29th International Cosmic Ray Conference Pune (2005) **00**, 101–106

Calibration of the surface array of the Pierre Auger Observatory

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The ground array of the Pierre Auger Observatory will consist of 1600 water Cherenkov detectors, deployed over 3000 km^2. The remoteness and large number of detectors required a simple, automatic remote calibration procedure. The primary physics calibration is based on the average charge deposited by a vertical and central throughgoing muon, determined with good precision at the detector via a novel rate-based technique and later with higher precision via charge histograms. This value is named the vertical-equivalent muon (VEM). The VEM and the other parameters needed to maintain this calibration over the full energy range and to assess the quality of the detector are measured every minute. This allows an accurate determination of the energy deposited in each detector when an atmospheric cosmic ray shower occurs.

1. Introduction

The Pierre Auger Observatory is a hybrid experiment consisting of an air fluorescence detector as well as a surface detector (SD) using water Cherenkov tanks. A description of the SD stations and their performance is in described in these proceedings [1]. SD reconstruction is performed by a measurement of particle density at the ground, and fitting to the signal to a lateral distribution from the core impact. The particle density is measured in units of the charge deposited by a vertical and central muon, termed a vertical-equivalent muon (VEM, or Q_{VEM}). The goal of the calibration procedure is to determine 1 VEM in electronics units to good accuracy.

Atmospheric muons passing through the detector give an excellent method for measuring the value of 1 VEM precisely, as they produce a peak in a charge histogram. The peak (Q^{peak}_{VEM}) is at 1.05 VEM for each PMT, measured with a muon telescope providing the trigger in a reference tank, as described in Arneodo *et al.* [2]. An example charge histogram produced by an SD station is shown in Figure 1.

This histogram is understandable as the convolution of distributions of three different classes of incoming particles: (a) muons which enter through the top and exit through the bottom, (b) muons which enter through the top or bottom and exit through the side, and (c) muons which enter through the side and exit through the side. Distributions for each of these three classes, along with the sum, are shown in Figure 2., as derived from a geometric model [3] with a distribution of incident muons ϕ such that $\phi = \phi_0 \left(\cos^2\theta\right)$ where $\phi_0 \approx 80$ muons $m^{-2}s^{-1}sr^{-1}$, with the charge deposition in the tank proportional to the track length in the tank. The peak produced by the first class of incident muons is clearly the VEM, as a vertical muon has the shortest track length possible. The shift observed in

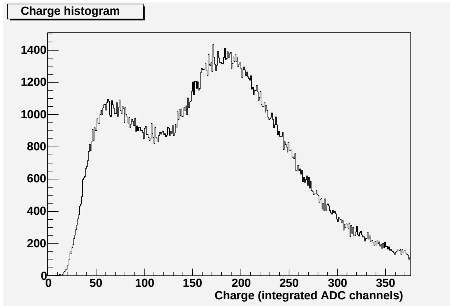

Figure 1. Charge histogram from a SD station, triggered by a 3-fold coincidence between all 3 PMTs, at a trigger level of 5 channels above baseline. The first peak is a trigger artifact. The second peak is due to vertical throughgoing atmospheric muons.

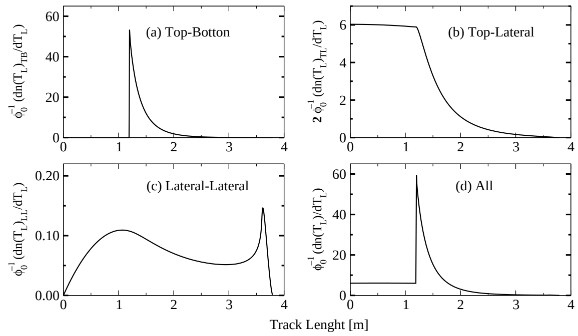

Figure 2. Distribution of track lengths for muons in a water tank from (a) muons which enter and exit via the top or bottom, (b) muons which pass through the side and the top, and (c) muons which pass through only the sides. (d) is the sum of all distributions [3].

the data is thus due to the contribution of the second and third classes along with spreading of the signal due to photoelectron statistics, and should have little tank-to-tank variation.

To maintain the efficiency of the array, the stations must also be able to maintain a common trigger threshold level in physics-based units. The trigger is set in electronics units - channels (ch) - and is a threshold-type trigger. Flash ADC channels are a measure of the PMT photocurrent, and so the station must also have a reference unit for threshold levels. Atmospheric muons again provide the baseline, as the same mechanism that produces a peak in the charge histogram also produces a peak in a pulse height histogram. This peak (I_{VEM}^{peak}) is used as the common reference unit for threshold levels. I_{VEM}^{peak} is related to the peak photocurrent produced by a vertical throughgoing muon (I_{VEM}) via a constant conversion factor, as with Q_{VEM}^{peak}'s relation to Q_{VEM}.

Thus, the local electronics must be able to continually perform a local calibration to determine the proper electronics-level trigger. The accuracy of this determination does not have to be high. The trigger units are quantized in channel units, and the target trigger level (approximately 0.2 I_{VEM} for the lower of the two triggers) and target calibration point for threshold levels (approximately 50 ch/I_{VEM}^{peak}) implies that the online calibration does not need to be much better than 10% (1 part in 10 ch) before the quantization of the trigger dominates.

In addition, the local electronics must be able to initially set up the end-to-end gains of the 3 PMTs to be similar - that is, ensure that I_{VEM}^{peak} is approximately equivalent in all 3 PMTs. This guarantees that the signal recorded from each of the 3 PMTs is roughly equivalent, and sets the proper dynamic range and signal size for the electronics.

2. VEM Calibration procedure

The end-to-end gains of each of the 3 PMTs are setup by matching a point in the spectrum to a measured rate from a reference tank. The reference tank is calibrated by obtaining a charge histogram and adjusting the PMT high voltage until the peak (Q_{VEM}^{peak}) of the three histograms agree. The singles rate spectrum of each of the PMT (*i.e.* no coincidence between the PMTs required) is then obtained

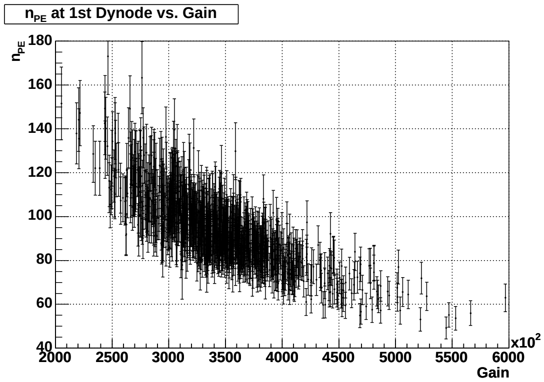

Figure 3. Number of photoelectrons at the 1st dynode vs PMT gain. The inverse relation is expected due to the requirement of equivalent end-to-end gain.

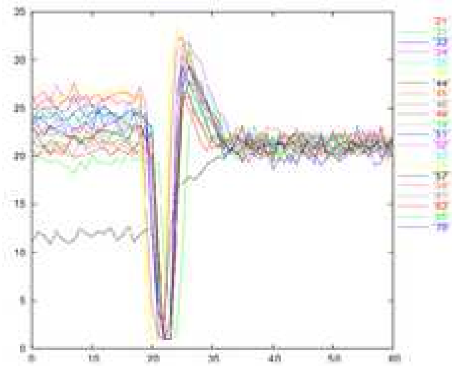

Figure 4. Convergence of the 3-fold coincidence trigger at 3.2 I_{VEM}^{est} to 20 Hz after the convergence algorithm based on the 2.5 I_{VEM}^{est} singles rate.

as a reference. A point on the spectrum convenient as a trigger threshold was chosen to use as a target calibration point for all tanks - namely, the singles rate of a PMT at 150 ch above baseline should be 100 Hz. From the reference tank, 100 Hz corresponds to a trigger point of roughly 3 I_{VEM}^{peak}. This choice sets up each of the PMTs to the target of 50 ch/I_{VEM}^{peak}.

When the local station electronics is first turned on, each of the 3 PMTs is then required to satisfy this condition by adjusting the high voltage until the rate is 100 Hz at a point 150 ch above baseline. This balances the PMTs to approximately 10% initially. Variations in the PMT temperature responses imply that the 3 PMTs will drift away from this point, so there is little need for even moderate accuracy in this step. The end-to-end gain measurement implies that the PMTs in the SD stations will *not* have equivalent gains. We expect an inverse relationship between the gain of each PMT and the number of photoelectrons per muon for each PMT. This is shown in Figure 3. The inverse relationship is quite clear, showing that the initial end-to-end gain setup is operating correctly.

Once the gains of the 3 PMTs are set up, the drifts in the end-to-end gain must be compensated to ensure that the SD triggers uniformly. This compensation is done via adjusting the trigger levels based on a continual online calibration. Adjusting the trigger levels rather than the PMT high voltage implies that the dynamic range of the array will not be uniform, but will likely vary from detector to detector. For most detectors, the drift of the end-to-end gain is minimal. The average value of I_{VEM}^{peak} for the SD is currently 46 ± 4 ch, consistent with an initial target of 50 ch and a slight cooldown of the PMTs.

The continual online calibration uses a similar technique to the initial end-to-end gain setup, with a $\sigma - \delta$ convergence algorithm. The online calibration begins with an estimate of I_{VEM}^{peak} as 50 ch ($I_{VEM}^{est} = 50$ ch). A 3-fold coincidence trigger is set up between the 3 PMTs, with a trigger level of 1.75 I_{VEM}^{peak} - based on a reference tank, this produces a trigger rate of approximately 100 Hz. The online calibration then records the rate of events (within those 100 Hz) above a threshold of 2.5 I_{VEM}^{est} - *i.e.*, based off its own estimate of what I_{VEM}^{peak} is for each PMT. These events are counted initially for a time $t_{cal} = 5$ s to obtain a singles rate for each PMT. From the reference tank, this rate should be 70 Hz. After t_{cal} seconds, a $\sigma - \delta$ convergence algorithm is used on I_{VEM}^{est} to tune the rate to 70 Hz, with $\sigma = 2$ Hz and $\delta = 1$ ch initially. That is, if the singles rate for a PMT is greater than $70 + \sigma$ Hz, I_{VEM}^{est} for that PMT is incremented by δ. If the singles rate is below $70 - \sigma$ Hz, I_{VEM}^{est} for that

PMT is decreased by δ. The process is repeated, incrementing t_{cal} by 5 s (to a maximum of 60) and decreasing δ by 0.1 (to a minimum of 0.1).

This convergence algorithm is quite successful in generating a uniform candidate shower trigger (3-fold coincidence at 3.2 I_{VEM}^{peak}), as seen in Figure 4. In addition, the ratio of the converged I_{VEM}^{est} with fits to the peak of a pulse height histogram is 1.06 ± 0.06. The online calibration also estimates Q_{VEM}, by computing the charge of pulses with a peak within 10% of $I_{VEM}^{est.}$, using a convergence algorithm as before. The ratio of the converged Q_{VEM}^{est} and Q_{VEM} determined from histograms is 0.96 ± 0.03. The offset of this ratio (and $I_{VEM}^{est.}/I_{VEM}$) is due to an inaccuracy in the initial rate, and is unimportant.

The local station electronics has a separate trigger specifically for collecting high-rate data at low threshold (0.1 I_{VEM}^{est}). From this data, each candidate shower event contains histograms (approx. 150,000 entries) of the charge from each PMT, the sum of the 3 charges, the peak current of each PMT, and the baselines of each PMT, as well as the average of all pulse shapes within 10% of $I_{VEM}^{est.}$. The second peak is fit to obtain the value of Q_{VEM} used to convert the integrated signal into units of VEM, which can also be crosschecked using measurements of the charge deposited by the decay electron from a stopped muon [4].

3. Additional parameters

The additional parameters required are the baselines of the 6 FADC inputs and the ratio between the two independent PMT signals ("dynode/anode ratio"). The baselines are determined from the calibration histograms, and the dynode/anode ratio is determined by averaging all large (peak between 10 I_{VEM}^{est} and 20 I_{VEM}^{est}) pulses and fitting the anode to a linearly shifted dynode. This compensates for phase offsets due to dynode amplifiers and avoids problems from < 1 ch FADC noise. This method determines the dynode/anode ratio to 2% accuracy, as determined by comparison to fixed-ratio pulses.

4. Conclusion

Q_{VEM} and I_{VEM} are determined through their relation to a peak in charge (Q_{VEM}^{peak}) and pulse height (I_{VEM}^{peak}) histograms, obtained with a high-statistics charge histogram every minute, and crosschecked with an independent measurement which agrees to 3%. I_{VEM}^{peak} is only required for triggering, which is uniform to about 6%. The dynode/anode ratio is measured by averaging large pulses and fitting the anode to a linearly shifted dynode, which determines the dynode/anode ratio to 2%.

References

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