The performance of the Pierre Auger Observatory

C. Bleve [1,2], G. Cataldi[2], M. R. Coluccia[1,2], P. Creti[2], S. D'Amico[2,3] I. De Mitri[1,2], G. Marsella[1,2], D. Martello[1,2], L.Perrone[1,2], V. Scherini[1,2]

[1] Dipartimento di Matematica e Fisica "Ennio De Giorgi", Università del Salento, Italy
[2] Istituto Nazionale di Fisica Nucleare sez. di Lecce, Italy
[3] Dipartimento di Ingegneria dell'Innovazione Università del Salento, Italy

1. Abstract

The Pierre Auger Observatory consists of a surface array of 1660 water Cherenkov detectors (SD), overlooked by 27 air fluorescence telescopes (FD) grouped in four sites. A system to monitor the status and the performance of the whole Observatory has been developed to ensure its smooth operation and optimal data quality for physics analysis. In addition to the on-line calculation of the SD exposure and the FD on-time, the available information is used to check the long term stability of key quantities and of data quality, thus defining the performance metrics [1].

2. Introduction

Designed as a hybrid detector, the Pierre Auger Observatory [2], located in Argentina (Pampa Amarilla, 1400 m a.s.l.), uses two techniques to measure the extensive air shower (EAS) properties by observing both their longitudinal development in the atmosphere and their lateral spread at ground level.

Charged particles and photons that reach the ground are sampled with the Surface Detector array (SD) which consists of 1660 independent water-Cherenkov detectors (WCDs), filled with 12 tons of pure water each, and equipped with three photomultipliers (PMTs) to detect the Cherenkov light emitted in the water [3]. The WCDs are spread on a triangular grid of 1.5 km spacing over 3000 km^2.

The fluorescence light generated in the atmosphere by the charged particles of the air shower through excitation of N_2 molecules is detected by the Fluorescence Detector (FD) [4] which consists of 27 telescopes, in five different buildings. The field of view of each telescope is 30° in azimuth, and 1.5° to 30° in elevation, except for three of them, for which the elevation is between 30° and 60° (HEAT telescopes [5]). Light is focused with a spherical mirror of 13 m^2 on a camera of 440 hexagonal photomultipliers. The FD can only operate during dark nights, which limits its duty cycle to 13% while the SD operates 24 hours per day.

Stable data taking with the SD started in January 2004 and the Observatory has been running with its full configuration since 2008.

3. Surface detector performance

Stable data taking with the surface detector array started in January 2004 and the Observatory has been running in its full configuration since 2008. Various parameters are continuously monitored to optimize the performance of the detectors and ensure reliable data.

The monitoring tool includes so-called performance metrics to monitor the overall performance of the surface detector array. Relevant data useful for long term studies and for quality checks are stored in the Auger Monitoring database on a one-day basis. For example, mean values over one day of the number of active SD detectors and the number of active hexagons as well as the nominal value (expected value if all the detectors deployed were active) are available.

As an example, figure 1 (top) shows the number of active SD stations normalized to the nominal number of stations in the array for the time between 2010 and 2013. This plot is a convolution of the status of the active stations and of the efficiency of the CDAS, which since the beginning is better than 99.5 %.

Figure 1(bottom) shows the number of active hexagons for the same period. This variable is a key parameter since it is the basis of the exposure evaluation. Indeed, the offline T5 fiducial trigger selects only events for which the hottest station is surrounded by an active hexagon. Thus, above 3×10^{18} eV, when the full efficiency of detection of the array is reached (at least three triggered tanks), the exposure is simply proportional to the integrated number of active hexagons during the period.

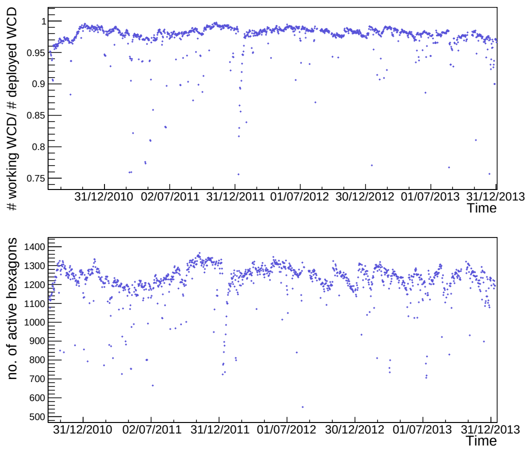

Figure 1. Top: number of active SD stations normalized to the nominal number of SD stations in the array, as a function of time. Bottom: number of active hexagons as a function of time

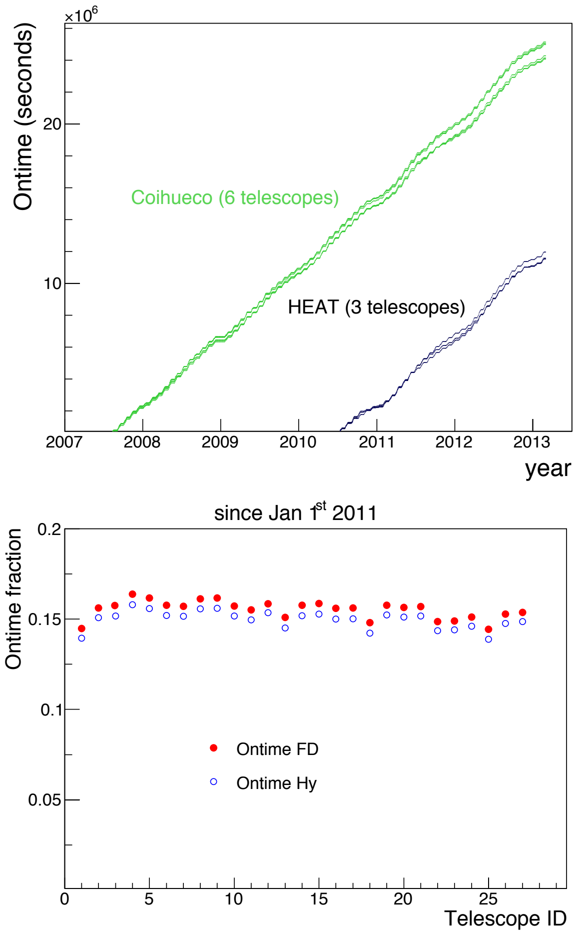

Figure 2. Top: accumulated on-time since 1 Jul 2007 for the 6 telescopes at Coihueco and for the 3 HEAT telescopes. Bottom: FD and hybrid on-time of individual telescopes since 1 Jan 2011. (1–6), (7–12), (13–18), (19–24), (25–27) for the sites of Los Leones, Los Morados, Loma Amarilla, Coihueco and HEAT, respectively.

4. Fluorescence detector performance

The data taking of the FD can only take place under specific environmental conditions and is organized in night shifts. The telescopes are not operated when the weather conditions are unfavorable (high wind speed, rain, snow, etc.) and when the observed sky brightness (caused mainly by scattered moonlight) is too high. As a consequence, the shifters have to continuously monitor the atmospheric and environmental conditions and judge the operation mode on the basis of the available information.

The performance of the fluorescence and hybrid data taking is then influenced by many effects. These can be external, e.g., lightning or storms, or internal to the data taking itself, e.g., DAQ failures. For the determination of the *on-time* of the Pierre Auger Observatory in the hybrid detection mode it is therefore crucial to take into account all of these occurrences and derive a solid description of the data taking time sequence.

Data losses and inefficiencies can occur on different levels, from the smallest unit of the FD, i.e., one single photomultiplier (pixel) readout channel, up to the highest level, i.e., the combined SD/FD data taking of the Observatory.

The active time of the FD data acquisition is calculated using a minimum bias data stream with a less restrictive trigger condition. Since July 2007, the relevant information concerning the status of the FD detector has been read out from the Observatory monitoring system. An on-time dedicated database has been set up by storing the average variances and the on-time fraction of individual telescopes in time bins of 10 minutes. The information on the veto due to the operation of the lidar or to an anomalous trigger rate on FD together with the status of the CDAS needed to form a hybrid event are also recorded. The method to calculate the on-time of the hybrid detector is described in detail in [6].

The accumulated on-time is shown in figure 2, top, for the six telescopes at Coihueco and for the three HEAT telescopes. The average FD on-time (full circles) of individual telescopes since 1 January 2011 is shown in figure 2, bottom. Requiring that the CDAS is active defines the hybrid on-time (empty circles).

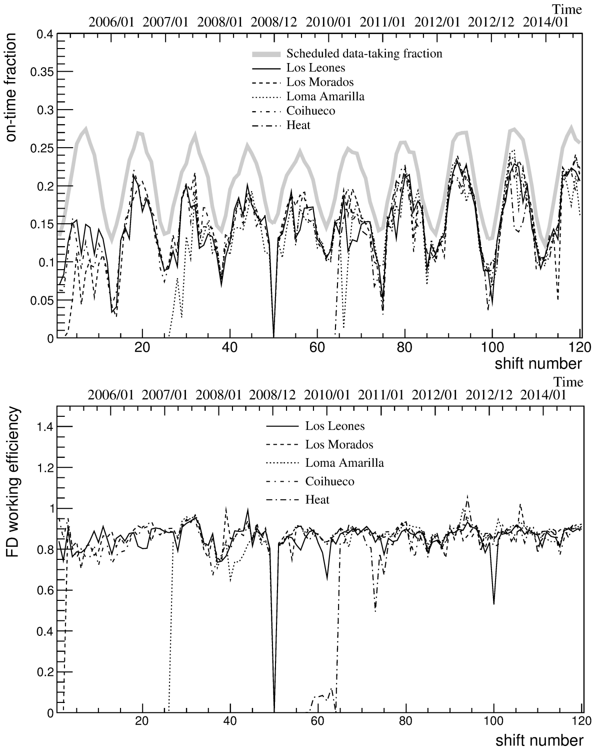

Figure 3. Top: time evolution of the average hybrid on-time fraction over 9 years of operation of the Pierre Auger Observatory. The thick gray line defines the scheduled data taking time fraction defined as the time periods with moon fraction lower than 70% and with the moon being below the horizon for more than 3 hours. Bottom: readiness of the FD detector (see text for details).

The time evolution of the full hybrid duty cycle over 9 years of operation is shown in figure 3, top, for all FD sites. Time bins are taken as the time intervals elapsed between two subsequent FD data taking shifts. The performance of the hybrid detector is compared to the nominal DAQ time in the top panel of figure 3. In the bottom panel, the FD on-time is normalized to the time with high voltage ON, leading to an average FD detector readiness of about 85% for all telescopes. The remaining inefficiency can be ascribed to different factors such as bad weather conditions (high wind load and/or rain) or high variances due to bright stars/planets crossing the field of view of the FD.

It should be noted that the FD site of Los Morados became operational in May 2005, Loma Amarilla starting from March 2007 and HEAT since September 2009. After the initial phase due to the start up of the running operations, the mean on-time is about 15% for all of the FD sites. Additionally, a seasonal modulation is visible, since higher on-time fractions are observed in the austral winter during which the nights are longer.

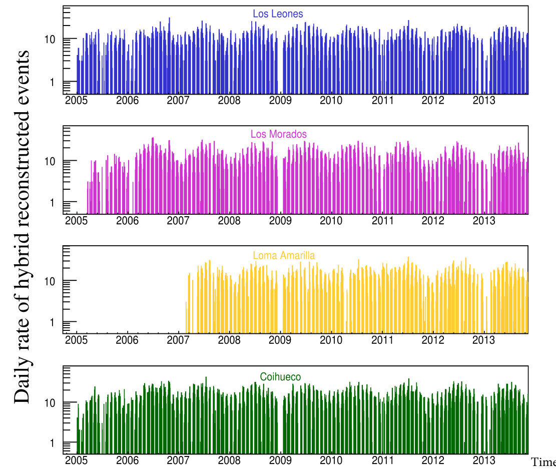

Figure 4. Daily rate of hybrid reconstructed events as a function of year, starting in 2005, for (from top to bottom) Los Leones, Los Morados, Loma Amarilla and Coihueco, respectively.

5. Performance characteristics of the Observatory

In Table 5 are summarized some of the important parameters that characterize the performance of the Observatory. These parameters include the event rate of the detectors and the resolutions of the different reconstructed observables.

6. Time stability of the hybrid detector response

The performance of the hybrid detector is demonstrated as a function of time using a sample of events fulfilling basic reconstruction requirements, such as a reliable geometrical reconstruction and accurate longitudinal profile and energy measurement. The daily rate of well-reconstructed hybrid events observed by individual FD sites is shown in figure 4 as a function of time, starting in 2005.

An important benchmark for the time stability of the hybrid detector response is the study of the effective on-time, defined as the fraction of all events that are well reconstructed hybrids. Its time evolution exhibits quite a stable behav-

SD	
SD Annual Exposure	$\sim$5500 km^2 sr yr
T3 rate	0.1 Hz
T5 events/yr, $E > 3$ EeV	$\sim$14,500
T5 events/yr, $E > 10$ EeV	$\sim$1500
Reconstruction accuracy (S_{1000})	22% (low E) to 12% (high E)
Angular resolution	1.6° (3 stations)
	0.9° (>5 stations)
Energy resolution	16% (low E) to 12% (high E)
FD	
Uptime	$\sim$15%
Rate per building	0.012 Hz
Rate per HEAT	0.026 Hz
Hybrid	
Core resolution	50 m
Angular resolution	0.6°
Energy resolution (FD)	8%
$X_{\max}$ resolution	<20 g/cm^2

Table 1
Key performance parameters for the Auger Observatory

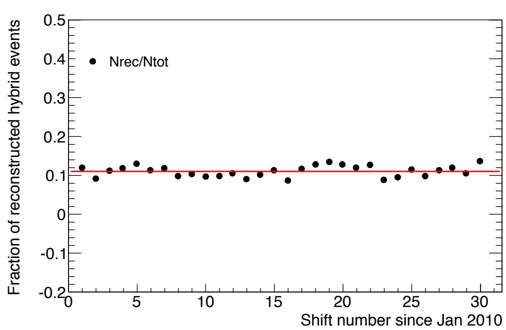

Figure 5. Fraction of all events that are well reconstructed hybrids since 2010.

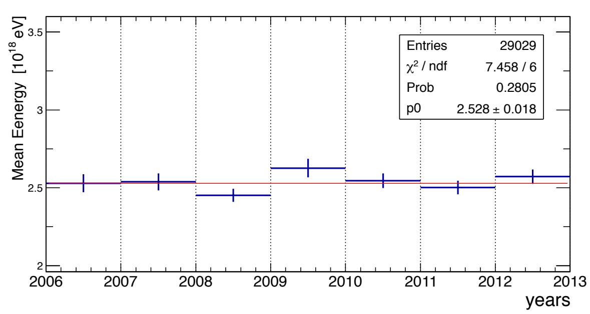

Figure 6. Mean energy for reconstructed hybrid events.

ior over time as shown in figure 5. Moreover the mean energy of the hybrid events above 10^{18} eV, with distance to the shower maximum between 7 and 25 km (corresponding to the 90% of the entire hybrid data sample), is shown as a function of time in figure 6. All these features demonstrate the quality of the collected hybrid data and directly assess their long term stability.

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