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The XY-Scanner for Absolute End-to-End Calibration of Fluorescence Detectors

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Abstract. The precise determination of the energy scale is a key part of experiments in astroparticle physics. At the Pierre Auger Observatory, the energy scale is set by the calorimetric measurement of extensive air showers with fluorescence detectors. Thus, the absolute end-to-end calibration of the fluorescence detectors is of utmost importance. In the past, this calibration was performed by illuminating the whole optical system of a fluorescence telescope with a large-scale extended uniform light source of the same diameter as the telescope aperture. However, handling difficulties, excessive manpower requirements, and degradation of such a source led to the need for a different approach for the absolute end-to-end calibration. The fundamental idea of the novel approach is to significantly reduce the geometrical size of the calibration light source, which is a near-UV LED source implemented in a portable integrating sphere with specifically designed interior. This light source is moved over the aperture by a rail mechanism with two independent linear stages named the XY-Scanner. Calibration data are evaluated from a series of light source positions instead of illuminating the entire aperture at once. The absolute photometric determination of the light source emission intensity is performed in a dedicated laboratory setup with a measurement uncertainty of 3.5 %. The XY-Scanner mechanics installed at the aperture gives also the opportunity to install other, devices for instance a narrow, collimated beam source to investigate local impurities of the telescopes. This contribution gives an overview of this novel XY-Scanner calibration method and presents preliminary results and discusses plans for the future.

1 Introduction

The Pierre Auger Observatory [1] is located in Argentina near the city of Malargüe. It covers the area of ~3000 km^2 deployed with water-Cherenkov detectors (WCDs) forming the surface detector (SD). There are ~1660 WCDs evenly distributed among the area (the exception is the North-West region, where the layout is denser). The whole SD array is overlooked by the 27 telescopes. Six telescopes at Los Leones, Los Morados, and Loma Amarilla sites, and nine telescopes at Coihueco site. Those three additional telescopes at Coihueco are called HEAT (High Elevation Auger Telescopes). Altogether, they form the fluorescence detector (FD), see the layout of the observatory in Fig. 1. Both SD and FD utilize different approaches to detect cosmic-ray-induced air showers. With this hybrid approach, Pierre Auger Observatory is a precise and highly sensitive observing instrument.

However, every instrument has to be calibrated to provide reliable data. This contribution summarizes the current calibration method as well as describes a novel method for the absolute end-to-end calibration of Auger FD. The main goal of the calibration of FD is to verify/set the energy scale at the Pierre Auger Observatory.

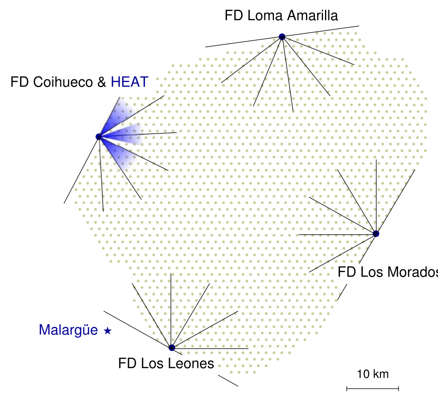

Figure 1. The layout of the Pierre Auger Observatory near the city of Malargüe. The SD array consisting of ~1660 WCDs is overlooked by the 27 FD telescopes at four sites.

2 The calibration of fluorescence detector

To perform the calibration task, all 27 FD telescopes need to be calibrated. The FD telescope [2] consists of a large spherical segmented mirror with a radius of 3400 mm. In the focal plane of the mirror, there is a camera with 440 PMT pixels. The whole aperture window of the telescope is 2200 mm in diameter. At the outer aperture perimeter, a

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corrector ring that provides a partial correction for spherical aberration of the mirror is installed. The aperture is filled with segments of near-UV filter glass transparent for wavelengths ranging from 290 nm to 410 nm.

To obtain the calibration constant for each individual PMT, the entire aperture has to be illuminated (in the ideal case) with a light pulse from an extended Lambertian source of known emission intensity (photon flux) located outside of the aperture. During the pulse, all PMT pixels of the camera are illuminated as well as FD telescope components. Thus, all of the components such as mirror reflectance, filter transmittance or quantum efficiency of the PMT, etc. contribute to the resulting signal detected on PMTs. The signal on individual PMTs is read out simultaneously at the time of the light pulse and the calibration constant is set according to the photon flux of the source.

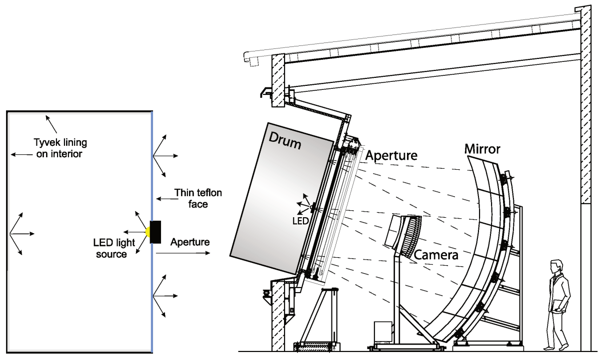

Figure 2. *Left:* The schematics of the Drum interior with the calibration LED source. *Right:* Schematics of the Drum absolute end-to-end calibration process [4].

2.1 Current calibration method

The current calibration method to determine the energy scale (performed in the past) is based on a unique design solution of an extended uniform light source (EULS) developed for calibrating Auger FD telescopes. According to its shape, it was called the Drum. In brief, the Drum was a hollow diffuse light source of a cylindrical shape with an outer diameter of 2800 mm, depth of 1500 mm, and the output aperture of 2500 mm. The sides and back surfaces of the Drum interior were lined with Tyvek, a material diffusely reflective in the near-UV spectral region. The front face of the Drum was made of a 0.38 mm thick Teflon sheet, which transmitted the light diffusely [2]. The primary point light source consisted of a near-UV LED with a nominal wavelength of 365 nm and a Teflon cylinder in front of the LED. Thus, uniformity was achieved by three diffuse components in the Drum. See Fig. 2 left. In addition, the Drum had an option enabling the calibration at multiple wavelengths within the region of 300-400 nm by means of a Xenon lamp with a series of 5 narrow-band optical filters.

During the calibration, the Drum was placed on the input aperture of the FD telescope and illuminated all 440 PMT pixels of the camera simultaneously, Fig. 2 right. Moreover, all individual components of the entire optomechanical structure of the telescope contributed to the calibration process. Therefore, this method of calibration is known as an absolute end-to-end calibration [3, 4].

Unfortunately, time has shown that the size and weight of the drum were very limiting in terms of its manipulation and maintenance. The absolute calibration of the Drum was rather cumbersome providing results with higher and higher uncertainties. In addition, the logistics of the Drum caused more uncertainties even within a single measurement campaign. In time, the calibration with the Drum has proved unsustainable and the need for replacement has become urgent.

2.2 Novel calibration method

The fundamental idea of the novel approach to absolute end-to-end calibration is based on the significant reduction of the size of the calibration light source, which reduces issues of the manipulation, weight, and absolute calibration of the new light source. However, with a smaller EULS, the aperture of the FD telescope will be illuminated partially instead of being illuminated at once. This is solved by summing every partial illumination, which in the end corresponds to the single flash of the Drum. The scanning of the FD aperture is done by moving the smaller calibration light source with a known photon flux (integrating sphere with an LED) on a motorized rail mechanism named XY-Scanner shown in Fig. 3. XY-Scanner utilizes two vertical stages (Y-axis) and one horizontal stage (X-axis). Vertical stages and their motor are permanently fixed at the aperture of every FD telescope. The horizontal stage with its motor is removable, portable, and easily mountable on a desired FD telescope aperture for calibration. On the horizontal stage, a universal holder to the calibration light source of a maximum weight of 2.5 kg can be mounted. Both motors and the calibration light source are connected via cables to the electronics box. The whole system is controlled by scripted software.

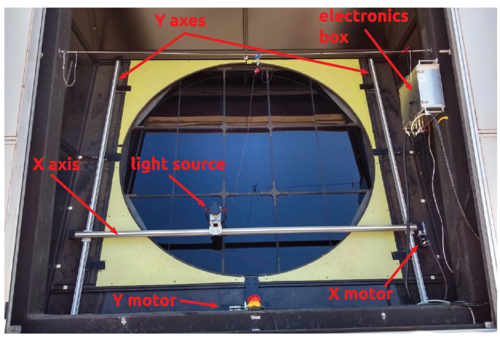

Figure 3. Photo of an FD telescope aperture with fully installed XY-Scanner. The Y axes and Y motor are permanently mounted at the aperture while the X axis with X motor, light source, and electronics box are portable.

Before each calibration measurement, a *Calibration A* reference measurement (consisting of an LED aiming directly at the PMT camera from the center of the FD telescope mirror) is performed [2]. During the calibration itself, a large number of scanning positions of triangular grid evenly distributed over the FD telescope aperture are measured, see Fig. 4. The calibration light source is moved across the FD telescope aperture following the black dots of the triangular grid with the sub-millimeter relative precision. The red circle is drawn at the border of the FD telescope aperture while the black-dashed circle shows the inner edge of the corrector ring. At each position, the calibration light source emits a 5 µs long light pulse of fixed intensity with the frequency of 1 Hz. This flashing frequency is limited by the read-out speed of the whole FD telescope camera. The calibration constant is obtained by integrating over all flashes from all measurement positions as long as the overall coverage of the FD aperture is sufficient.

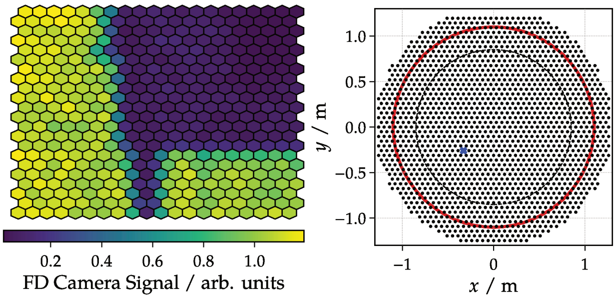

Figure 4. *Left:* an example of a signal detected at each PMT pixel for a single position of the calibration light source. The shadow of the camera and supporting structure are clearly seen. The position of the light source is marked as a blue spot on the right side of the figure. *Right:* a triangular grid (black dots) of all positions of the calibration light source at the FD telescope aperture.

The spacing of 6 cm between scanning positions results in ∼1700 iterations that are performed within an hour of measuring time. With a calibration light source of 5.08 cm diameter, the total coverage of the FD telescope aperture is ∼65 %, which is sufficient at the moment according to the preliminary measurements and simulations. The coverage could be possibly lowered in order to decrease the calibration measurement time. After the measurement run, another *Calibration A* reference is performed to determine the overall stability of PMT pixels over the calibration process. If they are stable, the calibration measurement is considered valid. Otherwise, it has to be discarded. Based on the previous results, an average of ∼1 % change in PMT signal is observed between the two measurements.

The up-to-date status by the end of 2022 after the autumn campaign is 19 fully installed XY-Scanner systems. The installation of the remaining 8 XY-Scanners (4 at the Los Leones site and 4 at the Loma Amarilla site) is planned to be completed in early 2023.

3 Light sources compatible with XY-Scanner

The versatile nature of the XY-Scanner allows the use of various light sources for different purposes. At the moment, the most important is the portable EULS that serves as a tool for the end-to-end calibration of the FD telescopes allowing them to set the calibration constant for their photomultiplier tubes (PMTs). While the requirement on the calibration source is the highest spatial and angular radiance uniformity possible, there is also another light source that utilizes a collimated beam and can be used with the XY-Scanner as well. Its purpose is to investigate the long-term stability of the local properties of the FD telescope.

3.1 XY-Scanner calibration light source

The calibration light source consists of a modified portable general-purpose integrating sphere 3P-GPS-053-SL with a diameter of 13.5 cm [5] and of a temperature-stabilized LED head holding a light source. The issue of integrating spheres as EULSs is summarized in [6]. The light source is a near-UV LED with a peak wavelength of 365 nm covered with an opal glass diffuser to approach the Lambertian emission profile. To achieve the uniform emission profile of the whole light source (integrating sphere with an LED), an exit port is reduced to a diameter of 5.08 cm (see Fig. 5). Moreover, a UV transparent plexiglass cover is mounted at the exit port to prevent any mechanical damage or dust pollution of the integrating sphere interior due to its use in the outdoor environment. The whole light source is mounted on the XY-Scanner using a universal holder enabling the rotation of the source along its optical axis with 15° stepping.

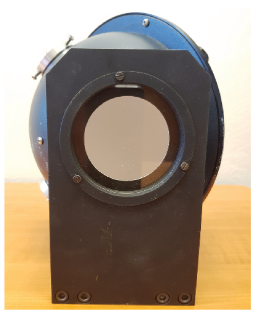

Figure 5. Front view on the integrating sphere exit port covered with the plexiglass. The integrating sphere is mounted in a universal holder.

To determine the far-field emission profile of the calibration light source a laboratory setup is developed. The light pulse of the calibration light source is detected by a 3.8 cm PMT located at 5 m distance from the source (the distance corresponds to the FD telescope dimensions), which is rotated using two motorized rotation stages. The setup is built in a dark room. Preliminary results of the measurement are shown in Fig. 6. These results are compared with the cosine emission profile of the ideal Lambertian source. The angular area of interest corresponding to the field of view of the Auger FD telescope is from −16° to 16°. The angle β represents the rotation of the source around the optical axis.

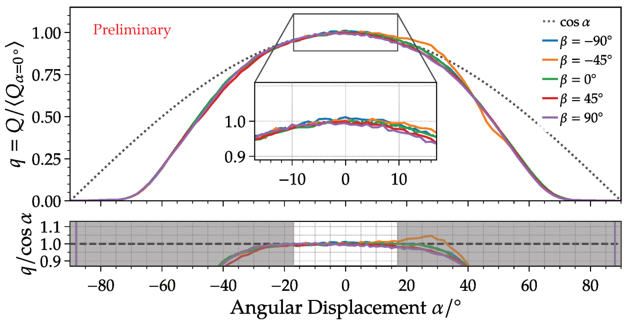

Figure 6. The emission profile of the calibration light source. Angular displacement area of interest corresponding to the field of view of Auger FD telescope is from −16° to 16°.

3.2 Optical collimator

The optical collimator is a device developed to further study the optical properties of the FD telescope such as local impurities or degradation of the FD telescope components. The impurities (for example the level of dust pollution) can be investigated at the UV filter, corrector ring, and mirror segments. The ideal spot of the emitting light beam has to fit in a single PMT after passing through transmissive components and after reflecting on the mirror. Any other detection on the neighboring PMTs indicates the higher degradation resulting in higher scattering. Thus, the emitting light beam has to be narrow with minimal scatter component.

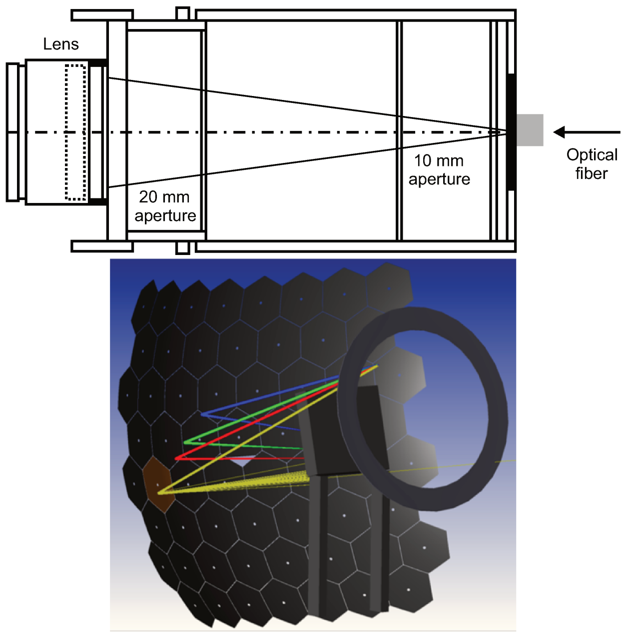

Figure 7. *Top:* the schematics of the optical collimator. *Bottom:* the layout of the optical simulation showing several light beams of the optical collimator reflecting on the FD telescope mirror.

The Fig. 7 (top) shows the schematics of the designed optical collimator that consists of an air-spaced doublet lens (focal distance of 99.9 mm and numerical aperture of 0.14) located at the front of a non-reflecting cylindrical tube with a diameter of 5.08 cm. Inside the tube, there are two apertures with diameters of 20 mm and 10 mm, respectively. The light is guided to the very back of the tube by an optical fiber with a core diameter of 0.1 mm and a numerical aperture of 0.1 resulting in a low divergence beam. The light source is a fiber-coupled LED with a peak wavelength of 365 nm.

Fig. 7 (bottom) shows the layout of the optical simulation with a collimated light beam reflecting on the FD telescope mirror and impacting the PMTs at the focal plane of the FD telescope. The optical collimator can be further used to study the point spread function (PSF) of the telescope affected by the FD telescope components. Either locally or for the whole aperture using the same principle of the end-to-end calibration utilizing the XY-Scanner.

4 Conclusion

The contribution summarizes the current status of the calibration of Auger FD telescopes and presents the XY-Scanner as a novel method for absolute end-to-end calibration of FD telescopes. The novel method utilizes the motorized rail system of two vertical axes and one horizontal axis, where a portable light source can be mounted. Furthermore, the contribution describes two of the possible sources designed for different purposes. One for the calibration itself and the second for the study of local properties of the FD telescopes based on PSF analysis.

At the moment, there are 19 XY-Scanner systems fully installed at Pierre Auger Observatory. The aim is to finish the installation for all 27 (4 remaining at the Los Leones site and 4 at the Loma Amarilla site) FD telescopes during early 2023. Regarding the calibration itself, the recent measurements show promising results that will be verified during the next campaign and discussed in 2023.

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