Performance and operation of the Surface Detector of the Pierre Auger Observatory

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***Abstract*. The Surface Array of the Pierre Auger Observatory consists of 1660 water Cherenkov detectors that sample at the ground the charged particles and photons of air showers initiated by energetic cosmic rays. The construction of the array in Malargüe, Argentina is now complete. A large fraction of the detectors have been operational for more than five years. Each detector records data locally with timing obtained from GPS units and power from solar panels and batteries. In this paper, the performance and the operation of the array are discussed. We emphasise the accuracy of the signal measurement, the stability of the triggering, the performance of the solar power system and other hardware, and the long-term purity of the water.**

***Keywords*: Detector performance, Surface Detector, Pierre Auger Observatory**

I. INTRODUCTION

The Surface Detector (SD) of the Pierre Auger Observatory is composed of Water Cherenkov Detectors (WCD) extending over an area of 3000 km^2 with 1500 m spacing between detectors. In addition to the detectors in the regular array, some locations of the array were equipped with two and three nearby detectors, placed at $\sim$10 meters from each other. These ”twins” and ”triplets” provide a very useful testbench for studies of signal fluctuation, timing resolution and energy and angular reconstruction precision. Combined with the HEAT telescopes and the AMIGA muon detector array, a denser array of WCD with detector spacing of 750 m has also been deployed. The total number of detector stations is 1660. The hardware of the surface detector is described extensively in [1], [2].

Installation of detectors started in 2002 and the Observatory has been collecting stable data since January 2004. The construction was completed in June 2008. Figure 1 shows the current status of the array.

The Observatory has been running now with its full configuration for nearly one year and its commissioning is completed. The failure rates of various components have been assessed and the Surface Detector is now entering into a regular long term operation and maintenance phase. Some detectors have been operational already for more than 8 years which permits the study of their long term performance. In this paper, after a short description of the Surface Detector, the detector response and uniformity, its acceptance and long-term performance, and finally its operation and maintenance are discussed.

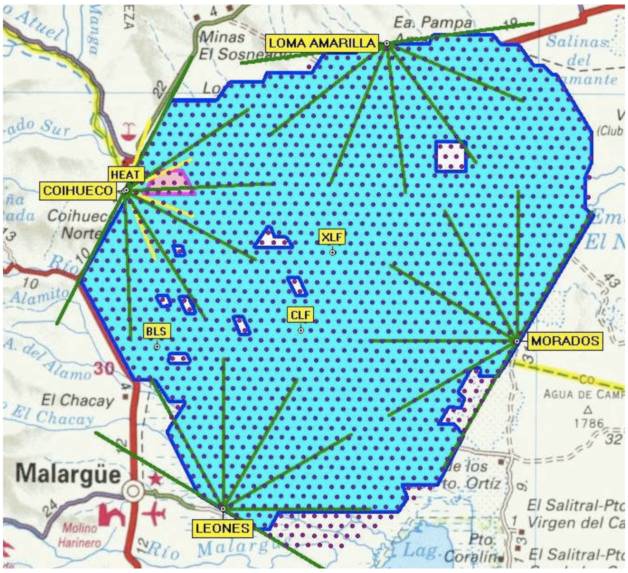

Fig. 1: Current deployment status of the array. Tanks within the shaded area are filled with water and in operation.

II. DESCRIPTION OF THE SURFACE DETECTOR

Each WCD consists of a 3.6 m diameter water tank containing a Tyvek® liner for uniform reflection of the Cherenkov light. The liner contains 12,000 l of ultra-high purity water with resitivity typically higher than 5 MΩ.cm. Three nine-inch-diameter photomultiplier tubes (PMTs) are symmetrically distributed at a distance of 1.20 m from the center of the tank and look downwards through windows of clear polyethylene into the water to collect the Cherenkov light produced by the passage of relativistic charged particles through the water. The water height of 1.2 m makes it also sensitive to high energy photons, which convert in the water volume. A solar power system provides an average of 10 W for the PMTs and the electronics package consisting of a processor, GPS receiver, radio transceiver and power controller.

The signals produced by the Cherenkov light are read out by three large 9” XP1805 Photonis photomultipliers. The PMTs are equipped with a resistive divider base having two outputs: anode and amplified last dynode [3]. This provides a large dynamic range, totaling 15 bits, extending from a few to about 10^5 photoelectrons. The high voltage is provided locally. The nominal operating gain of the PMTs is $2{\times}10^5$ and can be extended to 10^6. The base, together with the HV module, is protected against humidity by silicone potting.

The signals from anode and dynode are filtered and digitised at 40 MHz using 10 bit Flash Analog-Digital Converters (FADC). Two shower triggers are used: threshold trigger (ThT) and time-over-threshold (ToT) trigger. The first one is a simple majority trigger with a threshold at 3.2 VEM (Vertical Equivalent Muon). The ToT trigger requires 12 FADC bins with signals larger than 0.2 VEM in a sliding window of 3 μs. The time-over-threshold trigger efficiently triggers on the shower particles far away from the shower core. In addition, a muon trigger allows for recording of continuous calibration data. The third level trigger, T3, initiates the data acquisition of the array. It is formed at the Central Data Acquisition System (CDAS), and it is based on the spatial and temporal combination of local station triggers. Once a T3 is formed, all FADC traces from stations passing the local trigger are sent to the CDAS.

A common time base is established for different detector stations by using the GPS system. Each tank is equipped with a commercial GPS receiver (Motorola OnCore UT) providing a one pulse per second output and software corrections. This signal is used to synchronise a 100 MHz clock which serves to timetag the trigger. Each detector station has an IBM 403 PowerPC micro-controller for local data acquisition, software trigger and detector monitoring, and memory for data storage. The station electronics is implemented in a single module called the Unified Board, and mounted in an aluminum enclosure. The electronics package is mounted on top of the hatch cover of one of the PMTs and protected against rain and dust by an aluminum dome.

The detector calibration is inferred from background muons. The average number of photoelectrons per muon collected by one PMT is 95. The measurement of the muon charge spectrum allows us to deduce the charge value for the Vertical Equivalent Muon, Q_{VEM}, from which the calibration is inferred for the whole dynamic range. The cross calibration between the two channels, anode and dynode outputs, is performed by using small shower signals in the overlap region of the two channels [4].

The decay constant of the muon signal is related to the absorption length of the light produced. This depends on various parameters such as the Tyvek® reflectivity and the purity of the water. The signal decay constant correlates with the so called area-to-peak (A/P) ratio of the signal:

$$\mathrm{A/P} = \frac{Q_{VEM}}{I_{VEM}} \qquad (1)$$

where I_{VEM} is the maximum current of the muon signal. This area-to-peak ratio is a routine monitoring quantity that is directly available from the local station software.

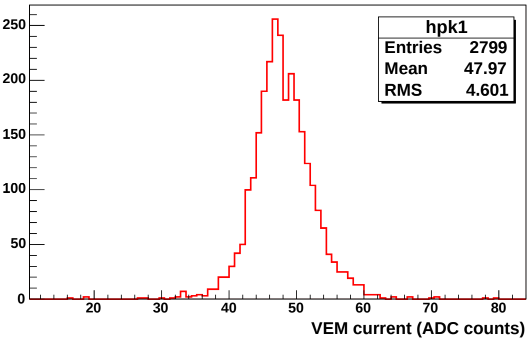

Fig. 2: VEM measured for 2799 PMTs.

III. Detector response and uniformity

Stable data taking with the Surface Detector started in January 2004 and various parameters are continuously monitored to ensure the good performance of the detectors. The noise levels are very low. For both the anode and dynode channels, the mean value of the pedestal fluctuation RMS is below 0.5 FADC channels corresponding to about 0.01 VEM. The intrinsic resolution of the GPS time tagging system is about 8 ns requiring a good precision for the station location. An accuracy better than 1 meter is obtained for the tank position by measuring the positions with differential GPS.

Figure 2 shows the muon peak current (I_{VEM}) values for a large number of PMTs. The mean value of the muon peak (I_{VEM}) is at channel 48 with an RMS of 4.6 showing a very good uniformity of the detector response. Trigger rates are also remarkably uniform over all detector stations, also implying good calibration and baseline determination. The mean value of the threshold trigger rate is 22 Hz with dispersion less than 2%. The time-over threshold trigger is about 1 Hz with a larger dispersion. This is due to the fact that this trigger is sensitive to the pulse shape and thus is more sensitive to the characteristics of the detector. It is observed that the new detectors often have ToT values which are higher and then stabilise after a few months to about 1 Hz. The trigger studies and the studies on the muon response show that the detectors have, after a few month stabilisation, a good uniformity.

Day-night atmospheric temperature variations can be larger than 20 °C. In each tank, temperature is measured on the PMT bases, on the electronics board, and on the batteries which allows to correlate various monitoring data with the temperature. Typical day-night variations are of the order of 2 ADC channels for the muon peak. This is mainly due to the sensitivity of the PMTs to temperature. These temperature variations also slightly affect the ToT-trigger. The muon calibration is made online every minute. This continuous calibration allows to

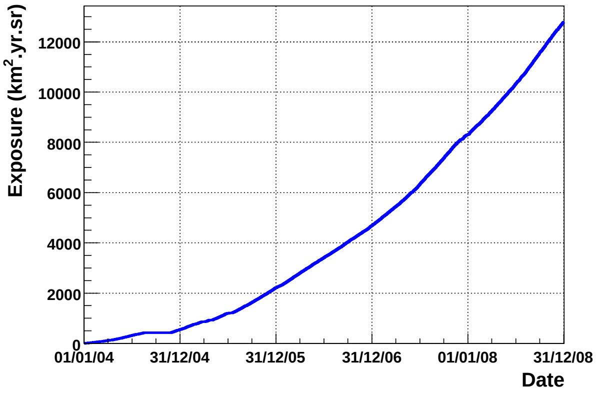

Fig. 3: Evolution of the exposure between January 1st, 2004 and December 31st, 2008.

correct for the day-night temperature effects.

IV. DETECTOR ACCEPTANCE

To ensure good data quality for physics analysis there are two additional off-line triggers. The physics trigger, T4, is needed to select real showers from the set of stored T3 data. This trigger is mainly based on coincidence between adjacent detector stations within the propagation time of the shower front. In addition, there is a so-called fiducial trigger, T5, which excludes events where a part of the shower may be missing. The full efficiency of the SD trigger and event selection is reached at 3 10^{18} eV. Above this energy, the calculation of the exposure is based on the determination of the geometrical aperture and of the observation time. Figure 3 shows the evolution of the integrated exposure between January 1st, 2004 and December 31st, 2008.

The fiducial trigger is based on hexagons allowing to exploit the regularity of the array. The aperture of the array is obtained as a multiple of the aperture of the elemental hexagon cell. In practice, any active station with six active neighbors contributes exactly to the elementary hexagon aperture, a cell. The number of cells, Ncell(t), is not constant over time due to possible temporary problems in the stations (e. g. failures of electronics, power supply, communication system, etc.). Ncell(t) is constantly monitored. In Fig. 4 the evolution of the number of hexagonal cells with time is shown.

The very precise monitoring of the array configurations has allowed us to exploit data during the construction phase. The evolution as a function of time of the number of trigger cells is globally similar to the evolution of the acceptance. Some differences however can be seen. For example, the pronounced dip seen in Fig. 4 in January 2008 corresponds to a large storm that affected the communication system.

V. LONG-TERM PERFORMANCE

Figure 5 shows the area-to-peak ratio for a typical PMT channel as a function of time. Two main effects are observed: a slight global decrease and small seasonal variations. The two curves reflect the maximum day-night variations (see figure caption).

The maximum day-night variations are due to outside temperature variations. As explained above, the muon calibration is made on-line every minute which allows to correct for this effect. Seasonal amplitudes of variaions in the area-to-peak ratio are ~1%. The seasonal effects are also mostly due to outside temperature changes. The global decrease of the signal as a function of time could be due to changes in the liner reflectivity or in the water quality. From the current studies, the expected fractional signal loss in 10 years is less than 10% which gives confidence in a very good long-term performance of the Surface Detector.

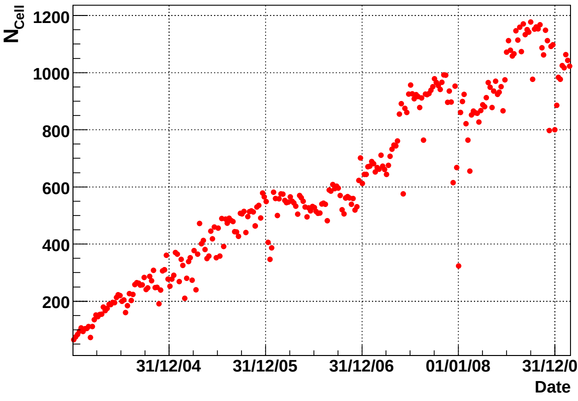

Fig. 4: Evolution of the number of hexagon cells as a function of time between January 1st, 2004 and December 31st, 2008.

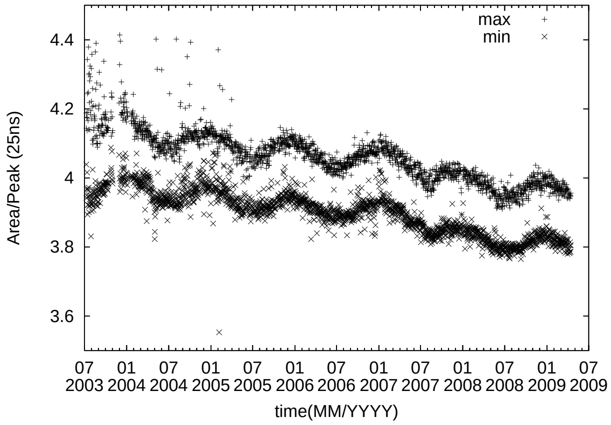

Fig. 5: Area-to-peak ratio as a function of time for a typical PMT channel. The upper curve corresponds to the maximum value and the lower curve to the minimum value during 24 hours reflecting the day-night variations.

VI. OPERATION AND MAINTENANCE

Currently more than 1600 surface detector stations are operational. Concerning the WCD itself, only very few failures have been detected. Only a few liners were observed to leak shortly after installation. In this case, which constitutes the worst failure mode, the tank is emptied and brought back to the Assembly Building for replacement of the interior components. Similarly, only a few solar panels have been damaged or were missing. Solar power system parameters are recorded and analyzed using the central data acquisition system. The average battery lifetime is 4 years, and batteries are changed during regular maintenance trips.

The PMTs and electronic boards are the most critical elements of the Surface Detector stations. They are subject to very severe environmental conditions: temperature variations, humidity, salinity and dust. The failure rates of the PMTs are about 20 per year (about 0.5%). Some HV module and base problems have been detected as well as some problems due to bad connections. All other failures except those concerning the PMTs (such as broken photocathode) can be repaired on site. It is currently estimated that the number of spare PMTs is sufficient for about 10-15 more years of operation. The failure rate of electronic boards is about 1% per year. Some of the problems are repaired simply by reflashing the software. Most of the electronic problems can also be repaired on site. All the spare parts are stored on site.

The operation of the array is monitored online and alarms are set on various parameters. The maintenance goal is to have no more that 10 detector stations out of operation at any time. It is currently estimated that the long-term maintenance (including the battery change) requires about 3 field trips per week. This maintenance rate is within the original expectations.The maintenance is organized by the Science Operation Coordinator and performed by local technicians. The Surface Detector does not require a permanent presence of physicists from other laboratories on site. However, remote shifts for the data quality monitoring will be implemented.

VII. CONCLUSIONS

The construction of the Southern site of the Pierre Auger Observatory in Malargüe, Argentina, was completed in June 2008 and the Observatory has been running now with its full configuration for nearly one year. The operation of the Surface Detector array is monitored online and alarms are set on various parameters. The design is robust to withstand the adverse field conditions. The failure rates of various components are low and most of the failures can be repaired on site. The maintenance is performed by local technicians.

The characteristics of the Surface Detector stations are very uniform and the noise levels and resolutions exceed original requirements. The acceptance of the array is constantly monitored. This has allowed to take reliable physics data also in the construction phase.

Some detectors have been operational already for more than 8 years which has allowed to study the long-term performance of the Surface Detector. In particular, these studies have shown that the water quality remains excellent over several years.

Intensive and automatic monitoring, low failure rates, and local maintenance capabilities give confidence in a very stable long-term operation of the Pierre Auger Surface Detector.

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