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The upgraded electronics of the Pierre Auger surface detector

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The upgraded electronics of the Pierre Auger surface detector

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Abstract. The surface detectors of the Pierre Auger Observatory are being upgraded by adding new detectors and replacing electronics.

The upgrade project, called "AugerPrime," includes the addition of a small PMT to increase the dynamic range of particle counting, a plastic scintillator above each water-Cherenkov detector to improve the discrimination between the electromagnetic and muonic shower components, a radio detector to measure radio emission from inclined air showers, and a set of underground muon counters to provide additional information on muon content in atmospheric showers.

The new electronics, dubbed Upgraded Unified Board (UUB), is designed to acquire all of these additional detectors and includes improved GPS receiver, higher sampling rate, increased dynamic range, greater processing capacity, and improved calibration and monitoring systems. In the following, we will describe the UUB design and discuss its performance as observed in the first data from the upgraded array.

1. Introduction

The Pierre Auger Observatory [1] is the most extensive experiment to study ultrahigh-energy cosmic rays (UHECRs), understand their nature, and identify their sources. It is a hybrid observatory and consists primarily of two kinds of detectors, the surface detector (SD) and the fluorescence detector (FD).

The SD [2] consists of 1600 water Cherenkov detectors (WCDs) deployed in a 1.5 km grid over a total area of about 3000 km^2 and is used to measure the density and the arrival time distribution of the shower particles at the ground. A map view of the Observatory is shown in the figure 1. The FD [3] is divided into four sites surrounding the SD's area, each composed of six telescopes with elevation angle from 1° to 30°, for the measurement of the energy deposit of the showers in the atmosphere.

In the northwestern part of the experimental site, two denser arrays with reduced spacings of 750 m and 433 m are present as part of the Underground Muon Detector (UMD) that aims to extend the measurable energy range down to $10^{16.5}$ eV. This region also contains three fluorescence telescopes with high elevation from 30° to 60°. Finally, to complete the measurements on the low energy showers, the Auger Engineering Radio Array (AERA) is used to detect the radio emission released by the secondary cosmic rays in the atmosphere.

[1] Full author list: `https://www.auger.org/archive/authors_2020_11.html`

Currently, an upgrade project dubbed "AugerPrime" [4] is being implemented on the Observatory. The upgrade project foresees a series of technological improvements to the Observatory: an additional small PMT (SPMT) in the WCD to increase the dynamic range; a surface scintillator detector (SSD) (a plastic scintillator) installed on top of the WCD to operate a complementary measurement of the shower particles; a radio antenna [5] (RD) that will be mounted on top of the WCD to detect radio signals (30 to 80 MHz) and provide a complementary measurement to the SSDs of the electromagnetic component of the showers. In addition, an underground muon detector (UMD) is starting to be deployed beside each WCD in the denser arrays of the observatory to provide direct measurements of the shower muon content.

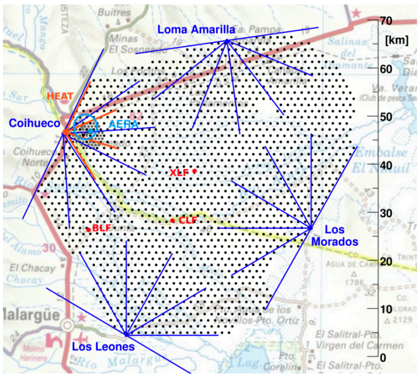

Figure 1. Layout of the Pierre Auger Observatory.

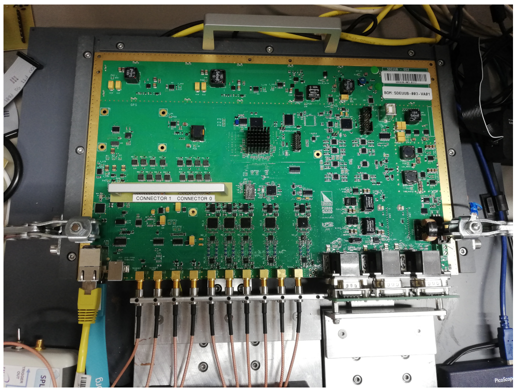

Figure 2. The latest version of the UUB during a test procedure.

As part of AugerPrime, an upgrade of SD station electronics was also arranged. The new electronics [6] (figure 2), dubbed Upgraded Unified Board or UUB, is designed to process the new signals of SSD and RD. With a new ADC, it is now possible to obtain a faster sampling of traces (120 MHz and 12-bit of accuracy) and increased data quality; moreover, with a more powerful station processor and a new Xilinx Zynq7020 FPGA, the local trigger and processing capabilities have been improved.

2. Digital functionality of the UUB

The firmware of the UUB's FPGA is written in IEEE standard synthesizable Verilog. Xilinx Vivado is used for the global framework and standard modules such as memories and interfaces. It is connected to a 4 Gbit LP-DDR2 memory and a 2 Gbit flash memory.

The logic functions encoded in the firmware include ADC reading, trigger generation, and interfaces with the LED flasher, GPS receiver, and memories. The pre-upgrade trigger logic has been transferred to the UUB FPGA. To not interfere with the data taking during the deployment of the UUBs, the ADC traces of the three WCD PMTs are digitally filtered and downsampled. However, the increased processing capabilities of the FPGA also allow new trigger types such as combined SSD and WCD triggers to be implemented.

The Xilinx PetaLinux operating system runs on the ARM processor. The data acquisition software (DAQ) installed implements high-level functions such as data management and communications with the communications radio transmitter.

The detector synchronization is done by tracking the variations of the local 120 MHz clock relative to the GPS 1 PPS signal. For the new electronics, the Synergy SSR-6TF timing GPS receivers were chosen. The FPGA, through the time-tagging module, manages the GPS and the data timing in an entirely consistent way with the one that was designed for the old electronics.

On UUB, there are also two connectors with eight differential LVDS lines (so-called digital interfaces), each of which can be, in the FPGA, individually defined as input or output. One of these is used for the RD, and the other is used for the UMD.

3. Front-end and Slow control

The ADCs at the front-end of the UUB are fed with signals coming from the SPMT, the PMTs (XP1805 PMTs) detecting Cherenkov light from the WCD, called large PMTs (LPMTs), and the PMT collecting light from the SSD. The five signals are divided into five high-gain and five low-gain signals, respectively. They are obtained by using two amplifiers in parallel with different gains; the signals of the LPMTs are divided with a gain ratio of 32 while the signal of the PMT of the SSD is divided to reach a gain ratio of 128, allowing for it a dynamic range of 20,000 MIP (minimum-ionizing particle).

As mentioned earlier, to increase the dynamic range of the WCD, an SPMT, a 1-inch Hamamatsu R8619 PMT dedicated to measuring significant signals, has been included. As shown in figure 3, the SPMT gain and amplification are set such that the dynamic range is extended by a factor of 30 at 20,000 VEM (vertical muon equivalent).

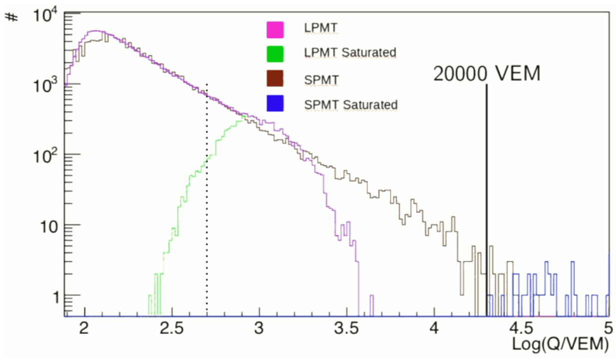

Figure 3. Charge spectrum in one of the upgraded WCD stations. The LPMTs is in purple and green and the SPMT is in brown and blue.

The VEM signal is used to calibrate the high-gain channels of the WCD; the procedure is carried out by the DAQ software and has been mainly inherited from the one carried out with the old electronics [7]. In addition, each WCD is equipped with two LEDs used for monitoring and linearity tests.

The SPMT cannot be calibrated using atmospheric muons, so a selection of small showers is used to cross-calibrate it with the VEM signals of the LPMTs. The SSD calibration is based on the signal of a minimum-ionizing particle (MIP) passing through the detector.

The management of slow control is performed by the MSP430 micro-controller. It controls the high voltage monitoring of the PMT, the supervision of the various supply voltages and the reset functionality. In addition, the micro-controller also provides a USB interface, which is very useful if you need to perform tests on the UUB. The 90 variables collected by the slow-control software are acquired by the DAQ software and sent to the Auger monitoring database.

4. Deployment and Performance

UUBs have been in production since 2020 by the SITAEL company in Mola di Bari. They undergo a general test before being taken to the experiment site [8].

The field deployment of the UUBs that have passed the test procedure began in December 2020. There are currently a total of 79 surface stations that have UUBs. These stations all have

SPMTs and SSDs. An Engineering Array of twelve AugerPrime stations has been in place since 2016 to test and monitor the performance of the upgraded detectors. Currently, two stations remain in this portion of the array.

Currently, the stations with the UUBs are under control and monitoring by the Collaboration. Noise studies, timing studies, and calibration studies for SPMT and SSD are being done on the array. Noise levels measured in the array are consistent with those in the design phase. The figure 4 shows the baseline RMS distribution in April 2021 acquired from all the stations with UUBs data.

Timing resolution was measured using showers triggering two neighboring upgraded test stations dubbed Clais and Trak in the EA. The end-to-end timing accuracy (figure 5) of a single station in real showers was measured to be better than 10 ns (vs. the current 13 ns).

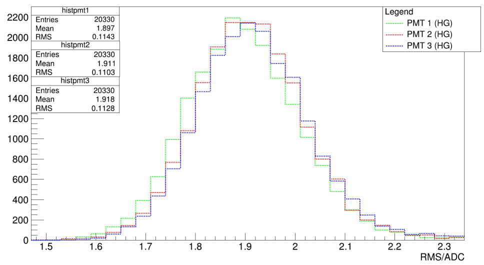

Figure 4. The baseline RMS of the high gain ADC signals of PMTs at surface stations with UUB.

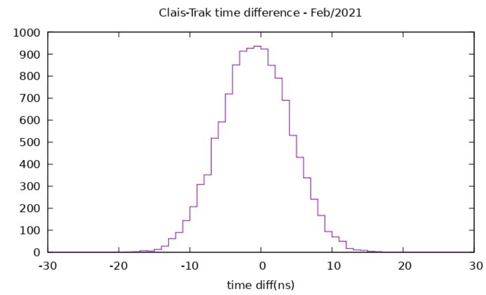

Figure 5. Measured timing resolution on showers using two nearby test stations.

5. Summary and outlook

The design aspects of the new electronics of the Pierre Auger Observatory were presented. Currently, 79 UUBs are in data taking and constantly monitored.

The observed performance of the UUBs was discussed and it was seen that they are stable and well within the initial requirements. New trigger studies are planned to take into account the newly installed detectors. Production continues without interruption and a full deployment is expected one year from now.

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