Proceedings of ICRC 2001: 756 © Copernicus Gesellschaft 2001

ICRC 2001

# Surface detector electronics for the Pierre Auger Observatory

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**Abstract.** The surface array of the Pierre Auger Observatory consists of Cherenkov water tanks which are read out by three large photomultipliers. The signals are processed locally and a two level trigger is applied before transmitting the data to the central acquisition system. This paper shortly describes the main features of the electronics and the trigger. The performances are discussed in the light of simulations and test measurements.

## 1 Introduction

The Pierre Auger Observatory (PAO) surface array samples the shower particles at the ground level by Cherenkov water tanks having a 1500 m spacing between each other (Design Report, 1996). The shower particles at the ground level are mainly gammas, electrons and muons with mean energies below 10 MeV for gammas and electrons and 1 GeV for muons. When impinging the water tanks, electrons and muons emit Cherenkov radiation. The gamma rays are converted by Compton scattering and pair production into relativistic electrons emitting similarly Cherenkov radiation. The Cherenkov light is detected by three large photomultiplier tubes (PMT) viewing the water tank from the top.

The shower front extends typically over several microseconds and its intensity varies strongly as a function of the distance from the shower core. In order to reconstruct the shower, the signals from different detectors have to be correlated in time. Information on the nature of incident particles has to be extracted from the signal shape and the energy is inferred from the signal density at about 1000 m from the shower core. A local intelligence is required for trigger, data acquisition and monitoring. Moreover, the electronics is powered by solar energy limited to 10 W per detector station, it is implemented in a non-laboratory environment, and it has to be reliable over 20 years.

Following these requirements, the PMT signals are processed and digitized locally before being sent to the central data acquisition system (CDAS). Each detector station has a two level trigger, memory for temporary data storage and a slow control module for monitoring. The time information is obtained from the Global Positioning Satellite (GPS) system. The local software processing is performed by the station micro-controller.

The "Engineering Array" (EA) consisting of 40 Cherenkov stations is being commissioned. Although the main features of the electronics have been fixed, some changes of the design will be implemented for the final deployment. In the EA, commercial elements and flexible, not fully integrated solutions have typically been used in order to allow optimization for the full array. In the following, the main characteristics and performances of the different parts of the electronics will be presented.

## 2 Readout and PMT electronics

The amount of light produced in the Cherenkov water tanks varies rapidly as a function of the distance from the shower core. Based on simulations, the maximum signal at the photocathode that should be considered is about 250 nA (Lhenry-Yvon et al., 2001). This corresponds to a $30^o$ proton shower at 5 $10^{20}$ eV measured at about 500 m from the shower core. In order to have a linear PMT response up to this value, a low operating gain, 2 $10^5$, is required. The EA is equipped with PMTs from three different companies: Hamamatsu R5912, ETL 9353 and Photonis XP1802. The final choice of the PMTs will be made in July 2001.

The PMT cathodes are placed near the water and therefore they have to be supplied with a positive high voltage. The HV is provided locally from a module integrated in the PMT base and powered with +12 V DC. The maximum output voltage is 2 kV and the total power consumption is required to be less than 500 mW. The remote programming and monitoring of the voltage and the current is performed by analog input/output signals from the slow control module.

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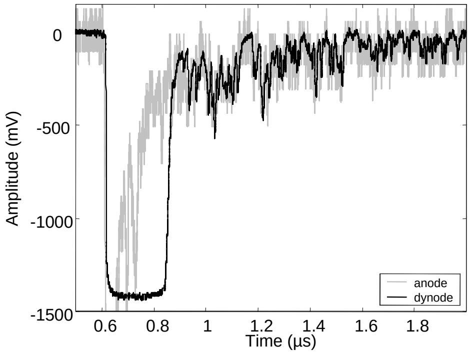


**Fig. 1.** Comparison of the anode and dynode outputs in the case of the dynode amplifier saturation (see text).

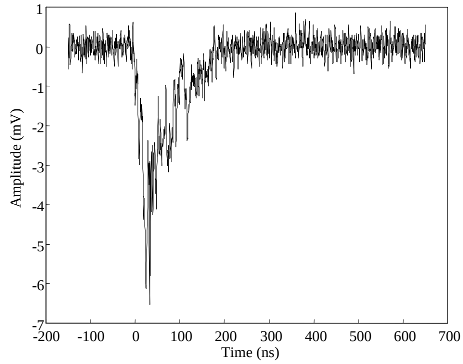


**Fig. 2.** Anode signal after a splitter for a muon detected by the PAO test tank with a Photonis XP1802 PMT at about 2 $10^6$ gain.

In order to match the dynamic range, the PMT base has two outputs: one from the anode (low gain channel) and the other one from an amplifier connected to the last dynode (high gain channel) (Genolini et al., 2001). The charge ratio between the two outputs is 32. In the current design the amplifier is a standard AD 8011. Due to the very low counting rate of about 2 kHz, mainly coming from individual muons, the mean current is very low and the base design relies only on resistors and capacitors.

The base behavior in the case of the saturation of the dynode amplifier was tested by using a CsI(Tl) crystal excited by a laser (Genolini et al., 2001). This allows to have a large signal followed by small signals over a long time period (several microseconds), similarly to large shower signals that will be detected by the PAO tanks. Figure 1 compares the saturated amplifier output to the anode output. A very short recovery time is observed even in the case of signals having amplitudes of 5 times the saturation limit.

Measurements with the PAO test tank on site have been performed. Figure 2 shows a typical anode signal for a muon detected by a Photonis XP1802 PMT. The background muons have a charge spectrum with a maximum at 25-30 pe and they will be used to calibrate the Cherenkov water tanks and their electronics (Salazar et al., 2001).

## 3 Station electronics

The station electronics contains the following parts: front-end electronics (FE) including Flash ADCs (FADC), buffering and a hardware trigger T1; a station controller composed of a microprocessor performing local software processing; a slow control module; a GPS receiver and a time tagging unit (Brunet et al., 1998, 2001). A block diagram and a schematic view of implementation are given in Fig. 3 and Fig. 4, respectively.

The electronics is packed in a metallic enclosure, protected by a plastic box, placed on top of one of the PMT hatch covers. The cables are connected to the PMT electronics through the hatch cover. For the EA, a modular conception (mother board with daughter boards) has been implemented in order to allow evolution of designs. In the final design, the station electronics will contain a unified board where the electronics hardware, except for the FE card, is mounted on a single printed circuit board (PCB). The FE card will be plugged in the unified board as a daughter board.

### 3.1 Front-end electronics and the T1 trigger

The front-end electronics provides the interface between the PMT signals and the station controller. Each of the three PMTs in the tank provides two signals to the front-end electronics: a high gain signal from the dynode and a low gain signal from the anode. On the front-end board each of these signals are filtered through a two pole filter with a 20 MHz cutoff frequency and fed to a 10 bit ADC (Analog Devices 9203) which samples at 40 MHz. At the input of the FADCs, the high gain signal is 32 times larger than the low gain signal from a PMT. The signal from each PMT is thus measured by two 10 bit FADCs whose ranges have 5 bits of overlap, which yields a nominal dynamic range of 15 bits.

A maximum PMT photocathode current of 130 nA with a standard setting for the PMT gain of 2 $10^5$ yields 20 pe/channel and 0.6 pe/channel for the low gain and high gain channels, respectively. However, since the PMTs are linear up to 250 nA, these ranges can be adjusted by simply changing the gain of the PMT (by changing the HV). The linearity limit allows to reduce the gain to 1 $10^5$ and, on the other hand, the PMT specifications allow to increase the gain up to 1 $10^6$.

The trigger of the PAO surface array has been defined in order to efficiently collect data for showers with incident energies above $10^{19}$ eV. It has 4 levels: T1, T2, T3 and T4 (Nitz, 1997; Ball and Nitz, 1998; Nitz, 2001). The first two levels are generated locally at each detector station while the levels 3 and 4 are performed centrally using information from all ground stations as well as from the fluorescence detectors.

The T1 trigger level is a hardware trigger and reduces the rate to about 100 Hz. It contains several trigger chains with two independent buffers. Two trigger chains are used to form the main shower trigger. The outputs of the 6 FADCs are fed into the trigger/memory circuitry. This has been initially implemented using a programmable logic device (PLD) and an

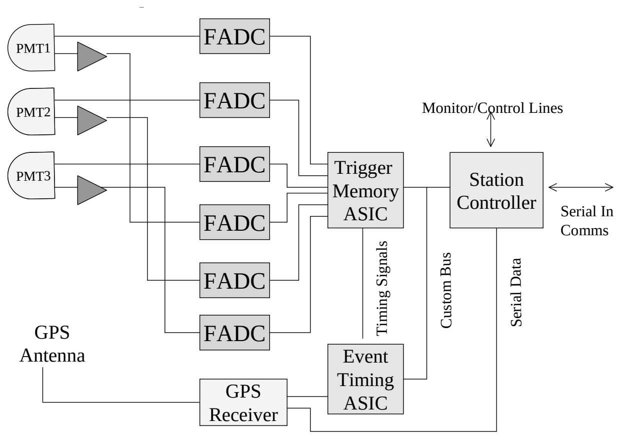


**Fig. 3.** Block diagram of electronics.

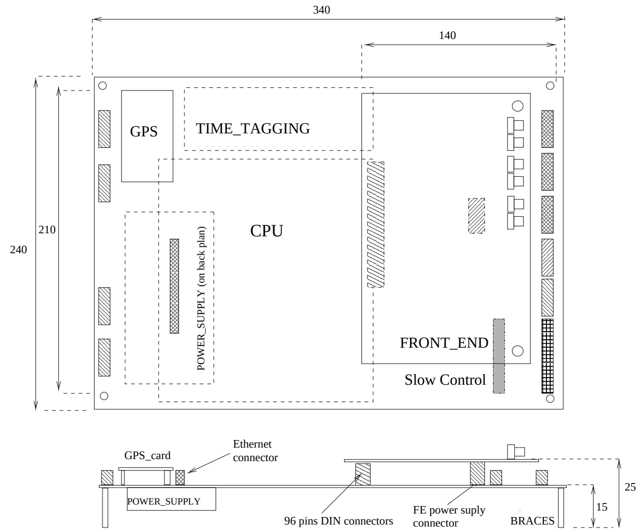


**Fig. 4.** Schematic view of electronics implementation.

external memory chip, but an application specific integrated circuit (ASIC) is under development for production deployment. The FADC data from the three low gain channels is simply stored in a 1024 word (768 for PLD) circular memory buffer until a shower trigger occurs. The data from the three high gain channels is used to form a shower trigger, in addition to being stored in the circular memory buffer.

The trigger is a logical OR of several trigger instances. A typical instance begins with multiplicity/sum logic, which requires that one of a set of specified patterns of PMTs be above thresholds and/or the conditional sum of the pulse-heights within any ADC time bin be above a threshold. The output of this first stage is then applied to digital time over threshold logic which scans the number of occupied time bins in a certain time interval. When a programmable number of time bins are found to be occupied, the corresponding trigger is generated. One trigger (FAST0) is intended for long, small traces further from the core, while the other (FAST1) is intended to capture short, large traces nearer the core. If the time over threshold trigger conditions are met, the buffer is closed following a post trigger delay, an interrupt signal is sent to the station controller to begin the direct memory access (DMA) readout and storage of the shower data. This signal is also used to record the time of the trigger in the time tagging unit. In parallel, the data storage/trigger evaluation continues in a second buffer. In addition to the shower trigger logic, a separate set of logic records larger signals corresponding to muons and small showers (SLOW trigger), primarily for monitoring and calibration purposes.

### 3.2 Station controller and the T2 trigger

The station controller is based on an IBM 403 PowerPC (80 MHz) microprocessor with 32MB RAM utilizing the OS-9000 real time kernel (Brunet et al., 1998, 2001). The controller performs the following tasks: second level trigger, data acquisition, calibration and slow control.

In order to generate the T2 trigger, the station controller reads the shower fronts in response to any of the FAST triggers, analyses them and makes a rough energy estimation. Every second, the GPS time (second) followed by all T2 triggers which occurred during this second are transmitted to the CDAS. The information concerning each T2 trigger includes the time information (in microseconds) and the energy evaluation. Level 2 trigger reduces the rate down to 20 Hz per station.

The central station generates a T3 trigger based on time and position information of T2 triggers from different detector stations. On a positive T3, at a trigger rate of about 0.2 Hz for the whole surface array, the CDAS requires data from all the local stations concerned by the trigger.

The data corresponding to SLOW triggers is regularly read by the station controller. The data is stored and scanned by software to develop calibration histograms and may be queried by the CDAS.

### 3.3 Event timing

In order to correlate data taken at different detector stations, a common timebase is established by using the GPS system. The GPS system consists of a constellation of satellites deployed by the U.S. military which broadcast signals from which the time and the position of the receiver may be derived. Each tank is equipped with a commercial GPS receiver providing a one pulse per second (p.p.s.) output and software corrections. The GPS time signal is used to synchronize a 100 MHz clock which serves to timetag the T1 trigger.

For the EA, the timing electronics is implemented by using PLDs while an ASIC will be used for the full array. The inherent accuracy of the time tagging subsystem is required to be 15 ns. A separate error contribution coming from the uncertainty in the GPS antenna position survey is likely to be of the same order. These are the main contributions to the total electronics timing error, which itself is a small contribution to the shower reconstruction error, except at very high energy.

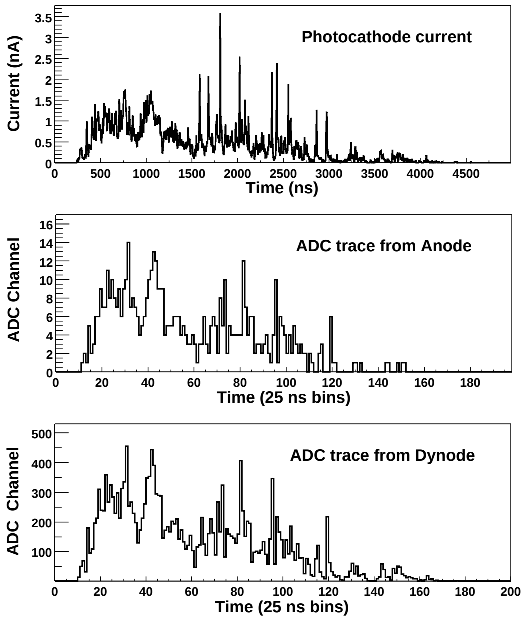


**Fig. 5.** Electronics simulation (see text).

### 3.4 Slow control

The slow control module reads data from sensors monitoring various functions of the detector station via analog inputs and remotely controls operation of different devices via analog outputs. The monitoring includes the survey of the PMT voltages, currents and the temperatures of associated electronics; the monitoring of the water level and the air temperature of the tank; the control of the solar panel and battery; the monitoring of the voltages and the temperature of the station electronics. In addition, the cloud monitor information for the fluorescence telescopes is collected by the surface detectors. For the readout of this data, the slow control module has 32 analog inputs converted by a 5 V, 12 bits multiplexed ADC.

In order to set the high voltages of the PMTs, to control the light pulse generator and to set the thresholds of the FE electronics, the slow control module is equipped with 8 analog outputs through a 2.5 V, 12 bit DAC. In addition, the slow control provides logic and digital outputs which are used for various controls (light pulser, FE electronics etc.)

For the EA, the slow control module is implemented as a daughter board on the mother board of the station electronics, but will be integrated into the unified board for the full array. The different functions of the module are supervised by the station controller.

## 4 Performances

Figure 5 displays a simulation for a 5 $10^{20}$ eV, $30^o$ proton shower detected by a tank at 1300 m from the core. The photocathode current measured by one of the PMTs is shown on top. The lower part displays the simulated FADC traces for the low gain (middle) and the high gain (bottom) channels. The simulation includes the PMT response at a gain of 2 $10^5$, the amplification of the dynode output, the 20 MHz FE filter and the 40 MHz sampling of the FADC. The different transfer funtions of the electronics tend to wash out narrow peaks but still conserve the rise time and gross features of the spectrum. This is important for the evaluation of the nature of the primary particle which is based on the rise time and shape of the signal.

The T1 trigger performance has been tested on the AGASA data (Ghia and Navarra, 2001). The AGASA data was converted to the PAO data by using a sampling frequency of 40 MHz (instead of 100 MHz of AGASA) and a calibration of 0.6 pe per FADC channel. The FADC threshold was adjusted in order to be below 20 Hz for the background data. A very good trigger efficiency, about 80%, was found at energy threshold about 3 $10^{18}$ eV (in the AGASA determination) for tanks far from core if a threshold of 2-3 channels and a time window of 6 $\mu$s was used. The actual noise level is about one channel allowing the use of such trigger condition. In particular, these studies show that the 40 MHz sampling rate does not deteriorate the trigger efficiency.

## 5 Summary

The signals issued from the PAO Cherenkov water tanks are characterized by a large dynamic range and long duration times. These features are matched by using two outputs, the anode and the last dynode, from the PMTs and 40 MHz sampling ADCs. The time correlation between different detectors is obtained with good accuracy by using the signal delivered by the GPS. Furthermore, the locally implemented time over threshold trigger efficiently triggers also on detectors far away from the core having small signals.

The installation of the EA electronics is now being completed and the test measurements on site are in progress.

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