The Front-End Cards of the Pierre Auger Surface Detectors: Test Results and Performance in the Field

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Abstract: The surface detector array of the Pierre Auger Observatory, presently under construction in Argentina, comprises 1600 water Cherenkov detectors distributed over an area of 3000 km^2. The Cherenkov light of each tank is detected by three 9-inch photo-multiplier tubes from which the signals of the anode and last dynode are digitized each by 10 bit 40 MHz FADCs. An Altera Cyclone FPGA is employed to generate different local triggers and to handle the data transfer to a communication board. After briefly discussing the design of the cards we present an automized test-bench including a climate chamber which has been set up in order to test the large number of boards prior to installation in the field. The qualification procedure and the results obtained in the laboratory are presented. Data collected during operation in the field demonstrate a very good performance and reliability of the Front-End cards.

Introduction

The Pierre Auger Observatory currently under construction in the Province of Mendoza (Argentina) aims at measuring cosmic rays at the highest energies with unprecedented statistics and resolution. The observatory comprises two major components: 1600 water Cherenkov detector stations distributed over an area of 3000 km^2 for measuring the charged particles associated with extensive air showers (EAS) and 24 telescopes with 30×30 degrees field of view and 12 m^2 mirror area each to observe the fluorescence light of EAS in clear moonless nights. The simultaneous observation of EAS by the ground array and the fluorescence light is called 'hybrid'-observation. It improves the resolution of the reconstruction considerably and, due to the calorimetric nature of the emitted fluorescence light, provides energy measurements virtually independent from hadronic interaction models used to model EAS. Details about the experiment can be found in Ref. [1].

Design of the SD front electronic boards

Three photo-multiplier tubes read out the Cherenkov light from the 12 000 liters of purified water contained in each tank. The signals from the anodes (low-gain channel) and dynodes (high-gain channel) are transported on equal-length shielded cables to the Front End Board (FEB), attached to a Station Controller. Splitting of the signals allows extending the dynamic range of the measured energy range to 15 bits with 5 bits overlapping. The system digitizes the 6 analog signals per tank (filtered by anti-aliasing 5-pole Bessel filter with a cut-off 20 MHz) at 40 MHz in AD9203 Flash ADCs. The outputs of the six 10-bit analog to digital converters (ADCs) are processed by a PLD Altera® Cyclone chip [2] working at 300 MB/s as trigger/memory circuitry (TMC) supported additionally by a Dual-Port RAM memory as a temporary buffer. The TMC evaluates the ADC outputs for interesting trig-

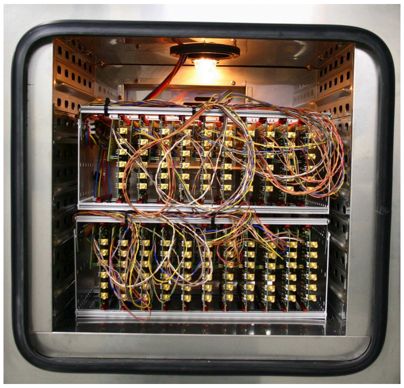

Figure 1: Up to 22 FEBs were placed in a climate chamber for burn-in under electric power.

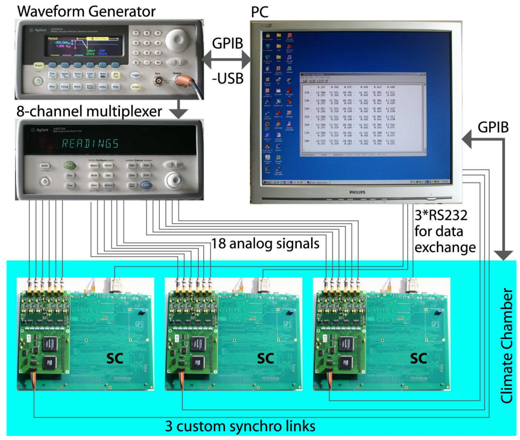

Figure 2: Sketch of the automized test system.

ger patterns, stores the data in buffer memory, and informs the detector station microcontroller in case a trigger occurs. The station controller sends trigger packets and, when requested, event data to the observatory campus via a wireless network. More details about the design, the firmware implementation and the triggers can be found in Ref. [3]. The Cyclone FEBs are employed in the second half of the ground array. The previous version of the FEB used two chips of the ACEX® family instead [4].

FEB appropriateness

Prior to production of the full batch of 900 FEBs at Intratec-Elbau (Berlin, Germany) [5], 10 units were manufactured in a preproduction batch to verify the new design. The boards were tested intensively in the lab and in the climate chamber and no malfunctioning was observed. In order to perform the acceptance tests of the full batch within a time period of about half a year, a highly automized test bench has been developed and installed in the laboratories at the Wuppertal and Siegen Universities.

First, the boards were powered up and the current in the digital and analog part was verified to be in the specified range. All manufactured boards passed these initial tests. Next, groups of up to 22 boards were placed into a climate chamber and a burn-in was performed under full current for 55 hours (Fig. 1). It started with 4 thermal cycles between 70° C and −20° C over a period of 10 hours, followed by a 35 hours burn-in period at 70° C followed again by 10 hours with 4 cycles between 70° C and −20° C. Formation of dew during temperature cycling was avoided by enriching the atmosphere in the climate chamber with Nitrogen.

Test set-up

A sketch of the hardware test configuration is depicted in Fig. 2. A waveform generator provided pulses of various forms to a high quality 3×6 channel multiplexer. The 18 outputs were fed into three FEBs for simultaneous testing. Each of the multiplexer outputs could be switched on/off individually via a GPIB interface so that selected groups of FEB channels could be tested and cross-talk tests be performed. Data readout of the FEBs was performed via the Pierre Auger surface detector Station Controllers (SC). Different from the operation in the field, data transmission was not done via a microwave link but via an extra RS232 interface integrated on the SC for diagnostic purposes when working on the station in the field. The RS232 interface could also be used for uploading the firmware into the SCs after powering up. The FEBs were controlled via custom made synchro opto-coupled links using the the parallel-port interface of the PC and the I^2C protocol for data exchange. The PC also controlled the waveform generator, multiplexer, and climate chamber, so that the full sequence of acceptance tests could be programmed and run in an automized way.

The full sequence of tests at −20, +25, and +70 °C and with data storage on the PC lasted about 4 hours for three simultaneously tested boards. Most of the time was actually needed for changing the temperature in the climate chamber. In this way, up to 9 boards could be tested per day.

Results of acceptance tests

The FEBs had to pass the following acceptance tests at each of the three temperatures:

1. ADC noise $\sigma_n < 0.8$
2. ADC pedestal between 20 and 80 channels
3. Cross talk between channels $< 10^{-3}$
4. Cut-off frequency of analog filter in the range 15 MHz $< f_C <$ 25 MHz
5. global ADC non-linearity below $2 \cdot 10^{-5}$
6. differential non-linearity $\sigma_{\mathrm{ADC}} < 0.95$

The distribution of the ADC noise and pedestals is shown in figure 3. Both, the noise and the pedestal are found to have a weak temperature dependence. The effect of increasing pedestal with increasing temperature to air showers triggers is discussed in [6].

The cross talk was measured by injecting signals at the saturation level to each channel and verifying the signals in the other channels.

The cut-off frequency was measured by injecting harmonic waves of 100 kHz, 18 MHz, 25 MHz and 30 MHz to the FEBs and analyzing the damping using the digitized signals. The cut-off frequency was defined by calculating the value at which −3 dB suppression was

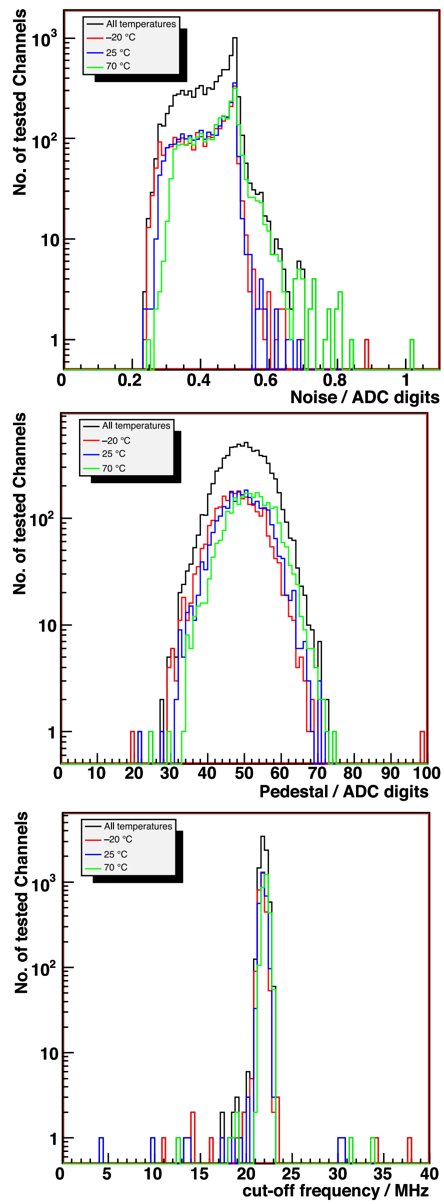

Figure 3: Distribution of ADC noise levels, pedestals, and cut-off frequencies (from top to bottom) for 400 tested FEBs at −20, +25, and +70 °C.

reached. The damping of the signals in the multiplexer and signal cables itself were measured independently and carefully corrected for. The result is shown in figure 3 (bottom). The majority of the FEBs shows cut-off frequencies in the expected range between 20 and 25 MHz.

The global and differential non-linearity was tested by ramping up the input signals using a saw tooth waveform and analyzing the digitized signals as a function of time (sample number). The rising edge of the analog signal was 19.2 μs corresponding to the 768 words length of the fast buffer registering the shower profile. For the global linearity the correlation coefficients (CC) were calculated for all 768 words. The values of $(1 - CC)$ typically were at a level of a few times 10^{-6}, slightly above the minimal value originating from the quantization of ADC-counts. The correlation between ADC-counts relating to consecutive time-bins allowed also finding suspicious transitions corresponding to differential non-linearities. For this purpose, 64 measurements with ramped up signals were repeated and the deviation of the measured and expected ADC value in each of the 768 samples was filled into a histogram. In case the standard deviation integrated over the full ADC range exceeded 0.95 ADC channels, the board has been rejected.

In total, 29 of the 900 tested FEBs were rejected by the acceptance tests because of their ADC pedestal (2) or noise (7), differential non-linearities (6), global non-linearities (4), cut-off frequencies (6), non working ADCs (2), cross-talk (2), and problems in programming of the boards or wrong communication with registers (4). Some of these boards didn't pass several tests.

Finally accepted boards were coated with humidity sealer and shipped to the experimental site for installation. The results of the individual tests are compiled in a MySQL database and a graphical web-based interface is provided to make the data available to the collaboration and for future verifications.

Performance in the Experiment

By now, about 300 Cyclone FEBs are in operation in the field. No failure or malfunctioning was detected and the noise (see figure 4) was found superior to the previous ACEX boards.

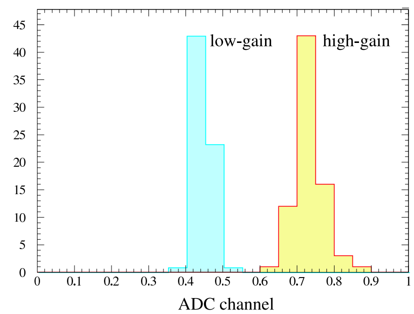

Figure 4: Distribution of ADC noise levels for the high- and low gain channels for data taken in the field.

Summary and Conclusions

More than 900 readout boards of the Pierre Auger surface detector array have been produced and were tested in the laboratory prior to installation in the field. The automized test system allowed to test 9 boards per day and Institute. About 3 % of the FEBs failed in the acceptance tests. Some of them could be repaired by substituting individual components. Operation in the field has proven a good performance and no failure up to now.

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