PROCEEDINGS OF SCIENCE

Layered Water Cherenkov Detectors for Next Generation Air-Shower Arrays

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The next generation of cosmic and gamma ray experiments plans to answer persisting fundamental questions in ultra-high-energy astroparticle physics: what sources and acceleration mechanisms can produce the most energetic particles ever measured, with energies greater than 10 EeV? Are there any photons produced in our galaxy at 10 PeV? A proposed measurement technique for next generation air-shower arrays is the layered water Cherenkov detector. The water volume is optically separated such that a majority of the electromagnetic component of the air shower will attenuate in the top part, while the bottom one measures mostly muons. Currently, at the Pierre Auger Observatory in Malargüe, Argentina, two prototypes are deployed and have been taking data for over 10 years. The calibrated signals from these detectors can be used to extract the muonic and electromagnetic signals on an event-by-event basis, allowing for a direct estimation of the muonic component and a muon-independent air-shower energy reconstruction. We present the calibration method and the next steps to assess the layered detectors' sensitivity towards a mass-composition measurement for an extremely large array, like the Global Cosmic Ray Observatory (GCOS), or measurements of ultra-high-energy gamma rays with the Probing Extreme PeVatron Sources (PEPS) experiment.

7th International Symposium on Ultra High Energy Cosmic Rays (UHECR2024)
17-21 November 2024
Malargüe, Mendoza, Argentina

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PoS(UHECR2024)086

1. Introduction

The next generation of air-shower arrays is on the visible horizon, with the first deployment planned within the coming ten years. The future upgrades aim to answer remaining questions about the origin of UHECRs and the existence of Galactic PeVatron sources. Science goals of future observatories are to perform charged particle astronomy of the highest energy cosmic rays, and obtain more stringent flux measurements of cosmic rays, and gamma rays, at these ultra-high energies [1, 2]. Deployment over large detection areas and the use of state-of-the-art detection and analysis techniques will achieve these goals.

Improving methods to discriminate between hadrons of different mass, and hadrons and gamma-ray photons, are important paths forward in doing charged particle astronomy. Past studies have shown the importance of simultaneously measuring the electromagnetic and muonic components of extensive air showers for mass separation on an event-by-event basis [3, 4]. The combination of the depth of shower maximum (X_{max}) and total muon content of an air shower (N_{μ}) is of particular importance because of their direct relations to the electromagnetic and muonic shower components. This combination also tests hadronic interaction models, a major systematic uncertainty in air-shower analyses due to the mismatch between simulated and measured muon content of air showers [5, 6]. Hence, detection techniques which simultaneously probe the electromagnetic and muonic air-shower components are of particular importance for future air-shower arrays.

Currently, the planning and R&D phases of next generation air-shower arrays are underway. One of the proposed detector types for future arrays is the layered water Cherenkov detector [7], a modified version of the water Cherenkov detector. The Global Cosmic Ray Observatory (GCOS), Probing Extreme PeVatron Sources (PEPS) experiment, and the Southern Wide-field Gamma-ray Observatory (SWGO) all plan to use layered water Cherenkov detectors as a detection technique [8–11], with the design originally being proposed as part of the AugerPrime upgrade of the Pierre Auger Observatory. The layered detector builds from the original design of a water Cherenkov detector. In a layered detector, the water volume is divided into two stacked layers by an optically opaque material. The position of the separation layer is chosen so most electromagnetic particles will attenuate in the top layer, leaving mostly muons to trigger the detector in the bottom layer. This design allows a single detector to directly access information of the electromagnetic and muonic particles within an air shower, and the potential to disinguish between them. We first introduce the prototype layered water Cherenkov detectors currently taking data at the Pierre Auger Observatory in Malargüe, Argentina. We then describe the calibration method of the photomultiplier tubes (PMTs) in the bottom layer for these prototype detectors. Finally, we discuss calibration ideas for the top layer PMTs and provide a roadmap for analyzing data from these prototypes for physics analyses.

2. Prototype detectors at the Pierre Auger Observatory

Two prototype layered water Cherenkov detectors were deployed at the Pierre Auger Observatory in early 2014. The prototypes are modified versions of the Auger water Cherenkov detectors. Standard Auger water Cherenkov detectors stand 1.2 m tall and 3 m in diameter, with three PMTs located at the top of the water volume. The prototype detectors are modified to include a fully reflective separation layer to divide the water volume at 0.8 m from the bottom of the detector. A fourth PMT is installed at the height of the separation layer to measure Cherenkov light generated by particles in the bottom layer. Figure 1 shows the configuration of the prototype layered detectors. The electronics used for the layered detectors are the same as the electronics used for the Auger water Cherenkov detectors (see [12] for a description of the electronics prior to 2023 and [13] for the electronics after upgrades in 2023). This allows local technicians in Malargüe to service the prototype detectors as needed at minimal detriment to their other duties.

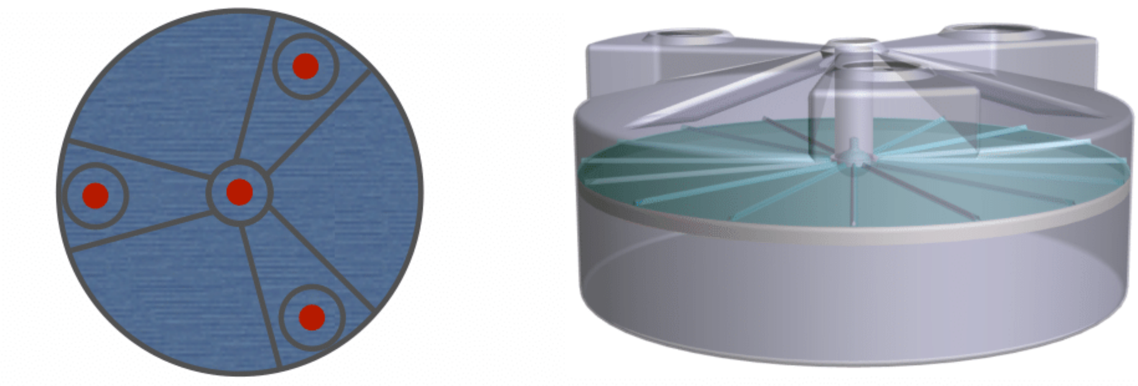

Figure 1: Design of the two prototype layered detectors located at the Pierre Auger Observatory. The three PMTs at the top of the water volume are in the same PMT locations as the standard Auger water Cherenkov detectors. A central PMT is installed 40 cm from the top of the detector to measure air-shower particles in the bottom layer. Design image taken from [7].

Since their deployment in early 2014, the prototype detectors have been recording air-shower data at a stable rate. The daily event rate for air-showers detected by the two prototypes is shown in Figure 2. Binning is done over a three month period, where the red circles (Clairon Jr.) and blue squares (Guapa Guerrera) represent the average daily event rate in that time period. The daily event rate is only recorded until early 2023 when the electronics for the prototype stations were changed.

The signals of the top and bottom layers can be represented by a combination of the signals deposited into the layered detector by the electromagnetic and muonic particles. In matrix representation,

$$\begin{pmatrix} S_{\text{top}} \\ S_{\text{bottom}} \end{pmatrix} = \begin{pmatrix} a & b \\ 1-a & 1-b \end{pmatrix} \begin{pmatrix} S_{\text{EM}} \\ S_{\mu} \end{pmatrix} \tag{1}$$

where a and b are determined by the specific design of the detector. Mathematically, a must be less than one, b must be greater than zero, and their sum is less than or equal to one. The electromagnetic and muonic signals can be separated on a per event basis if the 2×2 matrix in eq. (1) is invertible. This requires precise knowledge of a, b, and the calibrated PMT signals from the top and bottom layers of the detector. a and b can be derived from simulations of the detector response to electromagnetic particles and muons. A past simulation study for this specific prototype design determined $a \approx 0.6$ and $b \approx 0.4$, where these values were found to be independent of distance to the air-shower core, hadronic interaction model, simulated primary, and primary energy [7]. These values are also independent of zenith angle for vertical ($< 60°$) air showers. a

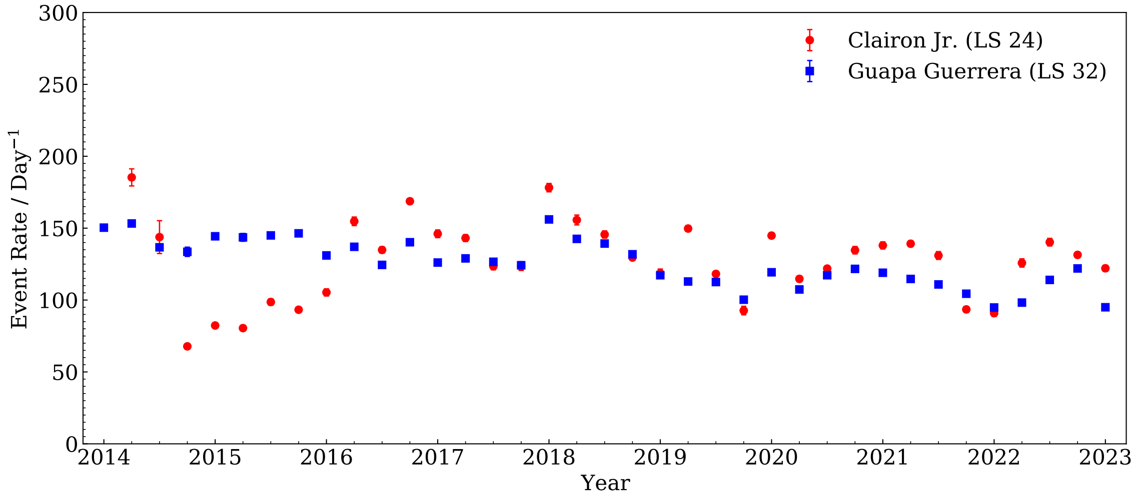

Figure 2: Average daily event rate for air-showers measured by the two prototype layered detectors, Clairon Jr. (red circles) and Guapa Guerrera (blue squares). Bins are three months in width. No data is available in the first bin for Clairon Jr. because the detector had not been deployed.

and b will change for inclined showers, as electromagnetic particles will attenuate in the atmosphere and only muons will reach the ground. This is beyond the scope of this study, although should be studied in a future analysis. As a and b are known for vertical showers measured with this prototype design, the remaining steps are to calibrate the PMT signals in the top and bottom layers.

3. PMT calibration

For standard water Cherenkov detectors, PMT calibration is performed by converting the PMT signal in FADC counts to units of a Vertical Equivalent Muon (VEM). One VEM represents the charge in FADC counts deposited by one vertical muon passing through the detector. To determine this conversion, charge calibration histograms from low-energy air-shower particles are compiled. Each entry in the histogram corresponds to an integrated PMT trace of the signal measured by a low-energy shower particle. For tanks with coincident PMT triggering above a determined signal threshold, the histograms show two distributions of measured charge signal. The first, at lower FADC counts, corresponds to electromagnetic particles, and the second, at higher FADC counts, corresponds to atmospheric muons. The peak location of the atmospheric muon distribution is used as a calibration constant proportional to one VEM of charge. Determining the location of this muon peak is necessary to standardize PMT calibration. For the layered detectors, a similar method to the Auger water Cherenkov detectors is used to compile charge calibration histograms (see Section 3.3 of [14] for an explanation of how the charge histograms are generated by the local station electronics).

3.1 Bottom PMT calibration

For water Cherenkov detectors with standardized PMT triggering above a baseline threshold, the electromagnetic distribution in charge histograms dominates the muon distribution. However, in the bottom layer of the prototype detectors, less electromagnetic particles will trigger the PMT as most of these particles will attenuate in the top layer. The charge histograms of the bottom layer PMTs illustrate this effect, as seen in Figure 3 for the Clairon Jr. prototype detector. The calibration data for this histogram was taken over a 60 second interval. The baseline was subtracted from each histogram entry. Here, the muon peak dominates over the electromagnetic peak, allowing for better separation between the distributions and cleaner determination of the muon peak location.

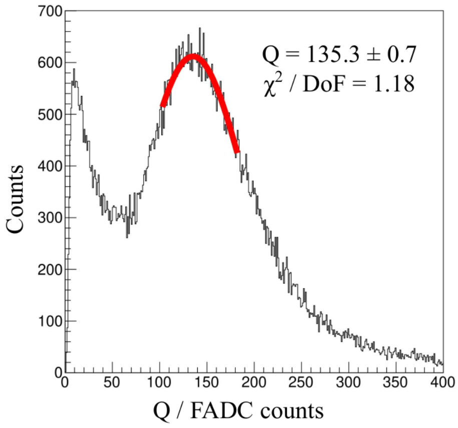

Figure 3: Charge calibration histogram for the PMT in the bottom layer of Clairon Jr. The histogram was compiled using 60 seconds of calibration data. The muon peak is visible above the electromagnetic distribution. A Gaussian fit is performed to the muon peak and overlaid on the figure.

A Gaussian fit is performed to determine the exact location of the muon peak. The fit is performed over a range of ±40 charge bins, centered on the histogram bin with maximum entries. The histogram maximum was determined after excluding the first 50 charge bins to account for calibration histograms where the electromagnetic distribution dominates the muon distribution. The Gaussian fit to the muon peak in Figure 3 is included as the solid red line. The location of the muon peak from the Gaussian fit is used as the calibration constant for the bottom PMT. For an Auger water Cherenkov detector, this constant is converted to VEM using measurements of vertical muons from a resistive place chamber hodoscope [15]. Direct measurements for this conversion are not available for the layered detector. Therefore, all calibrated PMT signals for the layered detector will be reported in terms of the calibration constant, with units of FADC counts. The conversion from FADC counts to VEM after determining the muon peak location is only a constant shift factor, so there is no difference in the physics.

Calibration data for the PMTs are available for all air showers measured by the layered detectors. The bottom PMT of each layered detector was calibrated by fitting a Gaussian to the muon peak of the calibration data. A violin plot of the calibration constants for the bottom PMTs of the two prototype layered detectors is shown in Figure 4. Data are binned in one month time periods, where the average monthly calibration constants are shown for Clairon Jr. (red circles) and Guapa Guerrera (blue squares). The seasonal modulation of the calibration constants is visible, caused by atmospheric changes that affect muon production in air showers and the temperature dependence of the detector response. Stable calibration of the bottom PMTs occurs several months after detector deployment, once the water inside the detector is settled. The average calibration constant of Guapa

Guerrera's bottom PMT decreases over several years of data collection due to an electronics issue. Stable calibration of Guapa Guerrera was achieved in 2021 after the electronics were fixed.

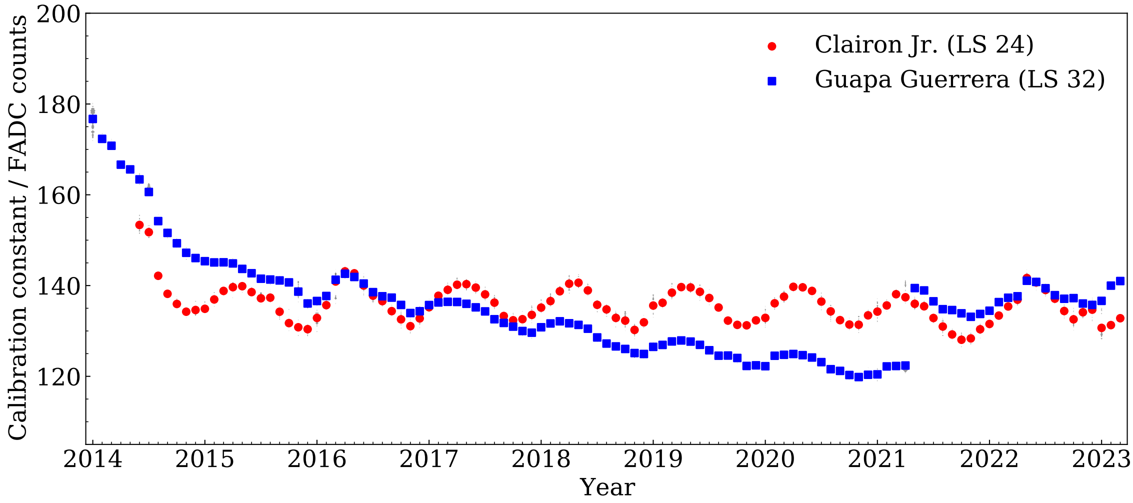

Figure 4: Violin plot of the per event calibration constant for the bottom PMTs of the two prototype layered detectors. The average calibration constants per time bin are represented by the red circles for Clairon Jr. and the blue squares for Guapa Guerrera. Time bins are one month in length. The calibration constant is defined as the location of the muon peak obtained from a Gaussian fit.

3.2 Top PMT calibration

In the top layer of the prototype detectors, a trigger method to separate the electromagnetic and muon charge distributions using real data is more challenging. Muons produce a similar charge to electromagnetic particles in the top layer due to their shorter track length in the detector. With the current trigger algorithm, the muon charge distribution is absorbed by the tail of the electromagnetic charge distribution. Collecting calibration histograms for a coincidence trigger of the top and bottom layer PMTs is proposed. The proposed coincidence trigger will occur when the bottom PMT measures a signal with a peak amplitude above a typical single muon threshold and the top PMTs simultaneously measure a signal above the determined background threshold. The thresholds will be determined from the current method for collecting calibration histograms. The top PMT signals of the coincidence trigger will be used to compile the calibration histograms. A majority of the PMT signals in the top layer resulting from this coincidence method will be muons. A fitting method to obtain the muon peak position of the charge distribution, similar to Section 3.1, can be implemented to determine the calibration constant for the top layer PMTs. Alternative methods proposed to extract the calibration constants of the top PMTs include using the shape of the muon signals or the measured water height within the layers of the prototype detectors (see [16]).

4. Conclusions and outlook

Two prototype layered water Cherenkov detectors at the Pierre Auger Observatory have been stably operating and recording air-shower data for the past ten years. Preliminary calibration studies for these layered water Cherenkov detectors are promising. The PMTs in the bottom layer of the detectors have been calibrated to signals from throughgoing, vertical muons. PMTs in the top layer do not yet have a standardized calibration; however, proposed methods are being studied. Compiling calibration histograms from coincident low-energy air shower particles in the top and bottom detector layers is the leading proposed calibration method for the top PMTs. After top PMT calibration, the resulting signals should be cross-checked with the calibrated signals of the standard Auger water Cherenkov detectors to ensure a successful calibration.

The matrix formalism can be used to extract the electromagnetic and muonic signals on an event basis after a successful method of top PMT calibration is determined. Signals can be used to determine average lateral distribution functions for the electromagnetic and muonic particles. From these signals, an estimate of the air-shower muon number and a muon-independent energy measurement are possible observables. Separate muon and electromagnetic signals could also be used as inputs to machine learning techniques to determine the depth of shower maximum, similar to [17], or other air-shower observables. Using layered water Cherenkov detectors as a detection technique for next generation air-shower arrays is optimistic given the stability and first results of the two prototype detectors operating at the Pierre Auger Observatory.

Acknowledgments: Supported by a Fellowship of the Belgian American Educational Foundation (BAEF). Funding for this research was provided by the United States National Science Foundation through NSF award #2046386. I.M. thanks the local staff of the Pierre Auger Observatory for their support.

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