

Nightly Relative Calibration of the Fluorescence Detector of the Pierre Auger Observatory

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Abstract. A relative calibration of the photomultipliers in the fluorescence telescopes at the Pierre Auger Observatory is made every night. The calibration allows the long term performance of the photomultipliers to be monitored and permits a relative calibration database to be created each night. Infrequent absolute calibrations are also performed to determine the conversion factor of photon yield to ADC counts. A stable procedure has been developed to produce absolute calibration constants, typically 2×10^6 calibration constants/year, based on the absolute calibrations but rescaled depending on the photomultiplier response on a nightly basis. Three years (2006–2009) of data were analysed to produce the latest version of the database, including for the first time calibration constants for the final six telescopes that were commissioned in February 2007.

Keywords: fluorescence detector, relative calibration, nightly database

I. THE PIERRE AUGER OBSERVATORY

Primary particles with ultra high energy from 10^{18} eV to the extreme region of the GZK cutoff [1] interact in the atmosphere at nearly speed of light and create extensive air showers (EAS). The Pierre Auger Observatory [2] measures their flux, arrival direction distribution and mass composition by detecting EAS with high statistics. The Observatory includes two sites: Auger South site fully completed and operational in the Pampa Amarilla (Argentina) and Auger North site planned to be installed in Colorado (USA). The Auger South detector consists of the Fluorescence Detector (FD), 24 fluorescence telescopes collected in 4 sites on the top of natural hills, overlooking the Surface Detector (SD), 1660 water-Cherenkov detectors deployed on a triangular grid of 1.5 km spacing over a wide area (3000 km^2). A single telescope is composed by an aperture system, a spherical mirror and a camera of 440 photomultipliers (PMTs). The signals from the PMTs are amplified, filtered and continuously digitised by 10 Mhz 12 bit FADCs [3]. The fluorescence telescopes take data every month for a period (FD shift) of approximately 15 days, since one week before to one week after the new moon.

II. AIM OF THE FD CALIBRATION

The amount of scintillation light produced by an EAS is directly proportional to the energy deposited by the shower in the atmosphere. One FADC bin from the j^{th} PMT represents light from a particular segment of atmospheric depth ΔX . The conversion from energy deposited to the FADC count is given by

$$n_{ADC_j} = \frac{dE}{dX} \cdot Y_\gamma \cdot \Delta X \cdot T \cdot \frac{A}{4\pi r^2} \cdot C_j^{abs} \quad (1)$$

where dE/dX is the rate of energy deposit in that segment of shower track, Y_γ is the fluorescence photon yield per unit of energy deposit, T is the atmospheric attenuation factor (mainly due to Rayleigh and Mie scattering), A is the telescope aperture and r is the light path in the atmosphere from the EAS towards the telescope, C_j^{abs} is the absolute calibration factor.

C_j^{abs} depends on the optical efficiency of the telescope, on the quantum efficiency, the photoelectron collection efficiency and the gain of the PMTs and on the charge-to-digital conversion in the FADCs. An absolute and relative optical calibration of all telescopes is needed to determine the absolute conversion of photon yield to ADC counts.

III. OVERVIEW OF THE FD OPTICAL CALIBRATION SYSTEM

Different methods are adopted to calibrate the FD [4], among these are the absolute calibration, performed occasionally to follow the long-term behaviour, and the relative calibration performed daily to follow the short-term behaviour of the photomultiplier. The absolute end-to-end calibration [5],[6],[7] uses a cylinder with a diameter of 2.5 m, called *drum* creating uniform illumination from an LED light source at 375 nm. The absolute calibration of the drum is based on a *Si* photodiode calibrated at NIST [8]. The *drum* can be mounted at each telescope entrance aperture once or twice in a year. This measurement gives the C_j^{abs} conversion factor from photons to ADC counts (eq.1).

Three different (**Cal A**, **Cal B**, **Cal C**) relative optical calibrations [9] are performed to monitor different parts of the telescope, its daily performance and time variations between two subsequent absolute calibrations.

- In the **Cal A** calibration (fig.1), the light pulses are produced with a bright (470 nm) LED, transmitted from the source to a 1 mm thick Teflon diffuser located in the

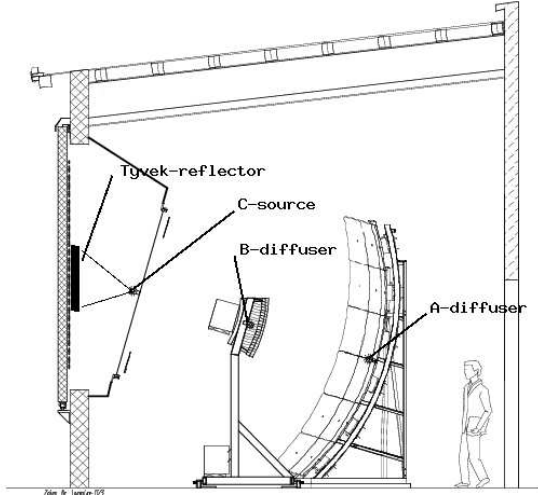


Fig. 1: A schematic lay-out of the fluorescence telescope of the Pierre Auger Observatory. The location of the light diffusers corresponding to the three **Cal A**, **Cal B**, **Cal C** optical relative calibrations is shown.

center of the mirror. The light illuminates directly the camera. This calibration monitors only the behaviour of the photomultipliers.

- In the **Cal B** calibration (fig.1), the light pulses are produced with a Xenon flash lamp and transmitted to a 1 mm thick Teflon diffusers located on the center of two sides of the camera. The light illuminates the mirror and then is reflected to the camera. This calibration is aimed at checking the change in the reflectivity of the mirror and the behaviour of the PMTs.

- In the **Cal C** calibration (fig.1), the light pulses are flashes from a Xenon lamp to diffusers located just outside the entrance aperture. The light illuminates a reflective, removable Tyvek screen inserted outside the UV filter and then is reflected back towards the mirror. This calibration is intended to check the whole chain through the filter, reflection by the mirror and the behaviour of the PMTs.

The relative calibration measurements are performed twice per night, at the beginning and at the end of the FD data acquisition, to track variations throughout the data taking, for every night during the FD shift.

IV. NIGHTLY CAL A RELATIVE CALIBRATION

To perform one **Cal A** calibration measurement, 50 LED pulses (N_{LED}) at a rate of 1/3 Hz with square-type waveform (fig. 2) are generated. The FD data acquisition is triggered externally and the PMT signals are stored in files of 25 MB size.

For a given telescope, calibration raw data are processed to extract the mean integral charge $\langle Q^{CalA} \rangle_{j,k}$ for the j^{th} photomultiplier computed as the average over N_{LED} in the k^{th} calibration measurement:

$$\langle Q^{CalA} \rangle_{j,k} = \sum_i^{N_{LED}=50} Q_{i,j,k}^{CalA} / N_{LED}; \quad (2)$$

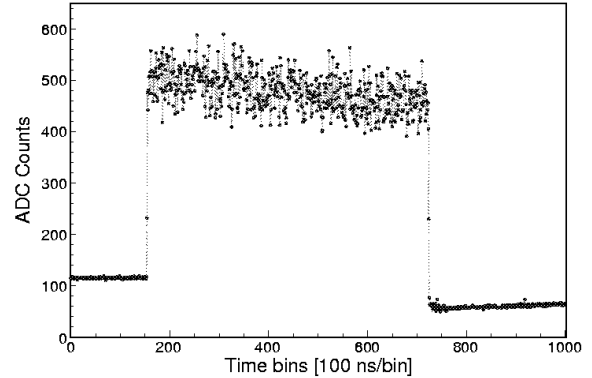


Fig. 2: The **Cal A** light pulses have a square wave form with a typical width of $57 \mu s$ and a drop in the height introduced by the control loop for very long-lasting signals. The difference in the pedestal before and after the pulse is due an undershoot of the system.

where

$$Q_{i,j,k}^{CalA} = \left(\sum_{l=t_{start}}^{l=t_{stop}} n_{ADC_l} \right)_{i,j,k} \quad (3)$$

is the sum of n_{ADC} FADC counts for the i^{th} LED pulse, subtracted the signal pedestal, in the $t_{start} \leq l \leq t_{stop}$ integration gate; l is a single 100 ns FADC time bin, t_{start} and t_{stop} are respectively the first and the last l where the signal can be considered over threshold according to given conditions. Different algorithms to scan the **Cal A** signal have been developed. Consistency cross-checks have been carried out and have shown an excellent agreement among different codes.

V. THE RELATIVE CALIBRATION CONSTANTS

The **Cal A** data amount (about 40 GB equal to 1.5×10^3 files per year per telescope) is stored partly on tapes and partly on disks at the Pierre Auger Observatory. In order to reduce the impact of data transfer on the existing

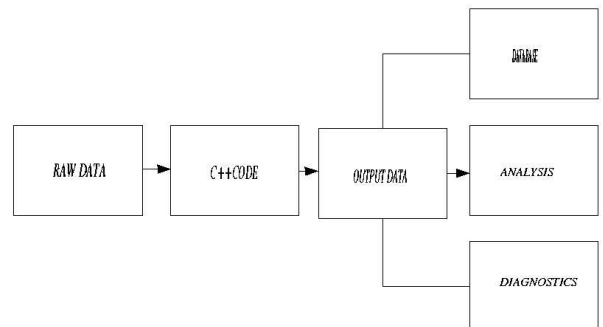


Fig. 3: Block scheme of the data processing and the further off-line analysis.

Internet link, the **Cal A** data processing is performed in the Pierre Auger Observatory and only the output results transferred outside of the Observatory for the further off-line analysis (fig. 3). For each **Cal A** calibration measurement, the value in the eq.3 is normalized by using the same quantity $\langle Q_j^{CalA} \rangle_{ref}$ calculated for a given reference run:

$$C_{j,k}^{rel} = \frac{\langle Q_j^{CalA} \rangle_{j,k}}{\langle Q_j^{CalA} \rangle_{ref}} \quad (4)$$

The reference run (one per each telescope) is taken within one hour after the absolute calibration measurement. The ratio in eq.4 is the $C_{j,k}^{rel}$ *relative calibration constant* for the k^{th} calibration measurement. It represents the relative change in absolute gain of the j^{th} photomultiplier. The relative calibration constant fluctuates around the nominal value (equal to 1) with a typical r.m.s. of a few percent.

VI. MONITORING THE STABILITY OF THE FLUORESCENCE DETECTOR

The **Cal A** relative calibration allows the short- and long-term behaviour of the photomultipliers to be monitored. Three years (March 2006 – March 2009) of data have been analysed for all the telescopes. The overall stability of the 24 fluorescence telescopes has been carefully and systematically studied.

The telescopes are quite stable on short-term, showing a 2 – 3% variation within each night (fig. 4a) and a 1 – 3% variation within each FD shift (fig. 4b), apparently induced by night sky exposure. On medium- and long-term, since the beginning of year 2007, owing to more restricting prescriptions in operation conditions, the FD response appears stable. The overall uncertainty, as deduced from the medium-term (approximately six months) monitoring, is typically in the range of 1 – 3% (fig.5). In addition, seasonal variations of 3 – 4% have been observed in all telescopes, likely due to temperature variations in the buildings lodging the telescopes (fig.5). The observed loss of gain, averaged over all telescopes, is less than 2% per year. It does not affect the life time of the FD so far. The system is currently very stable.

VII. PRODUCTION OF THE NIGHTLY ABSOLUTE DATA BASE

The **Cal A** relative calibration permits an absolute calibration database (DB) to be created each night. To compensate for the short- and long-term variations in the telescope response and to minimize calibration uncertainties, absolute calibration constants $C_{j,k}^{abs*}$ for the j^{th} photomultiplier and the k^{th} calibration measurement are produced on a nightly basis. They are based on the absolute calibrations but are rescaled depending on the PMT response according to

$$C_{j,k}^{abs*} = \frac{C_j^{abs}}{C_{j,k}^{rel}} = \frac{\langle Q_j^{CalA} \rangle_{j,k}^{ref}}{\langle Q_j^{CalA} \rangle_{j,k}} \cdot C_j^{abs} \quad (5)$$

To produce the nightly DB, only **Cal A** relative calibration measurements acquired at the end of the FD data taking are selected as their response is more stable.

A steady procedure has been developed to produce nightly absolute calibration constants. Three years (2006 ÷ 2008) of calibration data for all the telescopes, including for the first time the final six telescopes that were commissioned in February 2007, have been used to produce the latest version of the nightly database. It contains about 6×10^6 absolute calibration constants, its size is 0.9 GB. In the current DB, a flag is assigned to each PMT to record the goodness of the corresponding calibration constant, according to criteria that take any hardware or software failure in the calibration system, in the camera or in the front-end electronics into account. The 99.5% of calibration constants comes out to have an expected value, only the 0.5% of them is out of range and has to be rejected. Lastly, before each release of new constants, physics tests are performed and their outcome compared with known references to validate them.

VIII. CONCLUSIONS

Three years of relative calibration measurements for all the fluorescence telescopes of the Pierre Auger Observatory have been analysed. The short- and long-term behaviour of the photomultipliers of the Fluorescence Detector has been monitored. A steady procedure has been developed to produce 6×10^6 nightly absolute calibration constants, including for the first time the final six telescopes commissioned in February 2007.

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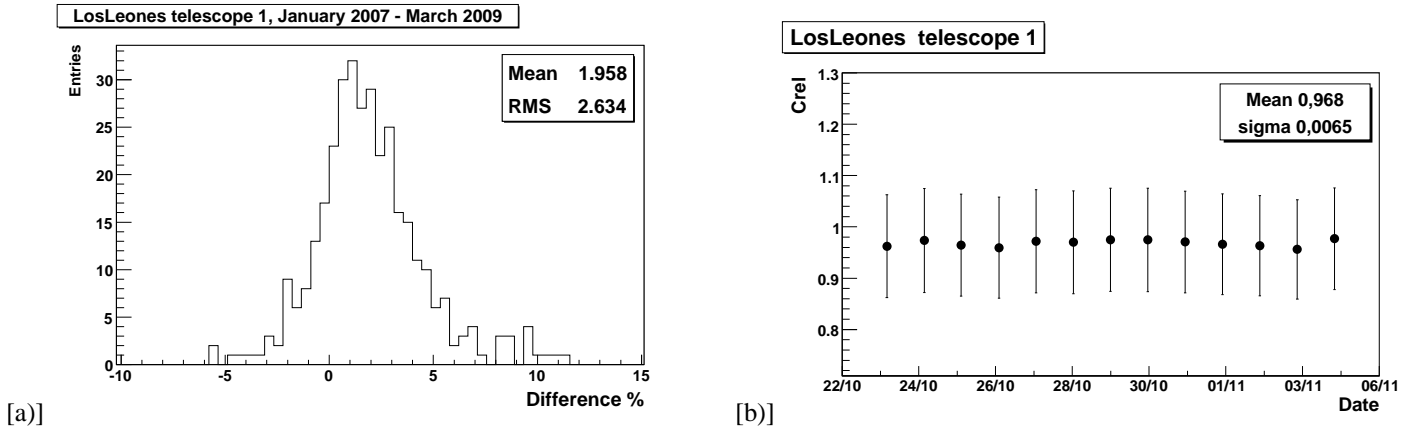


Fig. 4: Variations on the short-time behaviour of the photomultipliers within each night [a]) and each FD shift [b)]. On the left, the distribution shown is based off the difference per cent between relative calibration measurements acquired at the beginning and at the end of a given FD nightly data taking. On the right, the results are shown for a period of approximately 15 days (FD shift) of data taking. For each night in the FD shift, they are obtained by averaging over all 440 photomultipliers in the telescope. The error bars represent the one sigma fluctuations of the relative calibration constants over all the 440 PMTs.

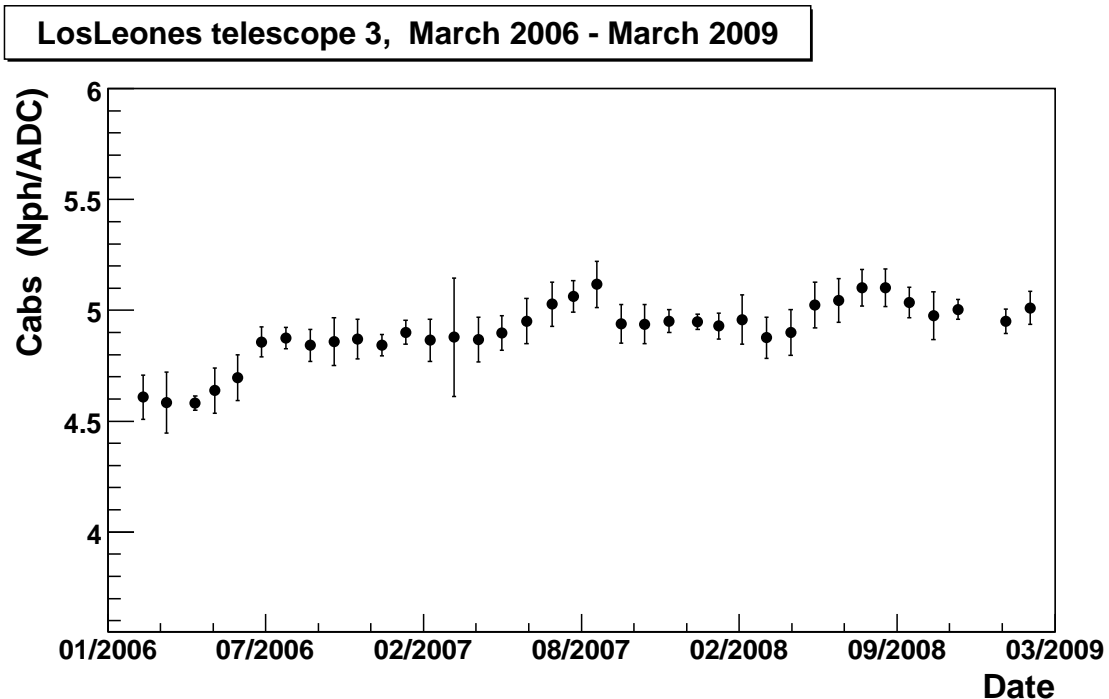


Fig. 5: Variations on the long-time behaviour of the photomultipliers over three years of the FD data taking. The results show the nightly absolute calibration constants as a function of the time. Each point is the mean value obtained by averaging over all the 440 photomultipliers in the telescope and over all the nights during one FD shift. The error bars represent the one sigma night to night fluctuations during each FD shift.