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Charge calibration of LHAASO-WCDA engineering array

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Abstract: The charge calibration is very important in detector long-term running. In this paper, an online PMT charge calibration method used in ground-based water Cherenkov detector is introduced, by using Cherenkov photons generated by secondary particles in water, both PMT low-range and high-range can be calibrated by single photon-electron and " μ -peak". Firstly the physical mechanism is introduced, then the result of charge calibration is shown and calibration stability is given at the end.

Keywords: LHAASO-WCDA, water Cherenkov, charge calibration

1 Introduction

In gamma ray astronomy, water Cherenkov is proved to be the very sensitive detection technique due to its background rejection power [1, 2]. The Milagro experiment [3] pioneered this technique, and next generation facilities like HAWC [4] and LHAASO-WCDA [5] that adopt this technique will be able to achieve the sensitivity more than 15 times better.

Spectral measurement of gamma ray emissions is one of the essential objectives of an observation. It is dominated by air shower fluctuations in the uncertainty of energy measurement, ground-based particle detector arrays usually show modest performance in this aspect. However, when the statistics reaches a considerable level, the mainly uncertainty remained comes from the detector itself, as the average behavior of the shower cascade can be modelled quite well by some code such as CORSIKA [6]. This therefore requires a good charge calibration of the detector, for ground-based detector array such as LHAASO-WCDA, 5% is enough.

Cosmic muons are commonly used for the charge calibration, as they are bombarding detectors all the time with a rather high rate and the interaction mechanism of it passing through the detector is well known and rather simple. In order to achieve such a goal, thin plastic scintillator detector of experiments such as $AS\gamma$ measures the signals of minimum ionizing particles [7], and water tank detector of experiments like Auger measures the vertical equivalent muon (VEM) signals [8]. As to water Cherenkov detector arrays such as LHAASO-WCDA, the "charge calibration" concept should be modified, cause the detector measures the cherenkov photons generated by cosmic secondary particles but not the particle number.

For the water Cherenkov detector array, as the signal of the single photoelectron dominates in the charge distribution which can be used to monitor the gain of the PMT, but it is not enough for high range calibration which includes the quantum efficiency and collection efficiency of the PMT. In the prototype experiment, cosmic muons can form a special peak which can reach hundreds of PEs in the charge distribution when they hit the surface of the PMT [9], the peak position mostly depends on the physical parameters (such as the shape, photo-cathode sensitivity, collection efficiency, etc.) of the PMT and it provides a possible way for high range "charge calibration". One needs to investigate how to sort out the peak with a simpler setup or even without any additional auxiliary instrumentations. This is one of the goals of the study.

In this paper, first the LHAASO-WCDA engineering array is introduced, including key functional sub-systems; then the charge calibration methods are studied and presented in details, demonstrated with the measurement results.

2 The WCDA Detector

LHAASO-WCDA, a water Cherenkov detector array with an area of 90,000 m², is planned to be built at Shangri-La, Yunnan Province, 4300 m a.s.l., in next a few years. To gain full knowledge of the water Cherenkov technique and to well investigate the engineering issues, acting as a sequel of the prototype detector [9], an engineering array of LHAASO-WCDA [10] was built at Yang-Ba-Jing in 2010 and has been operated since then for more than 2 years.

The engineering array of the water Cherenkov detector is located around 15 m northwest of the ARGO-YBJ experiment at an altitude of 4300 m a.s.l. The main part of the engineering array is a pool of water. The effective dimension of the pool is 15 m×15 m at the bottom, with the pool walls concreted upward along a slope of 45° until 5 m in height, leading to 25 m×25 m at the top.

Two kinds of 8-inch PMTs are deployed in the array: eight of type R5912 from Hamamatsu, and one of type 9354KB from ET Enterprises. A tapered voltage divider supplied with positive high voltage (HV) is adopted in the base circuit, which is potted to be water-proof with a special craft. With this base design and the readout from the anode, a dynamic range from 1/4 photoelectron (PE) to more than 700 PEs within a linearity level of 5%, at the operating gain around 2×10^6 , is achieved.

The PMT signal is transmitted to a preamplifier above the water surface via an 11 m cable, split into two signals, amplified to $25 \times$ and $1 \times$ individually. A 9-U VME board with 9 pairs of channels is designed as the front-end electronics (FEE) to read out and digitalize the PMT signals. Each pair of channels process a pair of signals from a same PMT. The pair of signals are shaped, digitalized with two Analog-to-Digit converters (ADCs), and passed to a F-PGA. A time measurement and two charge measurements form a hit datum of the PMT.

Environmental conditions of the control room and the water are measured once every several seconds by sensors connected to a slow control system. These measured parameters include temperatures of the control room, the outdoor, the water top and the water bottom, the pressures of the air and the water bottom.

3 Charge calibration of the low range channel

In the single channel mode of the data-taking, the PMT hits mostly comprise of single photoelectron (SPE) signals. These signals are mainly contributed from the low energy (<100 GeV) cosmic ray showers, whose major secondary components are photons, electrons (including positrons) and muons. The number of photons is about 10 and 20 times more than that of electrons and muons, respectively, at the altitude around 4300 m a.s.l., with energy greater than Cherenkov threshold in water. aking the detection efficiency and energy distribution into account, the contribution ratio of photons, electrons and muons to the single counting rate is roughly estimated to be 4:1:1. Besides, when there are fresh water filling into the pool, the alpha decay of radioactive Radon (^{222}Rn) bringing in with the water produces fluorescence lights in the H_2O molecular, radiating uniformly in direction and being collected by PMTs. Even when the pool is empty, radioactive Radon leaked from the bottom and bank of the pool diffuses inside the shut pool room, producing fluorescence lights in the air and generating PMT signals too. All above sources, working alone or together, lead to a high single counting rate of PMTs, and due to the low detection efficiency to these sources, SPE hits dominate in the PMT signals.

The charge distribution of low range output of a PMT is shown in figure 1 (top), where the bins around the peak position is fitted with a Gaussian function. Comparing it to the signal of very weak LED light dedicated for measuring the SPE curve, shown in the bottom of figure 1, it is found that the peak position is almost same, indicating the peak of the single channel signals rides precisely at the SPE position.

The SPE peaks of all PMTs are shown in table 3, in which 30 seconds' data are taken for each PMT, all value are obtained from the charge distributions fitting by Gaussian function.

The SPE peak position represents an overall effect of the low range channel of the PMT, including the gain of the PMT, the amplification factor of the preamplifier, the attenuation of signals in the cable, the gain and the metric of the electronics. Especially the gain of the PMT, which can be monitored with the SPE peak. One should be aware that, the quantum efficiency and the collection efficiency of the PMT is not included in this kind of calibration.



Fig. 1: Top: charge distribution of low range output of a PMT, fitted with a Gaussian function; bottom: SPE curve obtained with an LED light source for the same PMT.

Peak Value [ADC bin]
19.28±0.49
$19.32 {\pm} 0.28$
$20.57 {\pm} 0.19$
19.72 ± 0.22
$19.10 {\pm} 0.31$
20.29 ± 0.48
$20.84{\pm}0.25$
$20.58 {\pm} 0.24$
$20.59 {\pm} 0.32$

Table 1: SPE peak value for all the PMTs.

4 Charge calibration of the high range channel

The previous prototype experiment [9] shows that nearvertical cosmic muons can produce a special peak at position around 350–600 PEs, relying on shape and type of the PMT. The peak is mainly formed by Cherenkov lights of muon tracks hitting the photocathode, so that very little dependence upon the water quality and depth is expected. With help of this feature, the PMT and high range channel of its electronics is foreseen to be calibrated, including overall effects such as the gain, the quantum efficiency and the collection efficiency of the PMT, the amplification factor of the preamplifier, the attenuation of signals in the cable, the gain and the metric of the electronics.

With the pool instead of tank configuration in the engineering array as well as the future full array, coincident measurements with scintillators like the prototype experiment seem impractical. Monte Carlo simulations show that muons from all directions without the coincidence selection can form a peak too, but it is not very obvious, due to the disturbance from muons with large incident angles or far intersection points, and from high energy shower signals. Fortunately, proved by the simulation, a shading pad with a certain distance like 10-20 cm over the photocathode can well alleviate this disturbance and doesn't affect much the muon peak. That's why the devices of shading pads are put into two cells. Residing on rails, shading pads stay aside the PMTs in most occasions. To measure the muon peak, one can manually drag these pads along the rails, to ride over the top of the PMTs.

Nevertheless, the shading pad device, being a mechanical setup, is difficult to build and operate. Instrumenting all PMTs of future big array with this kind of device is not a good solution. With a multiplication of power law of the charge (x-axis) to the entries (y-axis) can make the muon peak much clear, see in figure 2, where the power law index of 2.5 is used. Fitting the curve in the nearby range with a Gaussian function, the peak position is then obtained. Same analysis to the simulation data shows that the transform with a power law multiplication shifts the peak position a little bit higher, but less than 2%. Anyway this shifting effect is uniform for all PMTs with the similar charge distribution, bringing nothing biased.



Fig. 2: Muon peaks of these two cells after a power law multiplication (power law index: 2.5), where Q is the number ADC bins divided by 150. Fitted with a Gaussian function, the peak position is obtained. Muon peak positions turn 4% smaller in case of shading pads being on due to the factor of the δ – ray signals generated in the muon tracks are screened by pads.

With this kind of treatment, muon peaks of all PMTs are obtained. The peak positions are not same, after eliminating the PMT gain and the front electronics' amplification between high and low range of each channel respectively, using one PMT as the reference, the related differences between each channel are given, see in table 4, the result demonstrates almost pure difference between PMTs themselves. The nonuniformity between Hamamatsu tubes is less than 10%, but the difference between ET tube and other tubes is more than 20%, such difference is mainly caused in two aspects: 1) the PMT shape differences; 2)

the quantum efficiency and the collection efficiency differences [9].

Channel No.	Ratio
1 (ET Tube)	0.734
2	0.967
3	1.003
4	1.058
5 (Ref. Tube)	1.0
6	1.093
7	1.085
8	1.002
9	0.951

 Table 2: Muon peak value ratio between reference PMT and others.

5 Calibration stability

To investigate the calibration stability and the dependence on environmental conditions, both low range and high range calibration are done intermittently (see section 2.3). The SPE peak and muon peak are fitted for every 30 seconds' and 30 minutes' data respectively. Figure 3 and figure 4 show the peak values distribution of one channel as the function of time in one particular month. During this month, the water depth and water quality changes quite a lot, and the temperature in the control room and in the water varies day by day. The SPE peak and muon peak position is quite stable, the variation evaluated by the average RMS of all channels is in the level around 2%. That means for both low range charge and high range measurement, after including the environment effect factors to the PMT, cable and electronics of all channels, the precision of the charge calibration is not larger than 2%, which satisfies the requirement of the experiment.



Fig. 3: SPE peak variation in one month. Fitted with a horizontal line.



Fig.4: Muon peak variation in one month. Fitted with a horizontal line.

In these distributions, the daily variation of the peak position is observed. If drawing the peak position as the function of the temperature of the control room, a correlation around $0.2\%/^{\circ}$ C in average is found. This correlation can



be overall temperature effect, including the cables and the electronics, most of which are outside of the water, and the PMTs, which reside in water, whose temperature is much more stable but still correlates with the room temperature. This temperature effect, which can be eventually corrected, is actually trivial in this analysis, as the data points used here are more or less concentrated in a small temperature range. Figure 5 and figure 6 show the correlation of SPE peak and muon peak value with room temperature of al-1 PMTs mentioned above. Table 5 demonstrates the SPE peaks and μ -peaks relative variation with the room temperature, considering the natural environment of Yang-Ba-Jing site, a variation of $35^{\circ}C$ is predictable in one year, but during one month, the whole temperature variation is around $15^{\circ}C$ and the correction of the SPE peak position and μ -peak position is 5% at the most.



Fig. 5: Correlation between SPE peak position and room temperature over one month. The RMS is the deviation of data points from the fitted line.



Fig. 6: Correlation between muon peak position and room temperature in one month. The RMS is the deviation of data points from the fitted line.

Channel No.	SPE peaks	µ-peaks
1	-0.0024	-0.0010
2	-0.0009	-0.0008
3	-0.0013	-0.0007
4	-0.0029	-0.0018
5	-0.0026	-0.0021
6	-0.0029	-0.0022
7	-0.0017	-0.0021
8	-0.0014	-0.0029
9	-0.0020	-0.0016

Table 3: SPE peaks and μ -peaks relative variation with the room temperature.

6 Conclusion

With the study carried out on the LHAASO-WCDA engineering array, a method for calibrating the charges for both the low and high range channels is developed. Natural sources of cosmic rays such as muons and photons can produce two kinds of nice peaks on PMTs, which can be nicely fitted with simple Gaussian functions. These peak positions are very stable, relying only on the PMT and the electronics, guaranteeing a precise calibration at the level 2% can be achieved. These peaks can be obtained by online analyzing the single channel signals during a very short datataking time window such as 30 seconds and 30 minutes, ensuring a PMT monitoring and a real-time calibration can be proceeded for the future LHAASO-WCDA experiment.

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