



Long Term Performance of the Surface Detectors of the Pierre Auger Observatory.

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Abstract: The Surface Array Detector of the Pierre Auger Observatory consists of about 1600 water Cherenkov detectors. The operation of each station is continuously monitored with respect to its individual components like batteries and solar panels, aiming at the diagnosis and the anticipation of failures. In addition, the evolution with time of the response and of the trigger rate of each station is recorded. The behavior of the earliest deployed stations is used to predict the future performance of the full array.

Keywords: Long term, surface detector, Pierre Auger Observatory

1 Introduction

The Surface Detector (SD) of the Pierre Auger Observatory [1] consists of about 1600 stations based on cylindrical tanks of $1.2 \text{ m} \times 10 \text{ m}^2$ volume filled with ultra pure water of 8 to 10 $\text{M}\Omega\text{-cm}$ [1]. Each station is autonomous and uses two 12 V batteries and two solar panels.

Particles of extensive air showers generated by primary cosmic rays produce Cherenkov radiation in the tank water. This light is reflected by a material (Tyvek[®]) which covers the inside of the water-containing liner and is observed by 3 photomultiplier tubes (PMT) of 9" diameter. The nominal operating gain of the PMTs is 2×10^5 and can be extended to 10^6 . Stations in the main array are distributed in a triangular grid of 1.5 km spacing, covering about 3000 km^2 . This design has a full efficiency for primary cosmic rays with energies above about $3 \times 10^{18} \text{ eV}$ [2] and is intended to be operational for at least 20 years.

An important issue is the signal stability which is related to the PMT gain, water transparency and the reflection coefficient of the Tyvek[®].

It is important for the station to be able to measure both the current I and the charge Q (time-integrated current) produced by the PMTs in response to an extensive air shower. The charge is used to determine the energy deposited in the tank by the shower, and the time distribution of the current is used to form the trigger in each station. The charge and maximum current due to a single vertical muon, Q_{VEM} and I_{VEM} , respectively, referred to in this paper as Area or A and Peak or P , respectively, are constantly monitored by the calibration and monitoring system and provide the basis for calibration of each station [2, 3].

These quantities together with others such as the baseline values and the dynode/anode ratio (the ratio of the output signal from the last PMT dynode to that of the anode) are available to evaluate the behavior of the stations. Although the calibration system provides continuously updated values of all these signals, it is important to model the underlying changes in detector performance in order to determine the long term effectiveness of the performance and calibration of the detectors. In this work we provide a method for the phenomenological understanding of the signal evolution allowing us to predict the long term performance of the detector. The model has been shown to be reliable previously [4, 5]. In this work we review the model presented earlier after more years of operational experience and apply it to the full SD array, which was completed in 2008. This allows us to predict the array lifetime.

In section 2 we will examine the power system of the stations as it is an important system for the stable operation of the stations. In section 3 we quantify and predict how much the signal properties will change in the next decade of operation, mainly through the Area over Peak ratio of the muon signals (A/P) as will be described.

2 Power system

Each station has its power supply running autonomously with solar panels and batteries. Two important issues then are the battery lifetime and solar panel efficiency loss over time. The main power system design consists of two solar panels of 53 Wp each connected in series and two batter-

1. Tyvek[®] is a registered trademark of DuPont corporation.

ies² of 12 V and 100 Ah also connected in series. A station with fully charged batteries can operate 7-10 days without further charging during a cloudy period. During all the operation of the observatory there has not been any general loss of operation due to extended cloudiness.

The current provided by the solar panels is monitored constantly and the information obtained is useful to determine when solar panels need attention. Because of modulation of the solar panel current by the solar power regulator it is challenging to remotely measure performance of solar panels that are working properly. So far, we do not identify a significant solar panel efficiency loss, though we have found apparent cell damage to many of the solar panels due to some not-yet-understood manufacturing problem. We are currently studying these solar panels to estimate whether or not this will adversely affect long term performance.

As the daily discharge is quite small (about 10% of the rated capacity), we estimate the end of battery life in this work to be when the battery voltage drops below 11V if the drop is not generated by a very long cloudy period or an apparent problem related to other part of the system. Note that it is quite different from the definition normally used in the industry which considers the lifetime to have been reached when the battery can not accumulate more than 80% of its rated capacity.

Figure 1 is a histogram of the time interval between initial battery operation and the time at which the battery voltage goes below 11V. In total, 808 pairs of batteries have satisfied this criterion. Some failures are observed in operation before reaching the expected lifetime in one of the two batteries, mostly for newer ones, populating the lower values of the histogram. From our experience we find that manufacture and quality of the batteries have not been constant.

Many batteries in the array have operated for more than 3 years with no sign of failure. As a consequence, they are not included in the histogram of figure 1 and their inclusion would have raised the overall apparent lifetime.

In most cases, a station can still operate for more than 3 months without data acquisition interruption even though we have considered the battery dead in this way. Therefore, the battery lifetime might be considered to be a little higher than obtained here. The average lifetime is then between 4.5 and 6 years.

3 VEM Signal: Area over Peak

The output signal from the PMTs of a single vertical muon has a fast rise and decays exponentially with time. The fast rise is dominated by the Cherenkov radiation which is only reflected once at the Tyvek[®], while the exponential decay is dominated by multiple reflections. As a consequence, the exponential decay has a strong dependence on the reflection coefficient of the tank wall and the transparency of the water.

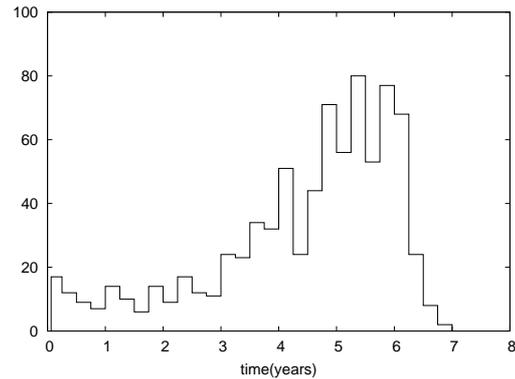


Figure 1: Histogram of the battery lifetime (see text).

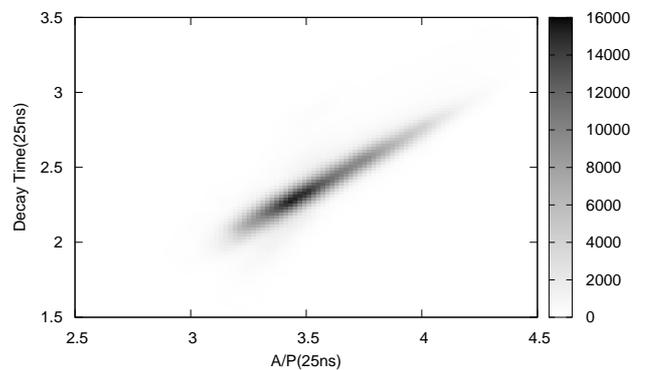


Figure 2: Histogram of correlation between the area to peak ratio (A/P) and signal decay constant for muon signals in SD array.

In figure 2 we can see a good correlation between the exponential decay constant and the parameter A/P ratio. As the A and P are directly available in the online monitoring of each station, we are going to look the A/P ratio, instead of the exponential decay constant.

The proper description of the A/P evolution with time might be very complicated, taking into account the daily and seasonal temperature variation, maintenance and hardware replacement of the stations for example. In this work we examine the main long term trend of the A/P . We consider that it might be described by an exponential behavior as:

$$\frac{A}{P} = s(t) \times \left[1 - p_1 \cdot \left(1 - e^{-\frac{t}{p_2}} \right) \right] \quad (1)$$

where $s(t)$ takes into account the seasonal variations and initial value, p_1 is the fractional loss and is a dimensionless quantity that varies between 0 and 1, and p_2 is the characteristic time in units of years. This decay assumes that the A/P will stabilize at $1 - p_1$ combined with a seasonal variations.

We propose the A/P seasonal variation as:

2. Moura Clean model 12MC105, a flooded lead acid battery with a selectively permeable membrane to reduce water loss. www.moura.com.br

$$s(t) = p_0 \times \left[1 + p_3 \cdot \sin\left(2\pi\left(\frac{t}{T} - \phi\right)\right) \right] \quad (2)$$

where p_0 is the overall normalization factor, p_3 quantifies the strength of the seasonal variation and is a dimensionless quantity that varies between 0 and 1. The T will be considered to be 1 year and the ϕ is just a phase parameter to adjust the annual temperature variation.

As the analog signal from the PMT is digitized at a 40 MHz rate (one sample every 25 ns), which is fast enough to have a good idea of the muon signal shape, A is basically calculated as the sum of digitized information around the region where the main signal appears and the P is the maximum value of this signal. To simplify this analysis, the ratio A/P as well as the parameter p_0 will be given in units of 25 ns. We calculate the mean and deviation of A/P over 7 days. We use these values to find the parameters of equation 1 using a least square fit.

For long term operation station maintenance may be required which might involve PMTs or general electronics replacement. This might adjust the voltage of the PMTs [3] and generate a slight gain change and, consequently, the values of Peak and Area. However, it is expected that most of these changes generate an almost unchanged A/P ratio. Some residual effects may remain and, in many of the cases, it is a little difficult to treat them properly.

The parameters which are expected to have big effects on A/P are mostly the water transparency and the coefficient of reflection of the tank wall. In particular what we are most interested in is the variation of the A/P with time and its correlation with possible degradation of the station. The analysis is thus rather complex and, to try to avoid bias, we considered only well operating stations that were installed before 2007 so as to have a long term operational period, and PMTs which also pass the following restriction: $1 \leq p_0 \leq 5.5$, in units of 25ns; $0 \leq p_2 \leq 500$ yr; $\chi^2/\nu \leq 2000$, where $\nu > 40$ is the number of degree of freedom.

The last constraint is much weaker than acceptable statistically. This is because there are many short term effects in the data which are not taken into account in a simple expression as considered in equation 1, although it describes quite well the general behavior, as shown in figure 3. In the local winter of 2007 we observed a deviation from the steady trend due to extreme low temperatures (below -15°C). This weather generated a 10 cm thick ice layer in the stations, which produced an extra drop, at a level of 1-3%, in A/P . Reasons of that drop are being studied.

In total we found approximately 1500 PMTs which pass the above restrictions. We obtain the characteristic time around few years, an overall normalization $p_0 \approx 3.5 \times 25$ ns and less than 1% for the seasonal amplitude.

In figure 4 we show an example histogram for the parameters p_1 of equation 1. We can see that the fractional loss factor (p_1) is below 20% in general.

In figure 5 there is an estimation of the A/P loss using equation 1 and the parameters predicted for the next 10

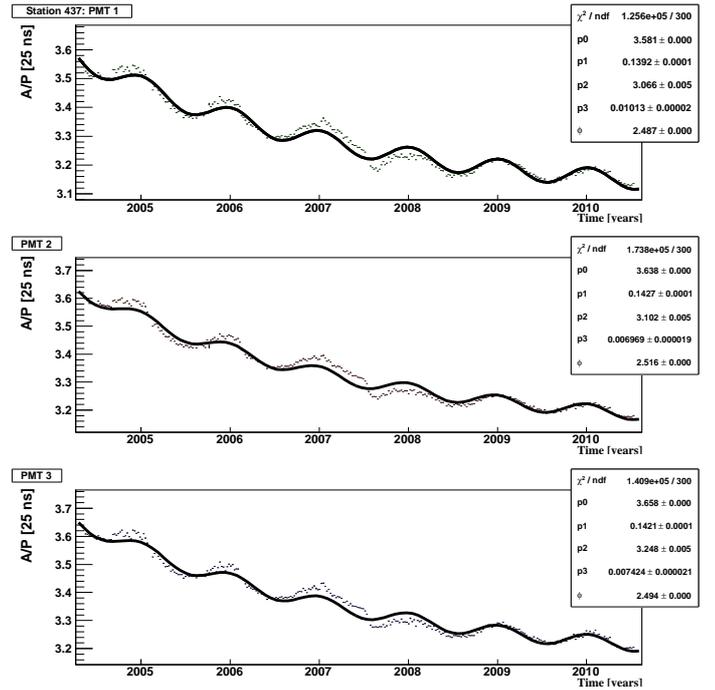


Figure 3: A/P as a function of time for station 437. The dots are the average of the A/P over 7 day and the continuous line is the fit of the equation 1.

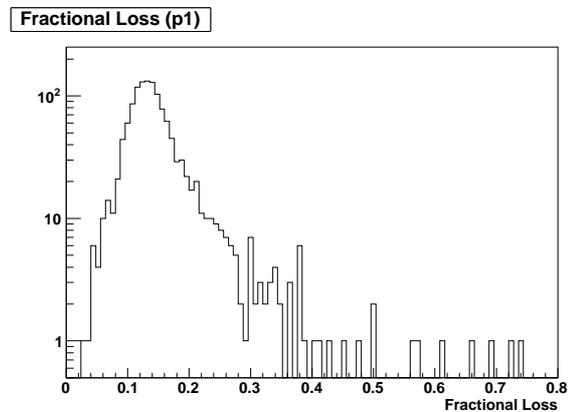


Figure 4: Values of the fractional loss p_1 .

years. We can see that the final A/P will be larger than 85% in most cases. There are a few cases for which this value is much smaller that may require some intervention in the near future. However, they are few and would not greatly affect the general operation of the surface detector array.

It is also important to monitor the trigger rates of the array. As an example we show the trigger rate of one particular station (see figure 6). The T1 and T2 triggers [2], which are just simple threshold triggers, are quite stable with time. On the contrary, the ToT (Time over Threshold) rate [2] which follows the A/P evolution, with an initial decay time followed by a stable operation in time. The

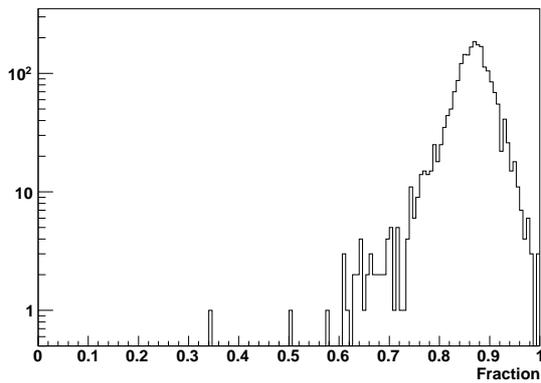


Figure 5: Estimated relative values (Fraction) of A/P after 10 years of operation with respect to its initial value.

ToT trigger requires thirteen 25 nsec FADC bins in a larger time window of 3 μ s to be above a 0.2 VEM threshold, so this trigger is sensitive to a broad time distribution of low energy showers and sensitive to the individual pulse width. The event rate of physical events above the threshold for SD full efficiency, was unaffected so far by the decreasing ToT trigger rate of individual stations.

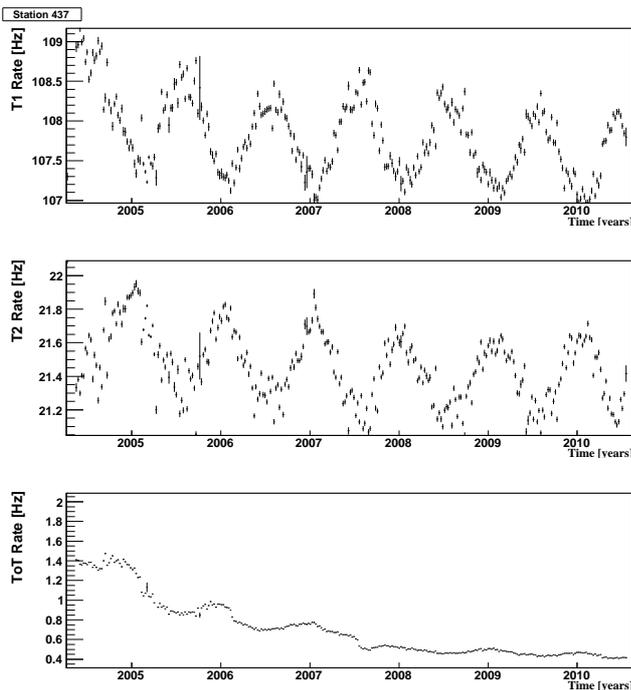


Figure 6: Trigger rate T1, T2 and ToT for the station 437 as function of time.

The A/P would be affected by growth of microorganisms in the water which could produce some turbidity. Bacteriological testing of the water and the surface of the Tyvek[®] is carried out regularly in some stations, but until now there has been no identification of relevant microorganism growth.

4 Conclusions

With the experience of more than 6 years of operation of the detector, a critical behavior has not been identified based on the studies of power system and single muon signals.

The batteries had been expected to have a much shorter lifetime than the operation time of the observatory. As the expected battery lifetime (about 5 years) is quite close to the one obtained in this analysis, we do not expect a particular increase in the maintenance cost.

The study carried out on single muons shows that the Area over Peak reduction will be less than 15% in the next decade. The reasons for the decay of A/P with time are a convolution of water transparency, Tyvek[®] reflection and electronic response of the detectors. The proportion of each of these three causes has not yet been determined. The overall event rate above the threshold for SD full efficiency have not been so far affected by the evolution of the signals described in this work.

References

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