Earthquake Studies Using a LAGO Water Cherenkov Detector in Ecuador

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Several studies have suggested the possibility of an interrelation between the occurrence of earthquakes and local disturbances in the geomagnetic field. On April 16, 2016, Ecuador suffered one of the strongest earthquakes in its history. One of the Latin American Giant Observatory (LAGO) water Cherenkov detectors (WCD) located in the city of Riobamba, Ecuador, was acquiring data before, during and after this seismic event. LAGO is an experiment that consists of a network of WCDs located at different altitudes and latitudes throughout Latin America, with the main purpose of studying the physics related to cosmic rays. In this work we revisit the idea, already explored by other LAGO groups, of using the data acquired by LAGO WCDs to study the interrelation between seismic phenomena and the geomagnetic field modulation of the flux of atmospheric muons originated in extensive air showers. We present the analysis strategy and preliminary results.

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1. Introduction

Particles of different kinds (from single protons to iron atoms) and sources are constantly hitting Earth's atmosphere. In astrophysics, these are known as cosmic rays. Cosmic rays that reach the Earth's atmosphere arrive in a wide range of energies; they can be as high as 10^{20} eV [1]. When these particles reach the atmosphere, they collide with the particles forming it. If an incident particle has enough energy in its collision, it will generate a shower of secondary particles, which will rush downwards towards the Earth's surface. For this reason, the incident particles are also known as primary particles. Not all of secondary particles will reach the surface, some will collide with other atmospheric particles, and if they are charged, they will be deviated from their vertical fall by the Lorentz force caused by their interaction with the magnetic field . The stronger the magnetic field the more the particles will get curved and if they enter the atmosphere with a particular velocity and direction they will not reach the surface (for more details see [2]). Therefore, if there is a change in the magnetic field, we would expect to detect a change in the secondary particle flux.

There is evidence suggesting that earthquakes can momentarily change Earth's magnetic field. For instance, on March 27 of 1964 a magnetometer located in Alaska, in the city of Kodiak, detected a significant change in the local magnetic field one hour before an earthquake occurred. The magnitude of the magnetic field increased briefly by an amount of 10^{-7} T, and during the working month of the magnetometer at no other time was a fluctuation of this strength recorded [3]. Also, on February 27 of 2010, a drop on the cosmic ray flux was reported by the Auger Observatory in Argentina, 90 seconds after an 8.8 magnitude earthquake occurred in Chile. As the authors claim, this time is comparable to the amount of time an s-wave would take to reach the observatory from the epicenter, causing a drop in flux with a significance of 24σ [4].

The Latin American Giant Observatory (LAGO) consists of a network of water Cherenkov detectors (WCD) distributed across Latinamerica with the purpose of studying the physics related to cosmic rays. The project is a collaboration of 27 different institutions located in 10 different countries. In this paper we report on the strategy used to analyze the data collected by one of LAGO's WCDs located in the city of Riobamba, Ecuador, during a strong 7.8-magnitude earthquake that happened in the evening of April 16, 2016. We sought for evidence of any hint of sensitivity of the apparatus related to this natural phenomenon.

2. Detector Description

Cosmic rays are not detected directly. They arrive to Earth at relativistic speeds. Some of its sub-products (secondary particles) can even go through matter barely interacting with it; therefore, they can reach the Earth's surface.

Our detector takes advantage of an effect known as Cherenkov radiation. When a charged particle goes through a medium, at a speed faster than light's phase velocity in that medium, electromagnetic radiation is emitted [5]. A water Cherenkov detector (WCD) consists of a tank filled with water, with a light detecting device inside, which is sensitive enough to detect Cherenkov radiation.

Data analyzed in this project was collected by a 1100 liter water tank, arranged to work as a WCD. The detector is part of LAGO's network and it is managed by Escuela Superior Politécnica

de Chimborazo, in Riobamba, Ecuador. It rests at 2700 m.a.s.l. The tank has a cylindrical shape with a circular base of 1.12 meters in diameter (see Figure 1). It is made of polyethylene and contains a black covering to prevent any light from entering. Its interior surface is covered with Tyvek®, a material made out of polyethylene fibers which reflect diffuse light. For optimum functioning the tank was filled with water, which underwent a process of distillation, reverse osmosis and chlorination. The electronic components of the detector are: a photomultiplier (PMT), located at the top of the tank, a digitizing card, a NEXIS2 field programmable gate array (FPGA), and a CPU. Figure 2 illustrates how the detector is set up [6].

Figure 1: Water tank at Escuela Superior Politécnica de Chimborazo. The picture shows the "undressed" plastic tank. The black cover rests at the bottom.
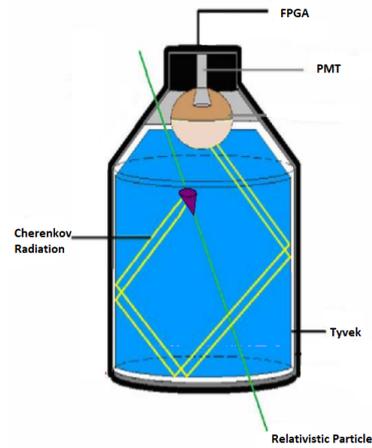
Figure 2: WCD Tank Scheme. Once a cosmic ray enters the tank it generates a light pulse. This pulse is detected and amplified by the PMT located at the top of the tank [7].

The detector contains a triggering system, which prevents any signal below the set threshold to be registered. The trigger has to be set just below the saturation point of the electronic system to allow the greatest amount of relevant data to be collected. To find this level, the trigger was raised in small steps while testing the signal until saturation stopped. This occurred at a threshold of 1450 V for the PMT.

3. Analysis and Results

Figure 3 displays the particle flux registered by the detector from April 10 to April 18, 2016. It is clear that the flux is not uniform over time and a 24 hour periodicity is observed. This is understandable given that factors like temperature, pressure and primary particle flux (all of which affect secondary particle flux) also have 24 hour periods. Our analysis strategy was rather simple: we searched for a sudden and inexplicable flux change over time. A quick eye inspection of Figure 3 reveals a sudden decrease in particle rate right before April 14th; no other fluctuation calls the attention. Finding an out-lier within the peaks, which already contain lots of flux variations, re-

quires a more careful and systematic examination. To do this we implemented the moving window average method (MWA), described later in this paper.

The earthquake in Chile, studied in the report mentioned above, resulted in an abrupt change in secondary particle flux, which had a deviation of 24σ; it later had a rather slow recovery [4]. This means that the standard deviation of the data containing the fluctuation will be greater than in a subset of data that does not. In search for a similar effect we implemented the aforementioned MWA method [8]. This method consists in calculating the average and the standard deviation of the flux in a 5-minutes window, starting from the first five minutes. Then, this window is displaced one second, i.e., it starts and ends one second after the previous window, and again the mean and standard deviation of the flux in that window is recorded. This process is repeated until all the data, from April 10th to April 18th, has been covered. The standard deviation of the set of standard deviation windows are then calculated. We are interested in finding windows that have a standard deviation that is greater than five times the whole set standard deviation.
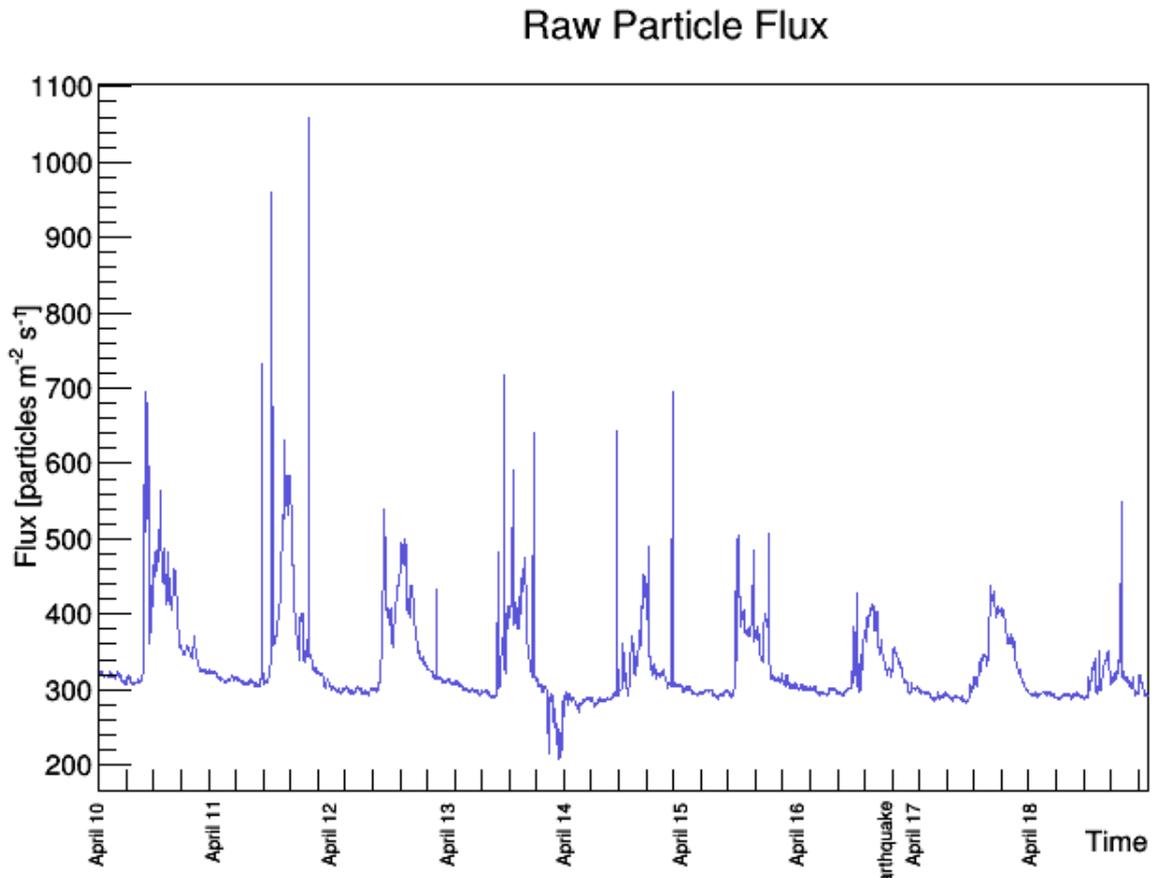

Figure 3: Particle incidence rate without any type of corrections.

However, before attempting to use the MWA method, we eliminated known electronic noise from our data. Firstly, the detector contains three channels of which only two where active during data collection: the main one with the active trigger, and an additional one to provide redundancy

at half amplification and no trigger. It was found that some registered events had activated triggers from channels other than the main channel (channel-1). These cannot be real events so they were discarded.

The electronic system of the detector stores signals as charge pulses. Each pulse is stored as a vector of 12 entries, where each entry contains the ADC arbitrary value of the pulse at different times and where the peak is always stored in the third entry. This detected signals can be generated by particles or by noise. Fortunately, noise signals are shorter in duration than real signals, which makes them identifiable. One way of doing this is taking the ratio of the total charge of a pulse (the sum of the twelve entries) and its peak. Shorter pulses will have a ratio closer to one than longer pulses. A histogram of this ratio can be seen in Figure 4 in blue. In principle the minimum value this ratio can take is 1 (if the only non zero entry is the peak) and the maximum is 12 (if all entries have the same value). There are clearly many events outside of this limits. Following a preliminary study within the LAGO Collaboration [9], instead of directly removing events that exceeded these limits, an analysis cut that consists of adding a second, off-line trigger was implemented.

All pulses that were registered had a peak greater than 63 ADC. For this second cleaning requirement we removed all events whose fourth entry (entry after peak) was also less than 63 ADC. Since noise generated signals are shorter in duration than real signals, it is more likely for them to have a fourth entry less this threshold in comparison to real signals. The resulting charge/peak histogram after this requirement can be seen in Figure 4 in red. It successfully removed the undesired events mentioned above.
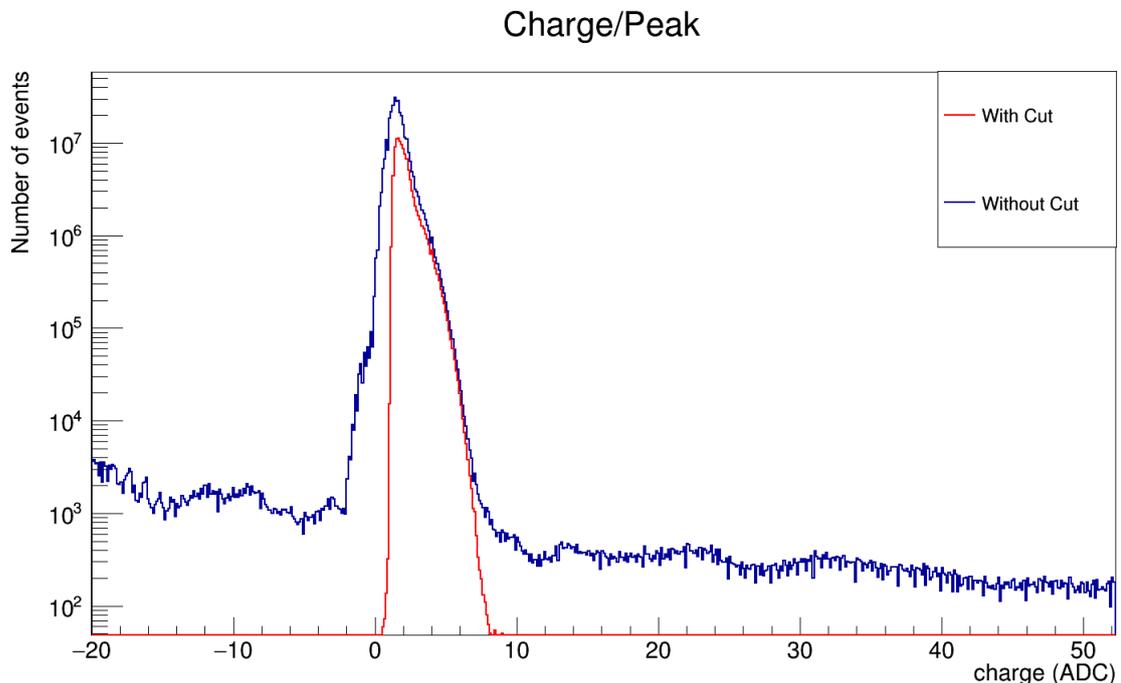

Figure 4: Charge/Peak Histogram. The distribution of the charge-peak ratio before and after the second trigger requirement was implemented in blue and red, respectively. The graph in blue shows events with ratios smaller than 1 and bigger than 12 which can not be real events. It can be seen the cut successfully removes those events.

In Figure 5 the flux after the two corrections is compared with atmospheric pressure (note that the scale for the atmosphere is inverted). It appears to be that the anti-correlation with pressure strongly decreases after April the 14th. Right before this date, a sharp decrease in flux is observed. The SOHO CME catalog and the GRB catalog (grbcatalog.org) were investigated in search for a possible solar, galactic or extragalactic event that could have caused the decrease but none was found. It is suspected that something interrupted the detector and caused it to stop working properly afterwards.
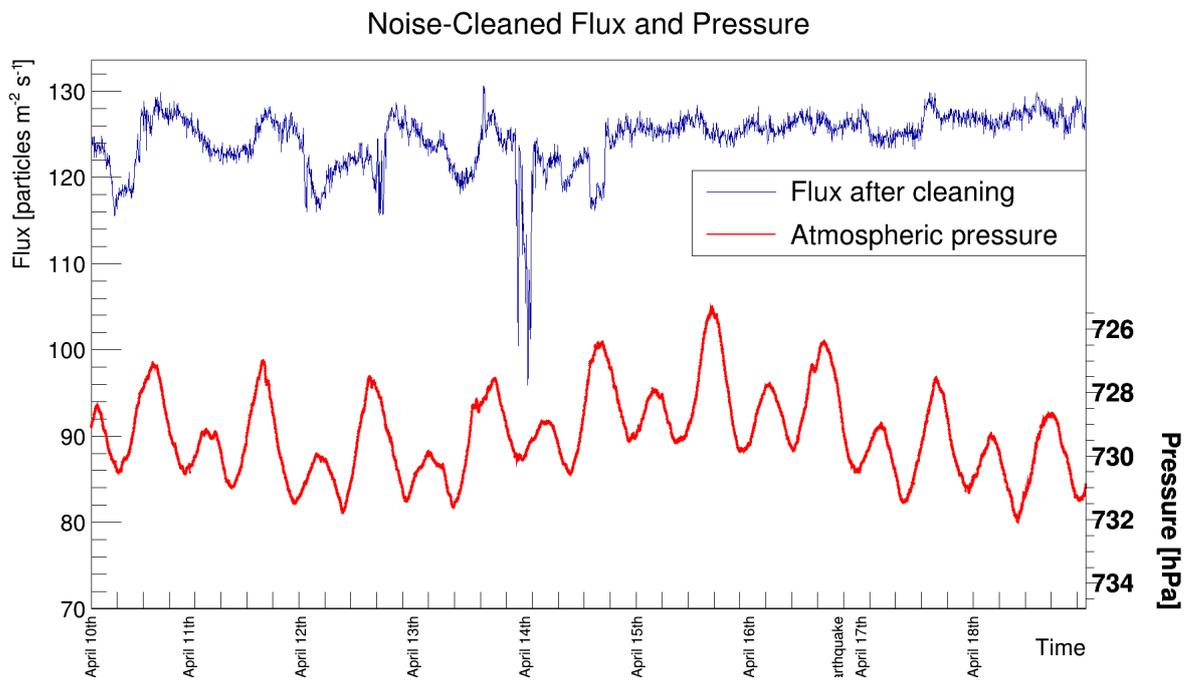
Figure 5: The particle flux after the cleaning is compared with the atmospheric pressure (with inverted scale). There appears to be a correlation with pressure up to April 14th which then is lost.

Nevertheless, having applied the noise-reduction requirements, the MWA algorithm was ran through the data. Figure 6 shows the distribution of the standard deviation of each window (the mean was subtracted).
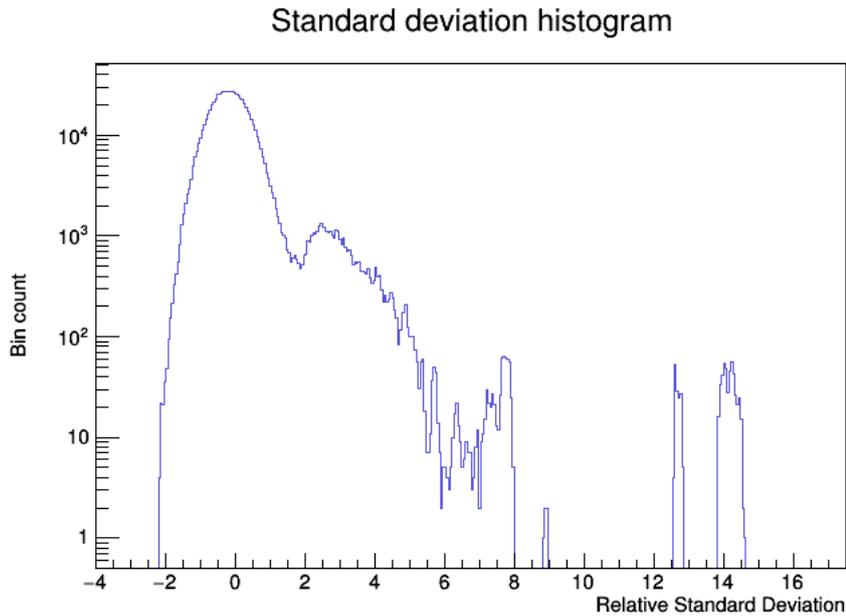
Figure 6: When the MWA method was applied, the standard deviation of each window was calculated. Here their distribution is shown (the mean was subtracted). Some windows show relative standard deviations greater than five but none correspond to the time of the earthquake.

A look at Figure 6 reveals that there are a couple of windows that had a standard deviation significantly higher than the rest. The time corresponding to windows that had a relative deviation greater than 5 times the standard deviation were identified. The highest variation corresponds to the depression before April 14th, other high variations appear in the 11th and 13th. There was no significant variation found near or at the time of the earthquake.

4. Conclusions

This was the first time data gathered by a WCD was analyzed for physics in Ecuador. We learned about and developed methods that analyze and clean data gathered by a WCD. After performing the analysis we were not able to find results similar to what was found at Auger Observatory, but the tools developed may be used in future investigations.

There are a couple of aspects to consider that may explain why our results are negative. First, our detector had a preliminary calibration and it appears that it suffered an interruption before April 14th. It also needs to be taken into account that Auger observatory had a very controlled set-up with 1660 calibrated WCD. It is a possibility that there was an effect caused by the earthquake in our detector but that it is covered by noise. Also, Chile's earthquake had a magnitude of 8.8 M_W. The one that happened in Ecuador was of 7.8 M_w. The effect may only be measurable above a certain threshold not reached by Ecuador's earthquake, or the waves it created did not propagate in a way that affects the geomagnetic field. We intend to keep our detectors with better preparation in case an event like this ever repeats. An effect caused by the earthquake was not found but this is an interesting subject which deserves more investigation.

5. Acknowledgements

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