Statistical Calibration and Background Measurements of the Auger Fluorescence Detector

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Abstract

In the framework of the hybrid cosmic ray experiment Auger a precise calibration of the fluorescence detector (FD) is necessary to ensure the energy scale of the measurement. Aging of the photomultiplier tubes (PMT) induce long-term variations of their response; whereas varying light intensities, and power-on and off cycles result in short term changes of gain. Therefore, a simple and fast statistical method was developed to calibrate the gain of all channels simultaneously. Test measurements with the prototype showed that our method is insensitive to drifts of the light intensity and could also be applied to evaluate PMT after-pulses. A simplified version of the method measures continuously the sky background and single stars down to 7^{th} magnitude.

1. Introduction

The prototype detectors of the Auger experiment [1] have been successfully tested and operated. Currently the final design version of the detectors and electronics are under installation. The electronics of the FD [2] continuously records the input of each pixel in a ring buffer of $100\mu s$ length with a $10MHz$ clock rate. Each PMT is powered by a positive high voltage at the anode; therefore its signal is AC-coupled to the front-end amplifier containing a 4^{th} order Bessel filter for anti-aliasing. The quantum and photoelectron collection efficiency of the system, gain of the PMTs and associated electronics, time constants of the filter, and their changes with time have to be included in event reconstruction and detector Monte-Carlo.

An absolute light calibration [5] will be performed several times a year. However, a prompt calibration after interesting events is necessary several times during a night of observation. The choice of a rectangular light pulse of a blue LED with a length of about $70\mu s$ allows us to collect in a very short time sufficient statistic for the evaluation of variance and mean value of ADC values. The gain is then deduced from the ratio of variance and mean [3]. Furthermore the measurement of the LED brightness by a Si-Pin-diode will calibrate the relative light sensitivity at the same time.

Although the entire electronic system was designed for best sensitivity to

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short PMT pulses we need also to determine the average DC light level or a current monitor at each PMT for 3 reasons: 1. Protection of the PMTs against excess light to avoid destruction or fast aging, 2. knowledge of the sky brightness on a pixel-to-pixel basis to determine atmospheric conditions, and 3. tracking of stars across the camera verify the absolute pointing of the telescopes. The AC coupling prevent a direct measurement of the PMT current. Thus, a statistical analysis of the ADC values [4] was installed to determine the sky brightness.

In the following sections we describe some results gained with the prototype applying the new methods of calibration.

2. Statistical Method

Illumination of a PMT may be considered as bombarding the PMT photocathode with a sequence of photons described by a Poisson process. That holds for the light produced by a LED and also by stars in the sky background.

In our model of the electronic system [3] the impulse response function is determined by the anti-aliasing filter and the AC-coupling network with its time constant τ_{AC} of $0.8ms$. The anti-aliasing filter with a time constant of about $150ns$ determines completely the high-frequency behavior of the system. The noise of the PMTs and electronics including digitization noise are small compared to the fluctuations of the photoelectron signal, simplifying the method.

From the theory of random functions generated by a Poisson process it follows that the mean of the response of the amplifier $M(t)$ to a step-like light impulse is well approximated by

$$M(t) \approx \overline{i_{phel}}\, G \,\exp\left(-t/\tau_{ac}\right) = M_0 \,\exp\left(-t/\tau_{ac}\right) \;(\mathit{ADC\text{-}counts}) \tag{1}$$

and the variance of the response D and the gain G are given by

$$\begin{aligned} D &\approx \overline{i_{phel}}\, G^2\,(1+\nu_g)\; F/5 \;(\mathit{ADC\text{-}counts}^2) && (2)\\ G &\approx 5\,D/(M_0\;(1+\nu_g)\;F)\;(\mathit{ADC\text{-}counts}/(\mathit{phel}/100ns)) && (3) \end{aligned}$$

with the average photoelectron current $\overline{i_{phel}}$ and the noise equivalent bandwidth $F(MHz)$. The approximations (1) and (2) are exact for times t considerably larger than the time constant of the anti-aliasing filter. Equ. (2) is valid for noise-free amplification systems. For a realistic case the variance of the electronic noise has to be subtracted.

For the current monitor we have to calculate the variance D of successive ADC values. Using Equ. (2) we derive the cathode DC current from the variance D for constant G, ν_g and F over the measuring period:

$$\overline{i_{phel}} \approx 5\,D/(G^2\;(1+\nu_g)\;F)\;(\mathit{phel}/100ns) \tag{4}$$

The value of ν_g varies from PMT to PMT within a batch in the 10% range, which induces an error of 2.8% in the number of photoelectrons.

The calculation of variance D is done continuously in the FPGAs on the frontend-boards described in more detail in [4]. The statistical accuracy of the method with 2^{16} samples was about 0.5% for the variance.

3. Measurement Results

3.1. Gain measurements, Drifts and noise equivalent bandwidth F

A series of 50 to 100 LED pulses ($70\mu s$ long) provides the necessary amount of samples for evaluation of the variance D and the parameter M_0 of the mean value. The illumination level was kept low enough to avoid short-term gain drifts of the PMTs. We confirmed the quality of the short-term stability of LED and PMTs gain, by comparison of the amplitude at both edges of the pulse. The total error of the gain measurements depends on the uncertainty of ν_g and the errors of variance and mean and is smaller than 5.5%.

The ratio D/M obtained with and without digital integration yields the noise equivalent bandwidth F of each channel. These values have to be evaluated only once and then with high statistics.

3.2. Distortions induced by afterpulses

We investigated afterpulses using our $50\mu s$ long LED pulses with a sharp falling edge. We found only very small distortions at the end of each pulse of the PMTs. The response of each channel was averaged over 100 LED pulses and normalized to the amplitude of the light pulse. After that an averaged response of all channels of the camera was calculated. We found an afterpulse ratio of 1.3%. We measured two well-separated peaks in the afterpulse distribution at 0.9 and $2.2\mu s$ after the falling edge.

3.3. Results and comparison with other measurements

Using 100 light flashes of $70\mu s$ we got 60 000 samples. We obtained an averaged gain of 1.84 ($ADC\text{-}counts/photoelectrons/100ns$) for the complete camera with a statistical error of 0.2%. We assume that all PMTs have the same single photoelectron resolution of 0.4. The fluctuation analysis applied to the absolute calibration data obtained with 150 LED flashes ($35\mu s$ long) produces an average gain of about 1.76 ($ADC\text{-}counts/photoelectrons/100ns$) [3], and both measurements are consistent within the errors.

3.4. Equalizing the gain of the detector

At first the amplification of the electronics was set to the same nominal value and the gain of the camera was measured with the described method. From the measurements we got a $\Delta G/G$ of 30% in the gain and calculated the amplification correction factors for each channel to obtain a uniform gain over the detector. Then the amplification of the electronics was adjusted accordingly and the absolute gain of the camera was re-measured. Uniformity of the camera gain was drastically improved. The remaining channel-to-channel deviation of the gain was on average 3%. In a few channels the regulation range of the gain was exceeded and the absolute gain could not be set to the desired value.

3.5. Statistical current monitor

Every 30 s the ADC variance and pedestal for each pixel was recorded. At the beginning we measured the variance with the shutter in front of the telescope closed and used this data to subtract the background caused by electronic noise. This contribution was stable over time and amounts to less than 10% of the variance due to sky background. The statistical current monitor was also applied to track stars in the field of view of one prototype camera. It was possible to find light peaks from stars if they cause at least a 5% increase in light intensity corresponding to a star of 7^{th} magnitude.

4. Conclusion and Outlook

The complete calibration procedure for each pixel of the detector including the analysis and adjustment of the amplifiers takes a few minutes, which is about an order of magnitude faster compared to previous methods [4]. Furthermore the described method evaluates the mean value for each macro pulse of $70\mu s$ and thus avoids problems due to drifts and AC-coupling.

Our measurements with the prototype detector proved that the statistical current monitor gives a very good approximation of the night sky light level and provides a precise instrument to measure the alignment of the FD telescopes.

The experiment started data acquisition with the final FD telescope design in May 2003. From this time on the statistical current monitor and gain calibration system willbe in routinely operation during cosmic ray measurements.

5. References

1. Blümer J. for Auger Collaboration 2003, 28th ICRC, Tsukuba
2. Gemmeke H. for Auger Collaboration 2001, 27th ICRC, Hamburg.
3. Menshikov A. et al 2003, to be published in IEEE Trans. Nucl. Sci.
4. Kleifges M. et al 2003, to be published in IEEE Trans. Nucl. Sci.
5. Roberts M.D. for Auger Collaboration 2003, 28th ICRC, Tsukuba