Statistical Current Monitor for the Cosmic Ray Experiment Pierre Auger

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***Abstract*--The air fluorescence telescopes are one essential part of the Pierre Auger Project, currently under construction in Argentina. With a pixel camera of 440 photomultiplier tubes the telescopes observe fluorescence light induced by cosmic ray extensive air showers passing through the atmosphere. In this paper we report on a method to monitor the DC anode current in each photomultiplier by statistical analysis of the signal fluctuations. The method has in our case the advantage that we were able to implement it using free resources of FPGA logic, therefore no additional electronics is required. We present details of the current monitor design and its performance measured with a prototype device.**

I. Introduction

THE Pierre Auger Observatory is a hybrid experiment which detects cosmic ray extensive air showers by a combination of a surface array and air fluorescence detectors (FD) [1]. The final surface array will consist of 1600 water Cerenkov tanks equally distributed over more than 3000 km^2 in the Pampa Amarilla located in the province of Mendoza, Argentina. It is complemented by 24 fluorescence telescopes observing the night sky above the surface stations from 4 FD buildings located on the perimeter of the experimental area. Each FD building will house 6 telescopes, each of them having a field of view of approximately 30° x 30° in azimuth and elevation.

The telescopes are based on wide-angle Schmidt optic. The light falls through the 2.2 m wide aperture system (which contains an optical filter and a corrector ring lens) on a spherical mirror and is focused on a 440 photomultiplier camera. For optimum coverage of the focal plane we use XP3062 hexagonal photomultiplier tubes (PMT) from Photonis arranged in a matrix of 22 rows by 20 columns.

For mechanical reasons and in order to avoid dust deposition due to electrostatic attraction the camera body and the PMT cathodes have to be grounded. Therefore the PMT signals of up to 5 μs length are AC coupled to the analog electronics.

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Although the entire electronic system was designed for best sensitivity to short PMT pulses we need also to determine the average DC light level for several reasons:

1. Protection of the PMTs against excess light of artificial (vehicles, air planes) or natural (rising sun or moon) origin to avoid destruction or fast aging.
2. Knowledge of the sky brightness on a pixel-to-pixel basis may be used to determine atmospheric conditions for the event reconstruction.
3. Tracking of stars across the camera allows verifying the absolute pointing of the telescopes.
4. Optimal trigger conditions depend strongly on the light level of each pixel.

But AC coupling does not allow in principle a direct measurement of the DC anode current that is proportional to the background light. Our idea was to determine the sky brightness by a statistical analysis of the ADC counts. Due to the random nature of the signal generated by the sky light, and because both the intrinsic PMT noise and the electronics noise are small with respect to the fluctuations of this signal, there is a well defined and direct relation between the fluctuations of the signal and its average. Consequently, this average can be inferred from the knowledge of the signal variance.

This statistical method – described in more detail in section III – was particularly attractive as it could be implemented without extra costs in already existing FPGA logic.

A more elaborate approach to measure the DC anode current directly through an opto-coupled feedback loop [2] was implemented in one prototype telescope. Although it could provide a higher resolution we have chosen the statistical method to reduce the number of components and thereby to increase the reliability with a simpler design.

Starting in May 2001 the Auger experiment has recorded shower and background data with a first prototype telescope. A second telescope followed in October 2001. In the following sections we describe in brief the front-end electronics of the telescopes, the (hardware) implementation of the statistical analysis and measurement results gained with one of the prototype telescopes applying the new method.

II. FRONT-END ELECTRONICS OF THE TELESCOPE

The main tasks of the telescope electronic system are to shape the PMT signals from the camera, digitize and store them, find pulses in individual pixels and generate triggers based on the camera image. These tasks are performed by analog electronic boards and digital First Level Trigger (FLT) boards. The two boards are mounted together to form a front-end module, which processes in parallel all 22 pixels of one camera row. The complete telescope electronics consists of 20 front-end modules plus one Second Level Trigger module. Altogether it fits in a compact 9U 19„ sub-rack.

possible to derive the cathode DC current (as the number N_{phel} of photoelectrons per 100 ns) from the variance σ^2 to [5]

$$N_{phel} = \frac{\sigma^2 \times 10}{G^2 \times (1+\upsilon_g) \times 2 \times F} \qquad (1)$$

Here G is the gain (in ADC counts per photoelectron), υ_g is the gain variance of the PMT of around 0.4 and F is the noise equivalent bandwidth of 2.69 MHz from the complete analog signal chain used in October 2001 [5]. The value of υ_g varies from PMT to PMT within a batch in the 10 % range, which induces an error of 2.5 % in the number of photoelectrons. However, this variation is determined by the annual absolute calibration using an external light source of known brightness [6].

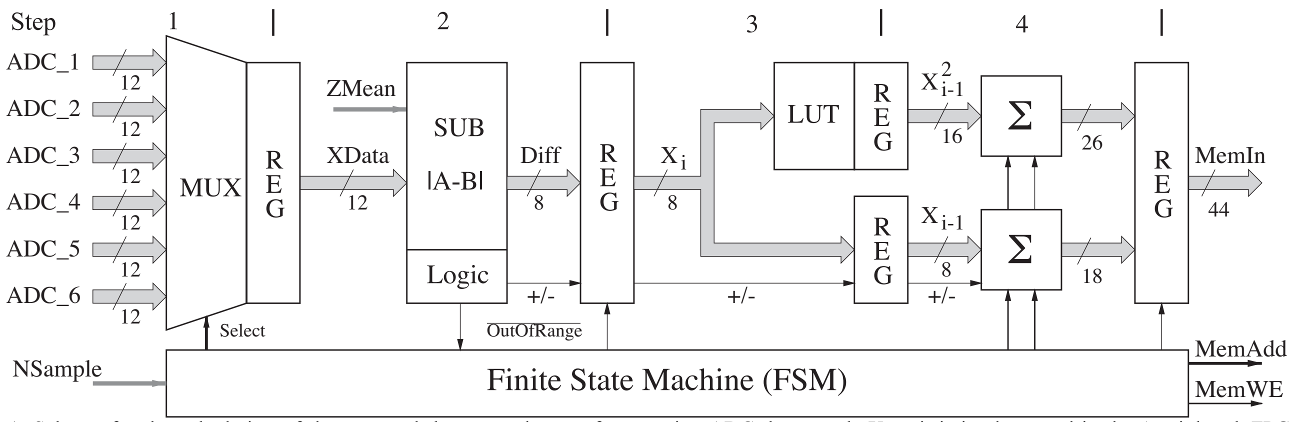

Fig.1. Scheme for the calculation of the sum and the squared sum of successive ADC data words X_i as it is implemented in the 'peripheral FPGA'.

After having passed anti-aliasing filters and amplifiers on the analog board the PMT signals are digitized with 10 MHz 12 bit ADCs. The data of 100 µs are recorded in ring buffers with 1000 samples depth and scanned by a digital filter to find pixels 'hit' by light pulses. Counters measure the hit rate for each pixel. The logic also adjusts the threshold of the digital filter automatically to keep the trigger rate constant at around 100 Hz independent from changing background light conditions [1],[3],[4]. As the regulation scheme affects only the trigger part it has no influence on the measurement of the signal variance.

All functions described above are implemented in re-programmable FPGA logic in order to achieve high flexibility, cost-effectiveness and ease of operation. Instead of using one huge FPGA chip we share functions common to all channels between 4 'peripheral FPGAs' (Altera Flex 10K50) – each FPGA handling 6 channels. In addition, there is a 'controller FPGA' (Altera Flex 10K100) on the FLT board to handle the communication with the readout PC and to interface the attached analog board.

III. STATISTICAL METHOD

The objective of the statistical method is to calculate the variance σ^2 and the pedestal μ of successive ADC values. Assuming random processes at the PMT dynodes it is

Equation (1) is valid for noise-free amplification systems. For the realistic case of small noise contributions the variance of the electronic noise has to be subtracted.

The (in hardware) implemented algorithm calculates over $n < 2^{16}$ successive ADC values x_i the quantities $\sum x_i$ and $\sum x_i^2$ necessary for the periodic calculation of the pedestal and variance for each channel. The 'peripheral FPGA' contains therefore a multiplexer to select 1 out of 6 channels, 3 arithmetic units for 8- to 32-bit operations and an 8x16-bit look-up table (LUT) for calculation of 8-bit squares.

The algorithm is performed in 4 pipelined steps controlled by a finite-state-machine (Fig. 1):

1. Select one ADC input channel from a group of 6.
2. Calculate the difference $\Delta_i = x_i - x_{mean}$ between the 12 bit ADC value x_i and an optimal guess of the offset x_{mean} common for this group of 6 channels. The optimal guess x_{mean} is once determined as the average pedestal of the 6 involved channels and was then kept constant. This can be justified by the high stability of the electronics. The spread of pedestals within a group of 6 channels was small enough to use one

common value x_{mean} in the calculation. Differences $\Delta_i \geq 256$ are regarded as shower signals and are excluded from subsequent steps. This cut excludes amplitudes of the sky noise much larger than $10 \cdot \sigma$ from the average and therefore doesn't reduce the precision of the variance calculation. On the other hand, the frequency of real showers below this cut is too low to give significant contributions to the variance calculation.

3. Generate the squares Δ_i^2 using the preloaded LUT.
4. Accumulate the differences Δ_i and their squares Δ_i^2 in 25-bit and 32-bit registers, respectively.

Repeat steps 2, 3 and 4 every 100 ns until a maximum of $n = 2^{16} - 1$ values are processed. Finally, the FPGA stores both sums for readout by the PC and the procedure continues with the next ADC channel. For every pixel the algorithm takes 6.5 ms. Considering all 6 pixel of the 'peripheral FPGA' the update interval of a single pixel is about 40 ms.

At typical night conditions the statistical accuracy of the method with $n = 2^{16} - 1$ samples was about 0.5 % for the variance and 0.02 ADC counts for the mean value corresponding to the pedestal.

Table I summarizes selected technical data to characterize the FPGA implementation.

TABLE I
TECHNICAL DATA OF FPGA

Resource	Total available	Total used	For statistical method
Logic equivalent Gates	50 000	46 000	6 900
Memory Bits	40 960	5 325	4 096
I/O Pins	185	185	0
Computing Power (MegaOperations/s)		350	50

IV. MEASUREMENT RESULTS

The statistical current monitor was applied to track stars in the field of view of one prototype camera. The measurement described below was performed in the early morning of October 21, 2001 in the building at Los Leones (69° 26' 59„ west, 35° 29' 47„ south). We used telescope #4, which was at that time equipped with an optical UV filter and the outer part of the aperture was covered by a corrector ring lens to limit the spot size to 0.5°. The field of view was up to 30° above the horizon and from the north direction 30° in azimuth towards the east.

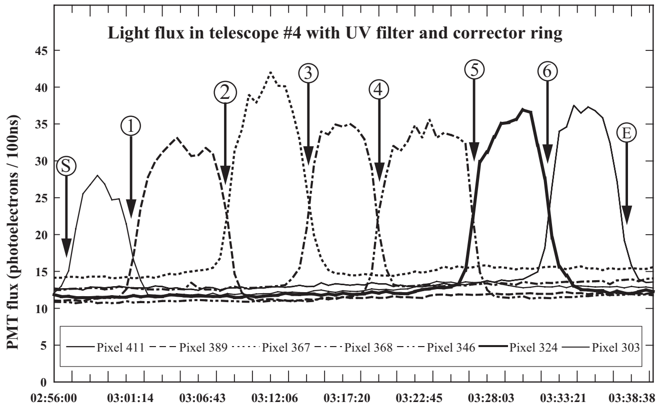

Fig. 2. Light intensity of several camera pixels as a function of absolute time. The arrows indicate the times the light spot transits from one pixel to another as given in Table II.

Every 30 seconds the ADC variance and pedestal for each pixel was recorded. At the beginning we recorded variance data with the shutter in front of the telescope closed and used this data to subtract the background caused by electronic noise. We have checked that this contribution is stable with time and amounts to less than 10 % of the variance due to sky light.

Fig. 2 shows, as an example, the light intensity of 7 adjacent pixels recorded during a period of 42 minutes. One can clearly see successive light peaks of 5 to 7 minutes width, which can be considered as light from the bright, bluish star Elnath (right ascension 81.6°, declination 28.6°, magnitude +1.64, B-V color index -0.12).

TABLE II
Position of Elnath at transition time between pixels

No.	Time (hh:mm:ss)	Azimuth (°)	Elevation (°)
S	02:57:16	29.5	19.2
1	03:01:41	28.6	19.6
2	03:09:08	27.0	20.3
3	03:14:48	25.8	20.8
4	03:19:50	24.7	21.3
5	03:27:04	23.1	21.9
6	03:32:41	21.9	22.3
E	03:37:47	20.7	22.7

We have scaled the pixels light intensity from Fig. 2 to the same mean background light level and calculated the crossing time between adjacent pixels. These times are summarized in Table II together with the position of the star Elnath in azimuth and elevation. The track is visualized in Fig. 3, where we also display the pointing of the involved pixels in elevation versus azimuth representation. The position of Elnath coincides or is very close to the pixels boundary at all calculated transition times. From this simple analysis we find no indication for a systematic camera misalignment.

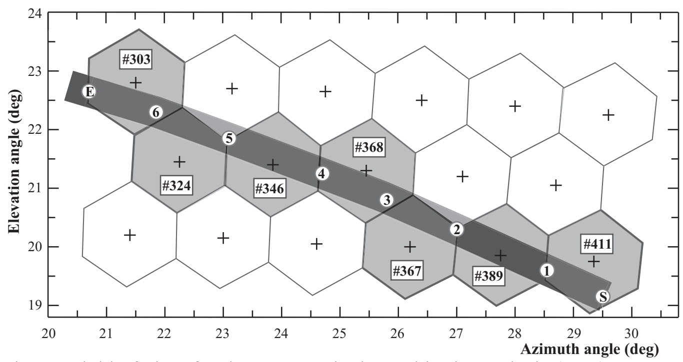

Fig. 3. Field of view for the camera pixels used in the analysis (grey) as a function of azimuth and elevation angle. The dark black line shows the track of the star Elnath at 8 points in time. The star is first seen at start time 'S' in pixels # 411 and passes through pixels # 389, # 367, # 368, # 346, # 324 before it leaves pixel # 303 at point 'E'. The width of the track indicates the spot size of approximately 0.5°.

The light intensity as displayed in Fig. 2 is given in photoelectrons per 100 ns at the PMT cathode. It was calculated from the measured variances using (1). In October 2001 the individual pixel gains g were known with 10 % accuracy leading to an uncertainty of 20 % for the light intensity, but the accuracy for gain determination has been improved to 3.5 % since then [4]. All pixels show a mean background level between 11.2 and 13.1 photoelectrons per 100 ns except for pixel # 367, which was found conspicuous during calibration and for which we suspect a calibration error.

In the same night we could also observe the much dimmer stars 72-tau (+5.5 magnitude) and v-tau (+4.3 magnitude). These stars caused a 20 % relative change in the background light level. It was possible to find light peaks from individual stars if they cause at least a 5 % increase in light intensity. This corresponds to a sensitivity for light from stars up to 7^{th} magnitude depending on atmospheric conditions and the color index of the star.

V. Conclusion and Outlook

Our measurements with the prototype detector have confirmed that the statistical current monitor gives a reasonable approximation of the night sky light level and provides a precise instrument to measure the alignment of the FD telescopes. It was implemented in existing FPGA logic on the digital first level trigger boards.

Furthermore the integration time of the variance of 6.5 ms is fast enough not to be affected by electronic drifts, which are on the scale of seconds or larger. On the other hand a sampling time of 30 s is sufficient to monitor the sky background. The change of the sky-background is on a scale of 100 s due to the rotation velocity of the earth and the angular resolution of 0.5° in the optical system.

The experiment will restart data acquisition with the final FD telescope design in spring 2003. From this time on the current monitor will be in routinely operation during cosmic ray measurements.

VI. References

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