for a complete calibration and characterization of expected detector function.

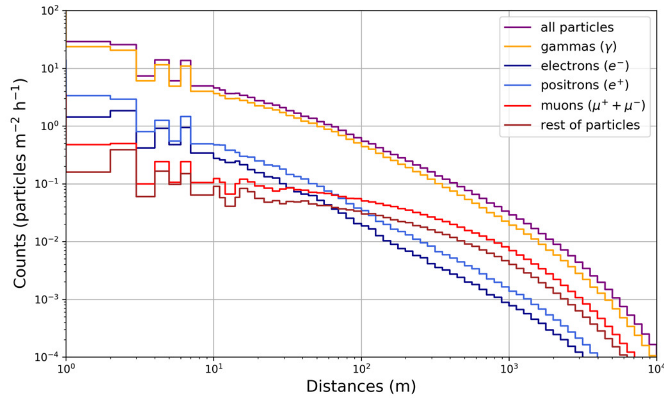

Fig. 2. Particles count from Corsika simulations for array of three detectors. Transverse distribution of particles in the full range of EAS.

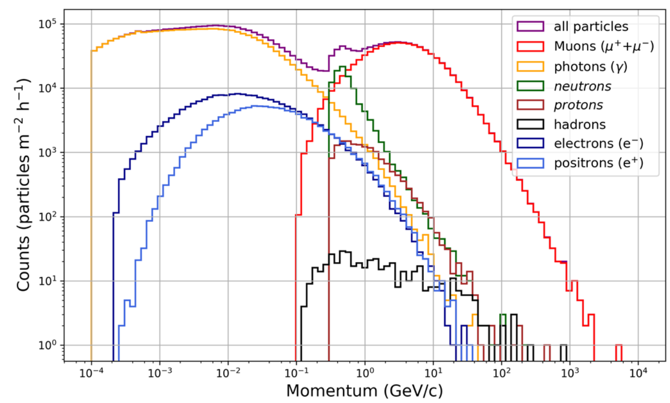

Fig. 3. Particles count from Corsika simulations for array of three detectors. Energy distribution (GeV) of the incident particles in bins of energies.

Figures 2 and 3 show the lateral distances and energy distributions from the center of EAS core. As can be seen in these figures, most of the particles accumulate within a radius of 100 meters which is the typical scale of the instrument.

The fraction of the electromagnetic part of the cascade is 0.679 (photons, electron or positron), 0.214 muons and 0.029 for rest of particles (mainly hadronic component). The array should be time synchronized to measure accurately the temporal arriving information of the particles hitting in each WCD. Therefore, we implement a very precise time stamp (25 ns), synchronized through a PPS signal (Pulse Per Second) provided for the Motorola UT Plus Oncore GPS. We also estimate the time delay of the transmission signal, defining the distance between the photomultiplier sensor into the WCD and the recording electronics to cause delays in the order of ns (length of cables of 2-3m). Correct characterization of the time delay properties of the connecting wires becomes necessary for posterior data processing in search for the EAS trajectory.

WCD in the GUANE array operate in two modes: as independent detectors and as an array. Individual detectors use the single particle technique to distinguish events from the background baseline [4]. WCD arrays, made of several detectors arranged over some area, can estimate the arrival direction of the primary particle by comparing the arrival time of the shower front in different detectors and evaluate primary energy by the number of secondary particles detected.

Individual WCD can detect variations in the cosmic ray flux such as Forbush decreases, but they cannot determine the energy or the direction of the primary cosmic ray. From individual detector data, we have recorded a modulation of cosmic occurred on September between days 4 and 5 [5], caused for a Coronal Mass Ejection that reached the Earth in 07-09-2017 at 22 UTC. One of WCD of the array registered this Forbush decrease measuring variations in the secondary cosmic ray flux (electromagnetic and muonic component) due to changes in the geomagnetic field [6].

On the other hand, the array is spatially and temporally calibrated, to study Space Weather events such as Forbush decreases as well as any modulation of cosmic rays by the solar activity.

III. Escaramujo Project

The Escaramujo Project (http://es.escaramujo.net/) is part of a series of laboratory workshops on High Energy Physics and Instrumentation in Astroparticles in Latin American institutions financed by Fermi-Lab. During the project, each institution built a modern cosmic ray detector based on the Plastic Scintillator (CP) and Silicon PhotoMultipliers (SiPM), designed specifically for measuring the muonic and electromagnetic component of cosmic rays. A functional detector remained in each institution to be used by the faculty to facilitate the training of future students and allow local research activities.

In addition to the goal of raising awareness of science, technology, and engineering, the Escaramujo Project was an effort to strengthen the integration of Latin American academic institutions in the international scientific community [7]. The detector consists of an arrangement of three plates of plastic scintillators (EJ-200) coupled to Silicon photomultipliers (MicroFC-60035-SMT, SensL). The size of the plates is 25×25×1 cm3. A SiPM connects each plate, assembled to one of the sides of the plate. Each plate is also wrapped with an inner layer of Tyvek paper and an outer layer of black opaque paper. Figure 4 shows the complete configuration of this device.

The main Escaramujo component is a time-to-digital converter (TDC) with a complex programmable logic device (CPLD). The TDC records the time of the leading and trailing edge of the pulse with a resolution of 1.25 ns. The CPLD allows the user to define settings such as level of coincidence; channels enabled, threshold voltage among others. The DAQ card, powered by 5 V DC, has a 5 V output connector to polarize other devices. The QuarkNet DAQ version 6000 card, initially designed to work with photomultiplier tubes, now has a four-channel polarization plate adapted to use SiPMs. The card takes the 5 V from the connector output of the QuarkNet card and generates ≈ 30 V with the DC-DC converter LT3571. The polarization voltage of each SiPM can be adjusted with a potentiometer located on the Bias T card.

A low-cost embedded computer (Raspberry Pi 2 Model B) and Minicom --a text-based serial communication software-- complete the configuration of the detector.

Raw data, stored in a text file in .dat format, can be copied to a PC via USB or through a remote system by SFTP) for further data analysis. The detector has GPS and temperature/pressure sensors.

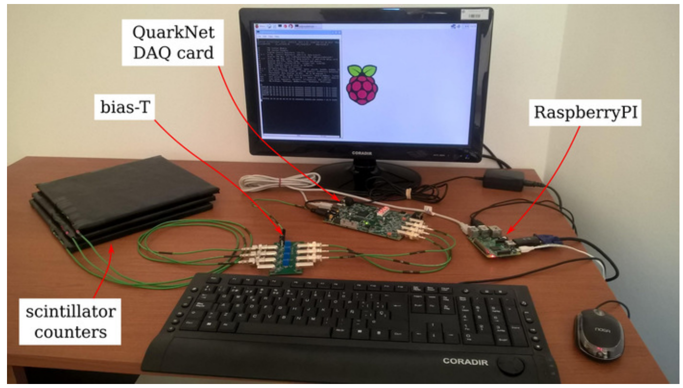

Fig. 4. Integrated full detector and connection scheme. The SiPM are attached to one side of the plasticscintillation plates and these in turn are connected to an acquisition card which is connected to the RasperryPi.

The detector has three parallel plates and sustains a solid angle (Ω) obtained analytically as

$$\Omega = 4\arctan\left(\frac{\sqrt{2}a^2}{4l\sqrt{a^2+2l^2}}\right) \quad (1)$$

where a is the side of each plate (all equals dimension) and l the separation between them. Assuming a separation of $l = 30$ cm with plates of $a = 25$ cm, we have a sustained solid angle of $\Omega_{1,3}$=0.5939sr and a geometric factor of $F_{1,3} = 371.18 cm^2$ sr with plates 1 and plate 3; considering plates 1 and 3; now considering plate 1 and 2 (or equally 2 and 3), the solid angle and the geometric factor are $\Omega_{1,2} = \Omega_{2,3} = 1.6891$ sr and $F_{1,2} = F_{2,3} = 1055.69$ cm^2 sr, respectively. Figures 5 and 6 show the values for the solid angle and geometric factor for several plate configurations. Based on these parameters, the acceptance (F geometric factor) of the detector can be defined as $F = S\ \Omega$, where S is the effective detection area of the scintillator plates (all area) and Ω the solid angle between the plates.

After a pre-calibration process --which consists in determining the thresholds suitable for the operation of the SiPM-- we proceed to calculate two critical factors to validate the laboratory measurements. The first consists of the calculation of the detector efficiency, i.e., the ratio between counts produced by the upper and lower plates configured in coincidence and the events measured simultaneously by the three plates. If the extremal plates (i.e., the upper and lower) detect a particle, then it must necessarily pass through the middle plate. We found an efficiency of 0.9964, which indicates a high level of reliability of the data collected.

Because of the distribution of atmospheric muons changes with latitude, height, and the local geomagnetic field, we have determined and described the angular dependence of the cosmic ray flux as $I(\theta) = I_0 \cos^n\theta$, where I_0 is the maximum flux measured at zero degrees of zenith angle for the particles arriving at the surface of the earth [8] [9] [10].

Using the Escaramujo detector we carried out an experimental design considering the counts of individual particles that cross the instrument with separation distances between plates of 30 cm and varying the angle of incidence with the help of a structure for this purpose. After adjusting the data, we have verified that the angular dependence of cosmic rays for the city of Bucaramanga has a relationship $I(\theta)=1.004\times10^{-3}\cos^{2.18}\theta$.

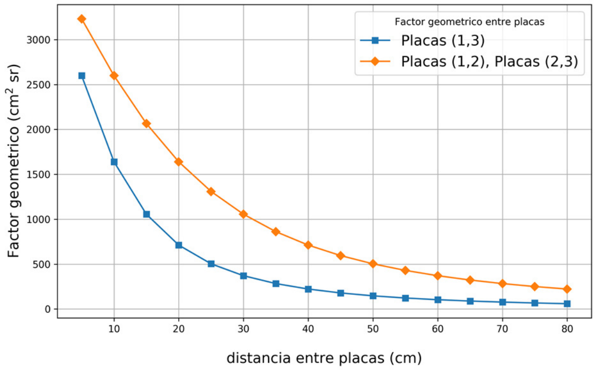

Fig. 5. Values for the geometric factor for various plate configurations of Escaramujo array.

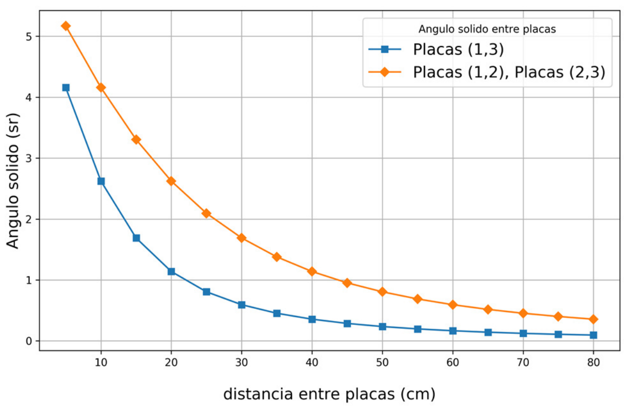

Fig. 6. Values for the solid angle for various plate configurations of Escaramujo array.

A second validation consists of the calculation of the lifetime of the muon. We have found 412.661 events with an average lifetime of 2.42 μs in three days of collected data and, we consider the detector reasonably calibrated with this tolerance of 10 % for the muon lifetime.

Another ongoing project is the determination of density profiles in various bodies obtained from attenuation of muons flux with plates covered with different materials.

Another application that is currently underway is to point this device at nearby mountains and establish validation with other devices and local geographic measurements to understand the attenuation of charged particles in dense media.

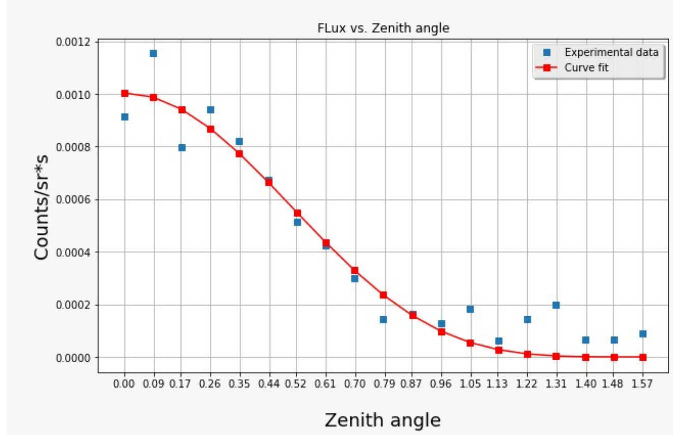

Fig. 7. Angular dependence os muon flux in terms of arrive direction into detector.

The detector is fully operational and is measuring continuously. Data analysis is carried out regularly to continue with the characterization of the flux of the muonic component of the cosmic rays.

IV. Volcanic Muography

Muons are highly penetrating charged particles, with 200 times the mass of the electron [12] and muography is a non-invasive technique which uses atmospheric muons to generate images --associated density distribution-- of geological and/or anthropic structures [11]. This technique applies in search of geothermal reservoirs and identification of radioactive materials in containers [13]. It has been also used to explore the internal structure of nuclear plants [14], dams, metallurgical furnaces, a search of hidden cameras in archeological structures [15] and even C02 monitoring on the sub-surface of the earth [16]. Our primary interest is to describe the distribution of density of the upper layers of volcano edifices and, eventually, to monitor its temporal evolution during an eruption [17].

Currently, several detectors perform muon tomography [18] [19], these instruments are typically made up of scintillation panels with large volume and weight, a complex electronic system, expensive and of significant energy consumptions. Besides, its assembly requires high logistical complexity for transport, installation, and commissioning, a significant obstacle for these detectors is the installation in remote locations challenging to access.

In 2015 started a project to apply the muography technique for Colombian volcanoes. The objective of this project is the construction of a portable and hybrid detector to determine the density distribution at the upper layers of volcanoes. One of the distinctive features our Muon Telescope, MuTe, is that it combines two scintillators panels with a WCD. Thus, MuTe is a hybrid instrument, combining two detection techniques -- a hodoscope made by two detection planes of plastic scintillator bars, and a WCD-- in an innovative manner which differentiates it from some other previous detectors.

Hodoscope of scintillators panels: Inspired by the experiences of other volcano muography experiments [20] [21], we have designed two X-Y scintillating parallel arrays of 30 x 30 = 900 pixels of 4cm x 4cm = 16 cm^2, which sums up

14,400 cm^2 of detection surface. The panels can be separated up to D = 200 cm (see figure 8) and can be easily transported and assembled at the installation site.

Water Cherenkov Detector: The WCD is a purified water cube of the 120cm side --located behind the rear scintillator panel (see figure 8) which acts as absorbing element and as a third active coincidence detector. Due to its dimensions and its location, our WCD filters most of the background noise (low energies electrons, protons, and muons moving in reverse) which could cause overestimation in the hodoscope counts [22]. Additionally, it also adds another detector, in coincidence with the hodoscope, to estimate the energy spectrum of the detected muons.

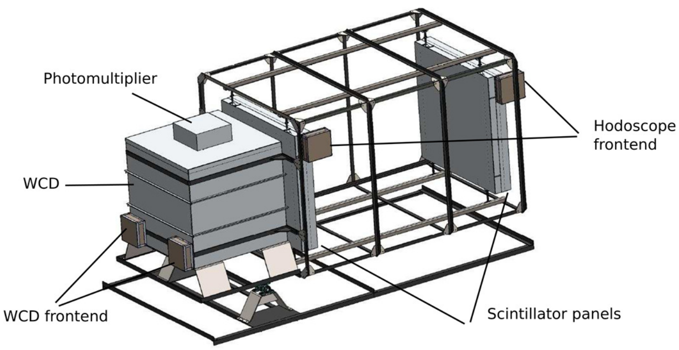

Fig. 8. Structure of the MuTe hybrid detector. This is composed by two scintillator panel hodoscope with their respective electronic frontend and a WCD which performs the energy loss estimation of the events coming from the volcano.

To test the electronics of MuTe we design and build a prototype of 9 pixels hodoscope (see figure 9). The light generated by the interaction of a charged particle (mainly muons) with each of the bars, collected by an optical fiber coupled to a silicon photomultiplier (SiPM), converts light pulses into an electrical signal.

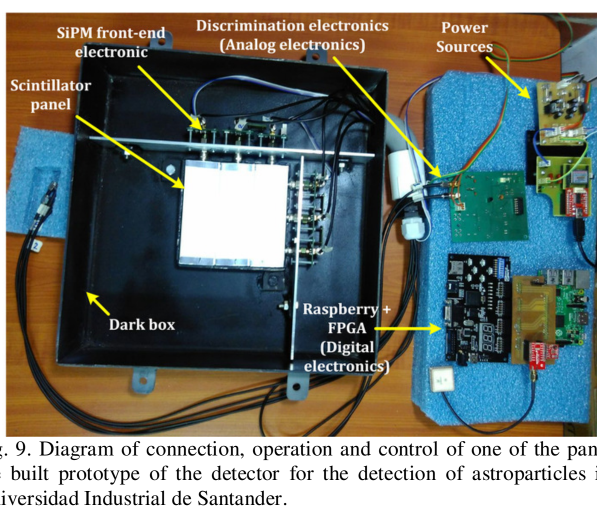

Fig. 9. Diagram of connection, operation and control of one of the panels of the built prototype of the detector for the detection of astroparticles in the Universidad Industrial de Santander.

Subsequently, an electronic system discriminates, digitizes and records the events associated with these particles impacting the instrument. These data --georeferenced, labeled with the time-stamp, pressure, and temperature-- become a highly portable file, sent for offline analysis. The electronic system consists of a MAROC3 board which manages the 12 signals from both panels, and there is no TDC system implemented. An FPGA, based on the Spartan 6 chip, collects the digitized information and transmit it to an embedded system (Raspberry Pi).

We carried out a systematic study to determine the best conditions and sites for the application of the technique in different volcanoes in Colombia [23] [24]. A part of the research, based on detailed simulations (using Corsika [25] and Geant4 [26]), allow us to infer the muon flux in different volcanic scenarios. In this way, it is possible to establish the best observation sites and points to place the telescope.

This device is operatively working in the laboratory and passing the design, calibration and measurement tests. For the moment, with excellent results and performance.

V. Conclusion

We have presented a review of a group of projects in astroparticles and their applications in the Eastern Colombian region. Three detectors using various techniques have proven to be useful for research in basic and applied areas of cosmic ray physics. From the collaboration of physicists, electronics specialists, geologists and scientists from different disciplines have work on high energy cosmic rays applications.

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