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Absolute photometric calibration of large aperture optical systems

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Abstract

A method of absolute calibration for the air shower fluorescence detectors of the Pierre Auger Observatory is presented, along with preliminary results from prototype equipment. A 2.5 m diameter light source uniformly illuminated by ultra-violet light emitting diodes is calibrated and mounted at the detector aperture. The resulting end-to-end measurement provides a 7% absolute photon calibration at a wavelength of 375 nm.

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1. Introduction

The Pierre Auger Observatory's (PAO) hybrid detector uses two standard methods of observing cosmic ray extensive air showers [1]. The more common technique employs a large ground array of water Cherenkov detectors to form a sampling grid, detecting shower particles as they reach the earth's surface. In addition, the PAO measures the N_2 fluorescence light that is generated by the passage of charged shower particles through the atmosphere. The light detected as a function of time is used to construct a longitudinal shower profile. The integral of this profile is directly related to the total energy of the cosmic ray shower, and to the incident energy of the cosmic ray. Thus precise determination of the incident energy depends critically on the ability to convert the detector response to an incident light flux at each point of the shower evolution.

Typically, a fluorescence detector (FD) telescope consists of an array of photomultiplier tubes (PMTs), or camera, at the focal plane of a large reflecting spherical mirror. In the PAO FD configuration, each of the 440 pixels in a camera sees approximately 80% of the defined aperture; the remainder is obscured by the camera itself. For each pixel the PMT signal is read out through a flash analogue-to-digital converter (FADC).

Measurement of the total light flux at the aperture requires evaluating the response of each channel in a camera to a known flux of incident

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photons into the solid angle covered by that pixel. This response includes the effects of all telescope components associated with that channel: the aperture projection, the optical filter transmittance, the mirror reflectivity, the PMT light collection efficiency and area, angle-of-incidence and multiple reflection effects from all these surfaces, cathode quantum efficiency, dynode collection efficiency, PMT gain, pre-amp and amplifier gains, and digital conversion factors. While the telescope response could be derived from independently measured quantities for each of the above effects, we describe an alternative method in which the cumulative effect is measured in a single end-to-end calibration.

The technique is based on a portable 2.5 m diameter light emitting drum, which mounts on the exterior of a PAO FD aperture. It provides a uniform pulsed flux of photons at sufficient intensity to trigger all the channels of a camera simultaneously. The absolute calibration of the drum itself is based on a UV-enhanced silicon photodetector, calibrated at the National Institute for Standards (NIST) [2]. While the surface area and sensitivity of this silicon detector are not large enough to detect the small photon flux from the drum surface directly, its calibration can be transferred to a more sensitive PMT system. Ideally, this calibration would occur at many wave lengths in the N_2 air fluorescence spectrum (300–400 nm), and at several intensities. At present, however, we discuss a prototype design that uses ultra-violet (UV) light emitting diodes (LED), emitting in a narrow band at 375 ± 12 nm.

The calibration procedure described here consists of four basic steps. First, the uniformity of the drum and light source is established. The photon flux from the drum is then measured by the PMT system, and the output is in turn compared to the NIST calibrated silicon detector. Finally the drum is mounted on the telescope and the response of the FD is recorded.

2. Drum and light source

The reflecting surfaces of the drum, sides and back, were made from a flexible laminate material, Tyvek [5] on one side and black plastic on the other. The drum is 2.5 m in diameter and 1.4 m deep. This provided a diffusively reflective interior at UV wave lengths. The front face was made from teflon (0.38 mm thick), which is diffusively transmitting in the UV. These flexible materials were held in shape by a skeleton frame made from aluminium tubing. The complete drum within its frame is shown in Fig. 1.

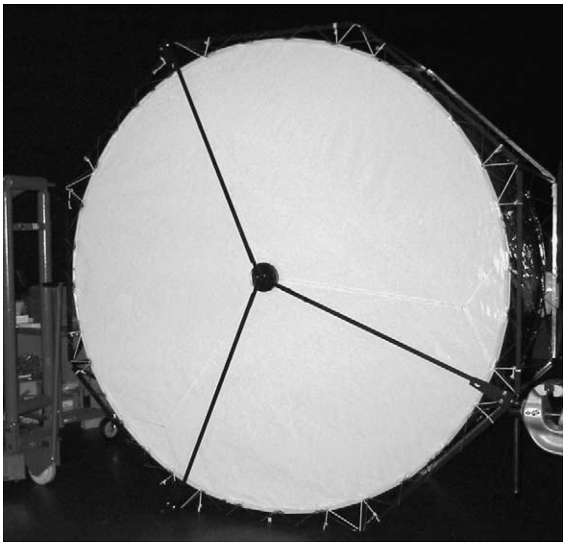

Fig. 1. Front surface of the drum and aluminum frame showing the teflon sheet and light source in the center. The frame is 1.5 m deep and 2.8 m across. The drum is 1.4 m deep and 2.5 m in diameter.

A pair of UV LEDs [3] in a light source at the center of the front teflon surface illuminate the interior of the drum through a 15 cm diameter hole in the teflon sheet. To enhance the uniformity of the emitted light, the LEDs are embedded in a 2.5 cm × 2.5 cm teflon cylinder. A UV-enhanced Si detector [4] attached to the end of the teflon cylinder is used to monitor the stability of the of UV LEDs during operation. The cylinder assembly is in turn mounted in a 15 cm diameter cup (see Fig. 2), lined with Tyvek.

3. Drum uniformity measurements

The uniformity of the surface emission of the drum was measured in a darkroom. The mea-

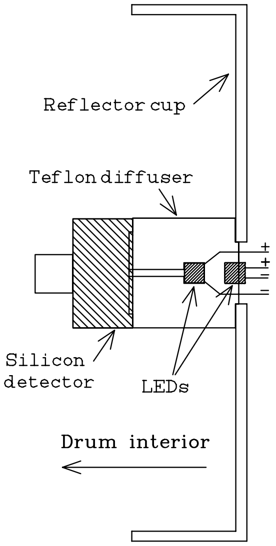

Fig. 2. Schematic diagram of the cup assembly showing the position of the two LEDs, the teflon cylinder and the monitoring silicon detector. The cup is 15 cm in diameter.

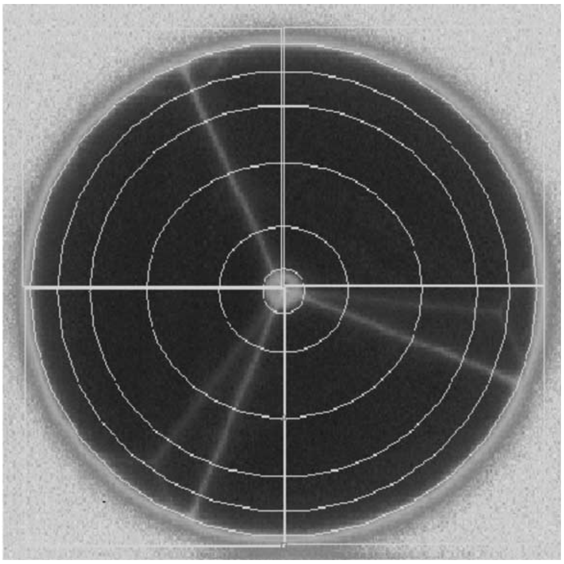

Fig. 3. A CCD image at 0° drum angle, showing the defined regions for relative intensity analysis. The radial struts of the supporting frame and seams in the teflon material can be seen.

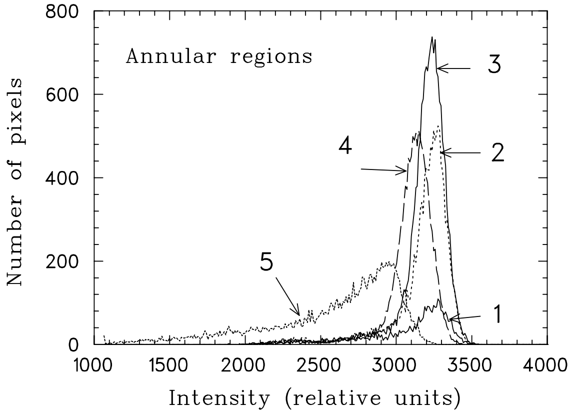

Fig. 4. A plot of the observed pixel intensities in the five defined annular regions of the drum, shown in the previous figure. Tails on left sides of peaks are due to shadowing of frame spokes and seams in the drum surface material.

surements were made using a CCD camera [6], viewing the drum from a distance of 14.40 m. Images were recorded by the CCD at angles of 0°, 10°, 20° and 25° relative to the drum axis, covering the full angular aperture for a PAO camera. For these images, the 2 UV LEDs were powered continuously. Background images with the UV LEDS off were taken and subtracted from each foreground image. All exposures were for 300 s.

The 0° image was used to analyze the uniformity of emission over the drum surface (see Fig. 3). Six concentric circles were drawn on the image, defining five annular regions of increasing radius. The light level of the pixels in each region was histogrammed to obtain the intensity for each annulus as shown in Fig. 4. The regions are labeled in order of increasing radius. The region outside the 5th circle (region 5, $R \geqslant 1.10$ m) is outside the telescope field of view. Between the four regions the variation in the mean intensity is about 2%.

Up/down and left/right asymmetries were evaluated in a similar fashion by defining drum quadrant regions outside the 1st circle and inside the 5th circle. Gaussian fits to the intensity distributions indicate variations of approximately ±1% in peak centroid locations (see Fig. 5). These small drum non-uniformities indicate that, except for angular effects described below and differences due to camera shadowing of the aperture, the FD telescope pixels should see similar intensities integrated over the drum surface. While perfect drum uniformity is desirable, small non-uniformities can be mapped and corrected for in analysis.

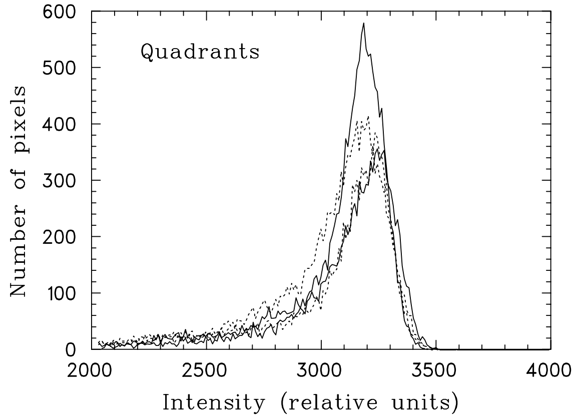

Fig. 5. As above, but for the defined quadrants of the drum.

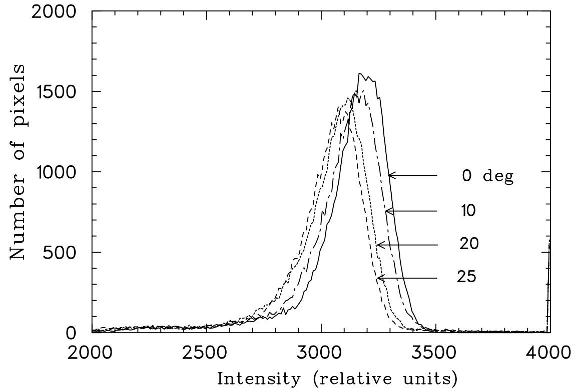

Fig. 6. A plot of the observed pixel intensities for drum viewing angles of 0°, 10°, 20° and 25°.

The variation of intensity with viewing angle is shown in Fig. 6 for the area inside the 5th circle. The intensity at a given point on the drum surface drops monotonically with increasing angle as shown by the centroids of the four peaks. The decreasing integrated area under each peak falls as the viewing angle of the drum surface increases, indicating the cosine effect. The maximum viewing angle for the extreme camera pixels in the FD telescope is about 21°. At 20° the relative intensity, as given by the centroid, is 0.97 relative to that at 0°.

4. Drum absolute calibration

The desired end result of an absolute calibration is to establish the number of photons/($\text{cm}^2 \times \text{sr} \times \text{s}$) emitted from the surface of the drum when the LEDs are on. The reference standard for this measurement was a UV-enhanced Si detector [4] calibrated at NIST [2]. This NIST Si detector was used to calibrate a 375 nm light source, which was then used to do a relative calibration of the PMT system used in the drum measurements. This system included the 3.5 in. diameter PMT, associated electronics and data acquisition system.

Note that to calibrate the drum, no absolute calibration of the PMT individually, or of the PMT-electronics combination, is required (see below, and Section 6).

4.1. PMT system calibration

The light source for the relative PMT calibration consisted of a collimated beam from a UV LED identical to those mounted in the drum. A well studied neutral density (ND) filter (attenuation of 4.04×10^4) was mounted on a rotating turret between colimation slits. The filter was inserted when illuminating the PMT to compensate for the difference in sensitivity between the NIST calibrated silicon detector and the PMT. The downstream element of the beam colimation was a 0.500 cm^2 precision mask supplied by NIST with the silicon detector. NIST provides a DC mode calibration of 0.128 A/W for this particular silicon detector at 375 nm.

The procedure consisted of three steps. First, the UV LED was operated in DC mode and the current output of the silicon measured using a Keithley electrometer. The measured LED output was 308 photons/μs. The second step involved pulsing the LED and integrating the current from the silicon detector using a charge integrator [7] combined with a voltage-to-digital converter (VDC). The LED pulse width was adjusted to 100 μs but the charge integrator gate was extended to 400 μs in order to include to long tail of the silicon detector signal. Using the manufacturer's calibration of the charge integrator, the pulsed and DC results agreed to within 3%. Lastly, with the ND filter rotated into the beam, the relative calibration (photons per VDC channel) of the PMT was performed. The PMT operating conditions closely resembled those of the drum measurement—a 5 μs pulse width (resulting in a flux of photons nearly identical to that produced by the drum), 12 µs integration time, and the same high voltage system and pre-amplifiers.

The procedure outlined above establishes the PMT calibration in the 0.5 cm^2 central area of the photocathode. The size of this region was dictated by the need to calibrate the beam using the 1 cm diameter NIST calibrated Si detector. In general, response is not uniform over the face of a PMT due to irregularities in the photocathode layer, non-uniformities of the focusing electric field, path length to the first dynode, etc. To relate the calibration of the central region to the full PMT surface, the PMT was exposed to a dispersed beam of 375 nm photons and the response with and without the 0.5 cm^2 mask was measured. It was found that the unmasked response was about 138 times greater than the masked response, giving an effective area of 68.8 cm^2. This is larger than the physical area of the cathode, indicating that the central cathode region has relatively weak response.

Using the light source calibration of 308 photons/µs, the response in the central region of the PMT of 714 ADC channels for 5 µs pulses, and the ratio 1.34 of the effective area of the PMT to the physical area, the calibration for the PMT, base, pre-amp, integrator, and VDC combination was 1.61 ± 0.09 incident photons per VDC channel when the full PMT surface is uniformly exposed to incident photons.

The uncertainty in the PMT system calibration is 5.8%, including uncertainties in the photocathode effective area (5%,) ND filter attenuation (1%), the UV Si detector calibration (1.5%, provided by NIST), the Keithley electrometer (2%), and the extraction of the centroid (1%).

4.2. Drum calibration

Within a darkroom, the PMT was positioned 14.40 m from the drum face, on the drum central axis, and was connected to the same electronics, power supplies, and data acquisition system as used for the PMT system calibration. Foreground and background runs were taken with the drum light source in pulsed mode. The results from the VDC are shown in Fig. 7. The centroid shift between the foreground and background PMT data is 752 VDC channels. Using the calibration values, an average of 1210 photons hit the surface of the PMT during each 5 µs pulse.

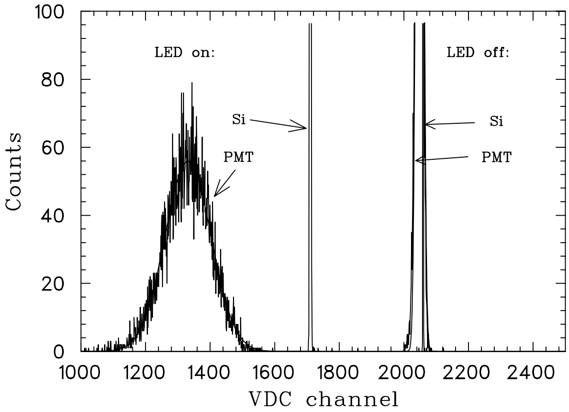

Fig. 7. The PMT response at 14.40 m from the drum, from separate runs with the LED pulsed and with the LED-off. Also shown are the narrow spikes from the Si monitor detector for each run, showing the consistency of the LED source. The PMT Gaussian is wide, but the good statistics determine the centroid to within a few VDC channels. The LED-off Gaussian for the PMT and both monitor spikes go off scale vertically. The 4096-channel VDC is bi-polar with 0 at channel 2048, and integrates negative values for the PMT and Si signals.

The angle-of-incidence at the PMT for all photons from the drum is less than 5°, so that angle-of-incidence loss effects are small and the drum can be treated as a point source. The result is that the drum surface emits 970 ± 70 photons/(cm^2 × sr) in each 5 µs pulse, where the surface area of the drum is taken to be $\pi \times 125^2$ cm^2 and the physical solid angle of the PMT photocathode is $(\pi \times 4.10^2)/1440^2$. The 6% uncertainty comes from the PMT calibration (5.8%), the centroid extraction (1%), loss of photons at the PMT due to unknown angle-of-incidence effects (2%), drum surface area (1.5%), and drum-PMT distance (1%).

5. Fluorescence detector telescope calibration

Calibration runs were performed in Argentina on an operating PAO FD telescope during February and March of 2002. With the drum mounted in the aperture, approximately 900 responses to drum flashes 5 μs wide were collected for every PMT in the camera in the FD telescope using the FD data acquisition system. Fig. 8 shows the average channel response plotted as a function of channel number. In this particular camera, various versions of prototype hardware and electronics were in use, resulting in a difference between those channels below approximately 100 and those above it.

The aperture area of the FD telescope was measured to be 3.80×10^4 cm^2. The average response of the camera PMTs to drum pulses was 5166 FADC counts. Using 970 photons/(cm$^2\times$sr) per pulse from the drum surface as above, and 5.94×10^{-4} sr pixel acceptance gives 4.0 ± 0.3 photons/FADC count.

Corrections have been made to the measured 0° drum intensity to correct for the average intensity seen by the 440 pixels during calibration. These corrections are 0.97 for the average reduction in viewed aperture area (average $\cos(\theta)$) and 0.98 for reduced drum intensity at an average angle. The result is then the averaged response to the actual number of incident photons on each of the 440 pixels.

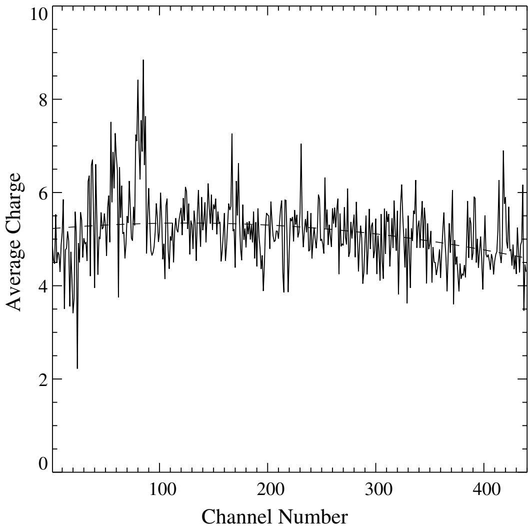

Fig. 8. The plot shows the average charge in each channel (divided by 1000) for the approximately 900 pulses. A second order fit to the data is also plotted (dashed line).

The 7% uncertainty includes uncertainties in the drum calibration (6%, see above) and in extracting the average FD camera pixel response (3%).

6. Discussion

The calibration result of 4.0 ± 0.3 photons/FADC obtained above for the FD telescope compares favorably to an alternative measurement of the FD response, in which remote laser shots were used and a value of 4.1 ± 0.5 photons/FADC count was obtained at 355 nm. FD camera efficiency varies as a function of wavelength, but the calibration numbers at 355 and 375 nm should be similar. One can expect the PMT quantum efficiency to drop at the shorter wavelength but the UV filter on the FD telescope aperture becomes more efficient. The two effects result in a nearly identical overall efficiency at the two wavelengths [8].

When the drum is mounted on the aperture, some light is reflected back to the drum surface from detector optical surfaces such as the UV filter and corrector ring. These reflected photons make the drum surface brighter, affecting the calibration. Such secondary reflections cannot occur for distant sources such as real cosmic ray events. We estimate this to be a 3% effect, but have not applied any correction.

The result shown for the FD telescope is a global average of the response of all 440 channels for this telescope. Calibration values for each channel are determined taking into account non-uniformities using ray tracing techniques.

It should be pointed out that in this technique, the 3.5 in. diameter PMT and associated digitizing electronics acted only as a black box transfer mechanism from the light source calibrated with the NIST Si detector to the drum. An absolute calibration of the PMT system was not required, merely the change in VDC values between the exposure to the drum and the calibrated light source.

The largest source of error was in determining the photocathode effective area (5%). We are currently evaluating methods to determine the area more accurately.

Acknowledgements

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