PROCEEDINGS OF SCIENCE

Use of a small photomultiplier tube to extend the dynamic range of the surface detectors of the Pierre Auger Observatory

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The Pierre Auger Observatory was built in Argentina to study cosmic rays with energy larger than 0.1 EeV. It applies two independent and complementary techniques to detect extensive air showers: an array of water-Cherenkov detectors (WCDs) and a set of fluorescence telescopes. About 40% of the events detected with the water-Cherenkov detectors, for energies larger than 30 EeV, present saturation. The installation of an additional photomultiplier tube (PMT) with a small cathode area in the WCDs was proposed to overcome this saturation. We analysed data from ten experimental WCDs equipped with small PMTs. We showed that the small PMTs can be calibrated using the standard PMTs. The mean calibration uncertainty was within 5% and the calibration becomes more accurate for larger signals. A correlation of the calibration with long-term variations of temperature was found. Finally, we showed that the implementation of the small PMTs extended the dynamic range of the WCDs by a factor of 25 times, which reduced the overall saturation occurance from 6% to less than 0.1%.

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1. Introduction

The sources of ultra-high energy cosmic rays (UHECRs) as well as the mechanisms to accelerate these particles and their interactions with the interstellar and intergalactic media are still mysteries of modern particle astrophysics.

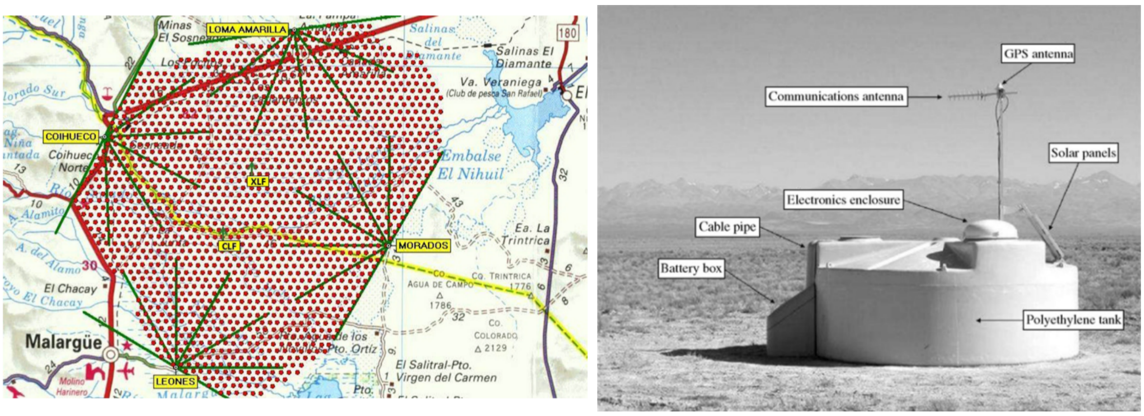
The Pierre Auger Observatory, the largest cosmic ray observatory in the world, was built in Argentina to address these open questions [1]. When energetic cosmic-ray particles penetrate the atmosphere, they interact with atmospheric molecules producing cascades of particles. This phenomenon is called an extensive air shower (EAS). The Observatory detects EAS with two independent and complementary techniques: the surface detector (SD) and the fluorescence detector (FD).

As the EAS develops, atmospheric nitrogen molecules are excited and emmit fluorescence light isotropically. This light is captured by the fluorescence detector composed of 27 fluorescence telescopes distributed in four sites. The FD is able to reconstruct the longitudinal development of the EAS and it also provides an almost-calorimetric measurement of the primary energy.

The surface detector is composed of 1660 water-Cherenkov detectors (WCD). They are arranged 1500 m from their nearest neighbours forming a triangular grid. An overview of the Observatory with the SD and the FD is presented in Figure 1a.

Each WCD consists of a liner filled with 12000 l of purified water. On top of the liner, three 9-in photomultiplier tubes (PMTs) look down into the water volume. The PMT signals are digitised by a fast analog-to-digital converter (FADC) with 10 bits at a sampling rate of 40 MHz. All the components of a WCD are contained inside a cylindrical structure made of polyethylene. The WCDs are self powered by solar panels which allows them to operate nearly 100% of the time. A picture of a WCD is shown in Figure 1b.

When charged particles from an EAS cross the water volume of the WCDs with speed higher than that of light in water, Cherenkov radiation is produced. The photons are reflected in the



(a) (b)

Figure 1: (a) Overview of the Pierre Auger Observatory. Each dot represents a water-Cherenkov detector. The fluorescence-detector sites are shown as well as the field of view of each telescope. (b) A water-Cherenkov detector and its components [1].

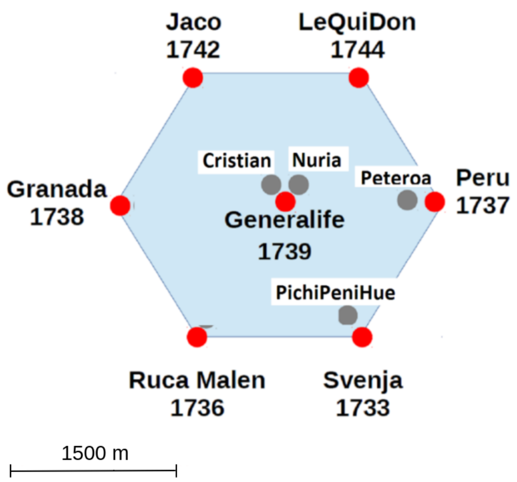
inner surface of the liner and produce a signal in the PMTs which is digitised in hardware units (FADC channels). The PMTs are calibrated so that the signals are converted to a physical station-independent unit called VEM (vertical equivalent muon), which is defined as the average signal produced by a vertical muon crossing the centre of a WCD [2].

For highly energetic events, many particles are produced in the EAS, especially close to the shower core. When this large number of particles crosses the WCDs, the amount of photons produced may saturate the PMTs. In fact, 40% of the events with energy higher than 30 EeV present saturation at least for the WCD closest to the shower core. The saturation impacts on the resolution of $S(1000)$, the estimated signal at 1000 m from the shower core, which is used for obtaining an estimation of the energy of the primary cosmic ray. The expectation value of $S(1000)$ is not affected by the saturation of the PMTs.

The installation of an additional PMT with a small cathode area in the WCDs was proposed to overcome the saturation problem, as part of the upgrade plan for the Observatory [3]. With a smaller area of about 1/100 that of the standard PMTs (model XP1805), a similar extension of the dynamic range of the WCDs can be reached. By adjusting the gain of the small PMT so that the ratio between the signals of the standard and small PMTs is roughly 32, the required dynamic range extension up to about 20000 VEM is achievable.

In this work, we analysed the data collected by ten experimental WCDs equipped with the small-area PMT. The data was acquired between April 21 and October 17 of 2016. For the sake of nomenclature, the PMT with small cathode area will be refered to as small PMT (SPMT). In contrast, the standard PMTs will be called large PMTs (LPMTs).

In Section 2, the experimental setup of the WCDs equiped with the SPMTs will be described. The results obtained will be presented in Section 3. In Section 4, we give the conclusions obtained from this work.



(a)

(b)

Figure 2: (a) Geometrical disposition of the WCDs forming the Engineering Array. (b) Hamamatsu models R8619 (top) and R6094 (bottom).

2. Experimental configuration

Ten WCDs of the surface detector were equiped with SPMTs to assess their performance in the field and validate the proposal of extending the dynamic range of the WCDs to reduce saturation. These ten WCDs form the Engineering Array (EA) and their geometric disposition is displayed in Figure 2a. Three SPMT models were tested: the models R8619 and R6094 from Hamamatsu and 9107FLB from ET enterprise. The Hamamatsu models are shown in Figure 2b. The model R8619 was chosen for the upgrade, after presenting a better performance at laboratory tests. The other two models have been tested as backup options.

The SPMTs were installed in a spare window of the WCD liner located 60 cm from its centre (as seen from the top of the WCD). This window has a diameter of 30 mm. Since the eletronics of the WCDs did not have a dedicated FADC channel for the SPMTs, their signals were digitised using the FADC of one of the LPMTs (the closest one). Therefore, the configuration of each WCD of the EA is one SPMT and two operating LPMTs.

The trigger condition set for the WCDs of the EA is that the signal amplitude of both LPMTs be larger than 120 FADC channels. When this condition was met the following data was recorded: the event time, the charge in the PMTs and the amplitude of their signals.

In the analysis here described, we also exploited the monitoring data, which store the information from various sensors installed in each WCD. In particular, we used the information about the temperature and VEM calibration of the LPMTs.

3. Results

As mentioned in Section 1, the VEM calibration of the LPMTs converts the signals from hardware units to VEM units. Being the signal from single muons too small to be detected by the SPMT, to convert its signals in physical units we used a cross-calibration method, exploiting the unsaturated signals detected by both the LPMTs and the SPMT.

In Figure 3, we plotted the average charge on the LPMTs, in VEM units, as a function of the charge registered in the SPMT, in hardware units (FADC $\times$ bins), for one of the WCDs of the EA. Only non-saturated events were used. Cuts on the SPMT charge were applied to avoid biases. We then performed a linear fit

$$Q_{<LPMTs>}(\mathrm{VEM}) = p_0 Q_{SPMT}(\mathrm{FADC} \times \mathrm{bins}) + p_1, \tag{3.1}$$

from which the coefficients p_0 and p_1 were obtained. Equation 3.1 gives a means to convert the signal of the SPMT from hardware units to VEM units.

To assess the quality of the calibration using the linear fit, the calibration uncertainty is defined as

$$Q_{unc.} = \frac{Q_{<LPMTs>}(\mathrm{VEM}) - Q_{SPMT}(\mathrm{VEM})}{Q_{<LPMTs>}(\mathrm{VEM})}, \tag{3.2}$$

where $Q_{SPMT}(\mathrm{VEM})$ is the charge of the SPMT, in VEM units, obtained using the linear fit (see Eq. 3.1). In Figure 4, we show a scatter plot of the calibration uncertainty as a function of $\log_{10}[\langle Q_{LPMTs}\rangle\ (\mathrm{VEM})]$. We also display the mean value and the standard deviation on the calibration uncertainty for bins of length 0.1 in $\log_{10}[\langle Q_{LPMTs}\rangle\ (\mathrm{VEM})]$. The calibration is unbiased

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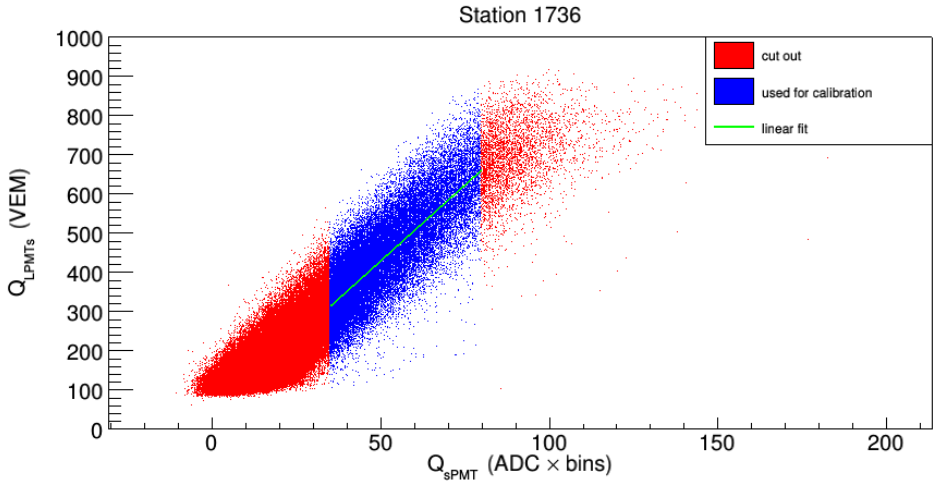

Figure 3: Average charge of the large PMTs (VEM) as a function of the charge of the SPMT (FADC $\times$ bins). Only non-saturated events were used. The red points were cut out to avoid biases. Then, a linear fit was applied (green line).

since the mean value for the bins are within 5%. Moreover, the distribution of the calibration uncertainty is wider for lower signals in the LPMTs. For larger LPMTs signals, the uncertainty becomes smaller which is desirable because the SPMT will be used for events with larger signals.

We also studied the dependence of the calibration with temperature. For the plot of Figure 5, we performed the SPMT calibration every 24 hours, then the calibration parameter p_0 (see Eq. 3.1) and the temperature, as recorded by a sensor in the PMT circuit board, were plotted as a function of time. An overall correlation between long-term variations of temperature and the SPMT calibration can be observed, although an opposite bahaviour is especially seen just after the date August 26. This correlation of calibration and temperature is important to take into account when defining a

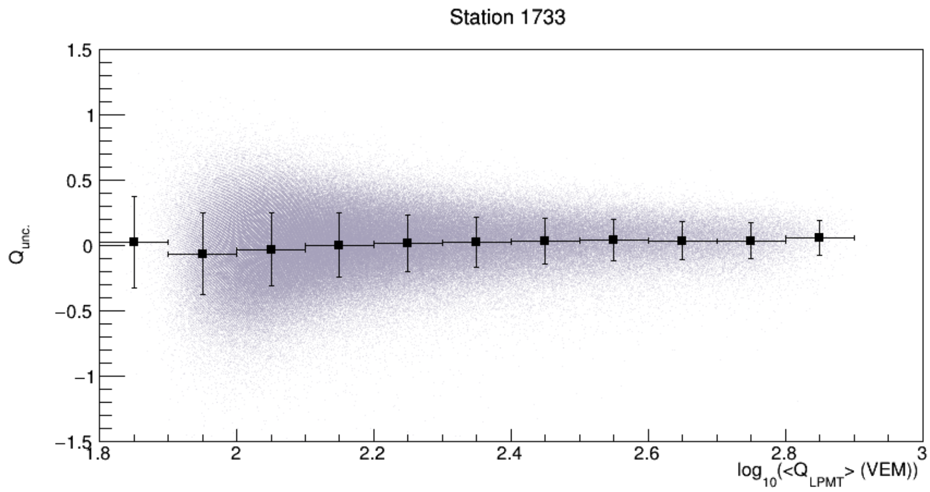

Figure 4: Calibration uncertainty as a function of $\log_{10}[\langle Q_{LPMTs}\rangle$ (VEM)]. The mean value and the standard deviation is displayed for bins of length 0.1 in $\log_{10}[\langle Q_{LPMTs}\rangle$ (VEM)].

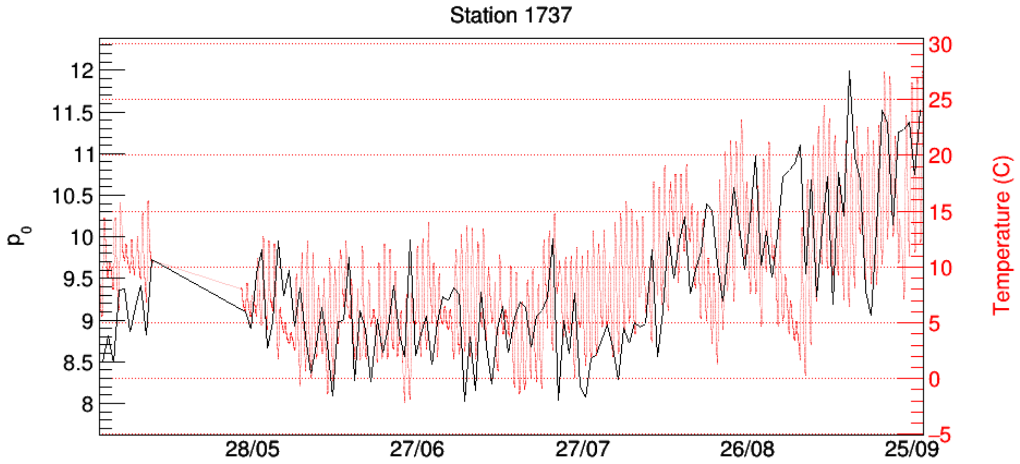

Figure 5: Calibration parameter p_0 (see Eq. 3.1) and temperature as a function of time. The SPMT calibration was performed every 24 hours.

rate at which to perform the SPMT calibration in the WCDs.

We plotted in Figure 6, the signal spectrum of the LPMTs and SPMT, in VEM units, of one of the WCDs of the EA. The LPMTs saturate for signals larger than about 1000 VEM. On the other hand, the SPMT offers non-saturated signals up to approximately 25000 VEM, an extension of dynamic range by a factor of roughly 25 times. We also verified that less than 0.1% of the events registered by the SPMT were saturated, whereas the LPMTs presented saturation in 6% of the events.

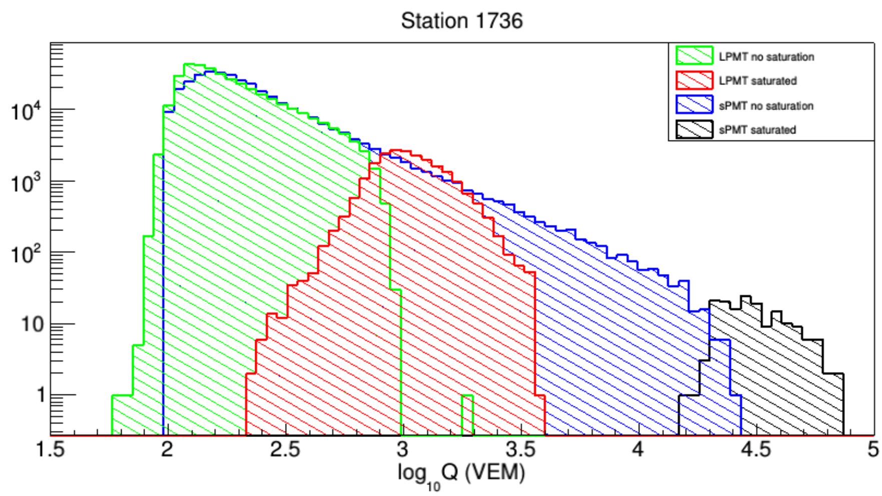

Figure 6: Signal spectrum of the LPMTs and SPMT of WCD 1736 of the EA. The LPMTs saturate for signals larger than about 1000 VEM, whereas the SPMT provides non-saturated signals up to 25000 VEM.

4. Conclusions

We used the data acquired by the WCDs of the EA to test the proposal of implementing a small PMT to address the saturation occurrence in the surface detector of the Pierre Auger Observatory. We showed that the SPMTs can be calibrated using the VEM calibration of the LPMTs. A calibration method using a linear fit was studied. The mean uncertainty of this method is within 5% for the whole range of signals in the LPMTs. Besides, the calibration accuracy improves for larger signals, which is the region of interest for working with the SPMT.

We have verified a dependence of the calibration with long-term variations of temperature. This could play an important role in deciding the calibration frequency of the SPMTs, once these are employed in the WCDs of the surface detector.

This work showed that the implementation of SPMTs in the WCDs of the EA extended their dynamic range by a factor of about 25 times, reducing the occurrence of saturation from 6% to less than 0.1% of the events.

After the analysis presented on this paper with data from 2016, more developments in the study of the SPMT proposal was carried out by the Pierre Auger Collaboration. In particular, the new eletronics for the WCDs was tested. It will allow the signals of the PMTs, including the SPMT, to be collected at a higher sampling rate of 120 MHz. Moreover, the SPMT model R8619, from Hamamatsu, was selected for the upgrade and further calibration techniques were investigated. More details on the development of the SPMT proposal and the upgrade of the Observatory can be found in References [4, 5].

All these results validate the SPMT proposal and are a step towards a more precise reconstruction of events detected with the surface detector of the Pierre Auger Observatory, which hopefully will help to understand the physics of ultra-high energy cosmic rays.

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