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The AugerPrime upgrade of the Pierre Auger Observatory

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Abstract. Operating since 2004, the Pierre Auger Observatory has yielded several important results. The suppression of the flux around $5{\times}10^{19}$ eV is now confirmed without any doubt, a large-scale dipole anisotropy has been found for energies above $8{\times}10^{18}$ eV, as well as an indication for some intermediate-scale anisotropy at the highest energies. Furthermore, strong limits have been placed on ultra-high-energy photons and neutrinos. In order to elucidate the origin of the flux suppression at the highest energies and search for composition-enhanced anisotropies, the Auger Collaboration is currently upgrading the Observatory. In the framework of the upgrade, called AugerPrime, the array of 1660 water-Cherenkov detectors is equipped with plastic scintillators, allowing us to enhance the composition sensitivity. The station electronics is also upgraded, including better timing with up-to-date GPS receivers, higher sampling frequency, and increased dynamic range. Currently, more than 40% of the surface detectors have been upgraded, and the commissioning studies are well advanced. In this paper, the design of the AugerPrime surface detectors will be presented, and the performance obtained from the analysis of the first data will be discussed.

1. Introduction

The Pierre Auger Observatory [1] is located near Malargüe, Mendoza, Argentina. The surface detector (SD) array of the observatory consists of 1600 water-Cherenkov detectors (WCD) on a 1500 m triangular grid covering 3000 km^2. Another 60 WCDs form an infill region. The array is overlooked by four fluorescence detector (FD) sites each containing 6 telescopes viewing a 180° azimuth by 30° elevation field of view. Three additional telescopes at one of the sites can be tilted 30° higher to view lower energy showers at their maximum and overlook a 30 km^2 infilled surface array with a 750 m spacing. Extensive air showers (EAS) induced by ultra-high-energy cosmic rays (UHECRs) are sampled at ground level by the SD. The FD measures the EAS development by detecting the nitrogen UV light produced by the shower particles along their passage through the atmosphere. Additional instrumentation for R&D on muon and radio-based detection is also located on the site.

Since the start of its operation in 2004, the Pierre Auger Observatory has made significant contributions to the study of UHECRs (see ref. [2]). In order to make further progress and more fully harness the power of statistics, the Auger Collaboration decided to improve the sensitivity to the composition of the SD. The observatory is therefore undergoing a significant upgrade of

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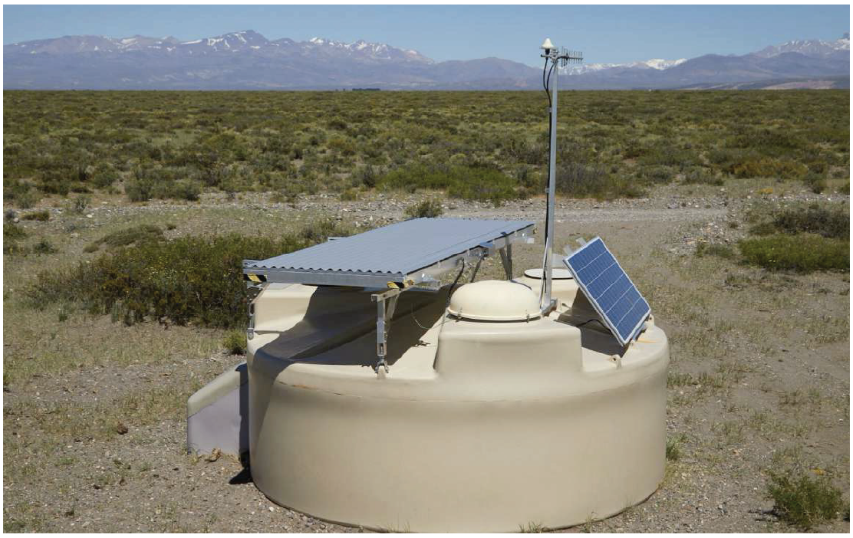

Figure 1. AugerPrime detector with the SSD atop the WCD. The UUB is hidden underneath the dome visible on top of the WCD.

its experimental capabilities called AugerPrime. It will allow us to disentangle the muonic and electromagnetic (EM) components of extensive air showers, thereby enhancing the ability to study UHECR composition, composition-assisted anisotropies, and hadronic interaction effects at the highest energies.

AugerPrime consists of a scintillator-based surface detector (SSD) and a radio detector (RD) added atop each WCD. A small PMT (SPMT) is also added to the WCD to increase the dynamic range. The upgrade of the SD electronics (SDEU) allows us to accommodate added detectors and to improve resolutions and data processing capabilities. The WCD has good sensitivity to both muonic and EM components while the SSD and RD are predominantly sensitive to the EM component. These different responses are exploited (by using shower universality or matrix methods) to enhance the composition sensitivity. Furthermore, the SSD and RD are complementary in their solid angle coverage, with the SSD being optimized for more vertical showers, and the RD optimized for showers with higher zenith angles. The Underground Muon Detector (UMD), consisting of buried muon counters, is also incorporated and will give a direct measurement of the shower muon content and its time structure (23 km^2 infill area). These measurements can also be used to train analysis methods for other AugerPrime detectors. Both SSD and RD will use the communication infrastructure of the stations, and therefore, no upgrade of the communication system is required. The station power system will remain unchanged except for new solar panels to accommodate the increased power consumption due to RD. A detailed description of AugerPrime can be found in the Preliminary Design Report [3]. An AugerPrime detector station with its scintillator atop the WCD detector is shown in Fig. 1.

The deployment of AugerPrime is currently in progress, and the performances are being monitored. The SSD detectors and about 40% of the new electronics together with the SPMT are already installed. Production of electronics boards will be completed in November 2022, and the deployment will continue up to mid-2023. The RD detector prototypes have been tested in the field, and their installation will start shortly. The Auger Collaboration plans to take data with AugerPrime for eight years, from 2022/23 to 2030. This would yield an exposure of 40,000 km^2 sr yr for showers with zenith angles below 60 degrees. This data sample is referred to as Phase II. The current data sample, called phase I, is about 80,000 km^2 sr yr. In the following, the design of the AugerPrime surface detectors, including SSD and the upgraded electronics, will

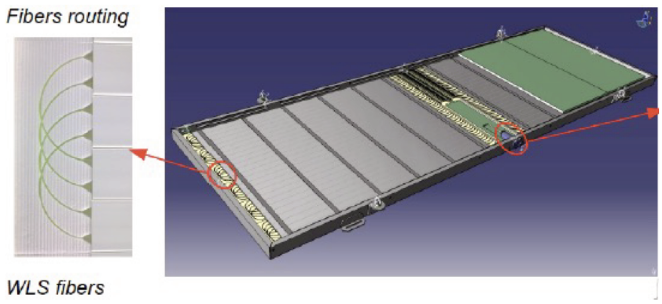

Figure 2. SSD detector: scintillator panels and fiber routing.

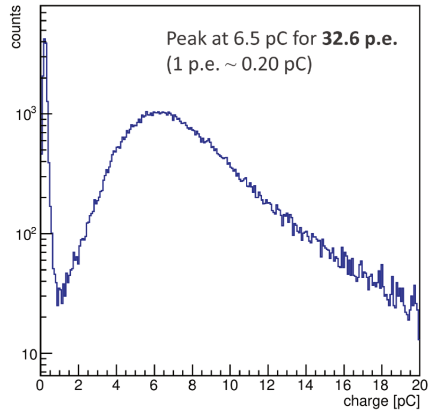

Figure 3. The MIP value measured in laboratory.

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be presented, and the performances obtained from the analysis of the first data will be discussed. For the UMD and RD, the reader is referred to refs. [4] and [5], and references therein.

2. Design characteristics

An SSD detector consists of a box of 3.8 m $\times$ 1.3 m, containing two scintillator panels, each composed of extruded polystyrene scintillator bars of 1.6 m length, 5 cm width, and 1 cm thickness. The two panels are enclosed in a light-tight, weatherproof enclosure and are mounted on top of the existing WCD with a strong support frame. The scintillator light is read out with wavelength-shifting fibers inserted into straight extruded holes in the scintillator bars. The 1-mm diameter fibers, Kuraray Y11(300)M S-type, are positioned following the grooves of the routers at both ends in a U-configuration, as shown in Fig. 2. They are bundled in a PMMA cylinder whose front window is connected to a single PMT. The PMT is a bi-alkali Hamamatsu R9420, 1.5" diameter, with 18% quantum efficiency at a wavelength of 500 nm. The power supply of the PMT is based on a custom-made design manufactured by the ISEG company. A scheme of the SSD scintillator panels together with the fiber routing is shown in Fig. 2. The charge value for the Minimum Ionizing Particle (MIP) measured by using a hodoscope trigger is more than 30 p.e., see Fig. 3.

For consistency with the associated WCD, the dynamic range of the SSD must span from the signal of a single particle, as needed for calibration, to large signals, up to more than 100 MIPs. To achieve the appropriate dynamic range, the anode current of the SSD PMT is split into two different channels, the first one amplified (high gain) and the other attenuated (low gain). The SSD detectors are triggered by the signals in WCD. A more detailed description can be found in refs. [3] and [6].

A design goal of AugerPrime is to measure shower properties at energies above 6×10^{19} eV as close as 250 m from the shower core. For this purpose, the WCD is equipped with an additional extra small PMT (SPMT), a 1-inch Hamamatsu R8619 PMT, dedicated to the unsaturated measurement of large signals. The SPMT is installed on an available view port on the liner, located close to one of the large PMTs (LPMT1). The SPMT gain and the amplification are set such that the dynamic range is extended by at least a factor of 30 to about 20,000 VEM (Vertical Equivalent Muon). A more detailed description of the SPMT can be found in refs. [3] and [7].

The design objectives of the electronics upgrade globally aim to increase the data quality (faster sampling for ADC traces, better timing accuracy, increased dynamic range), enhance the local trigger and processing capabilities (more powerful local station processor and FPGA), and improve calibration and monitoring capabilities of the SD stations. Backwards-compatibility with the current dataset will be maintained by retaining the current timespan of the PMT traces and providing for digital filtering and downsampling of the traces to emulate the current triggers in addition to any new triggers. The design objectives also aim for higher reliability and easy maintenance.

The anode channel of the large XP1805 PMTs is split and amplified to have a gain ratio of 32. The signals are filtered and digitized by commercial 12-bit 120 MHz FADCs. We have chosen to use commercial 12-bit 120 MHz AD9628 FADCs, which achieve this performance with minimal power consumption, an important consideration due to the low station power budget (10 W without additional solar panels required for RD). The anode channel of the SSD PMT is split, one is amplified to have a gain ratio of 32 and the other one is attenuated by a factor of 4. This yields a total gain ratio of 128. The signals are filtered and digitized similarly to the WCD PMT signals. The expected dynamic range for SSD is 20,000 MIP. The SPMT anode signal is also digitized with 12-bit at 120 MHz in a separate channel. The overlap in the dynamic ranges of LPMTs and SPMTs is about 5 bits which is sufficient to obtain the cross-calibration for SPMTs and still allow us to extend the dynamic range up to 20,000 VEM.

Synchronization of the detectors is provided by tracking variations of the local 120 MHz clock with respect to the 1 PPS signal of the Global Positioning System (GPS). For the upgraded electronics we have selected the Synergy SSR-6TF timing GPS receivers. This receiver is functionally compatible with the Motorola Oncore UT+ GPS, the one that is used with the current electronics. The fundamental architecture of the time-tagging firmware module parallels the time-tagging design concept used in the current electronics and is implemented in the UUB board FPGA. The on-board software for initialization of the time-tagging modules, GPS hardware control, and timing data is similar to the current one, with minor modifications needed for the new UUB hardware. The intrinsic GPS device accuracy after the applied granularity correction (the so-called negative sawtooth) is ≈ 2 ns.

A micro-controller (MSP430) is used for the control and monitoring of the PMT's high voltage, the supervision of the various supply voltages and the reset functionality. For that purpose, it controls 16 logic I/O lines, steers a DAC with eight analog outputs, and senses through multiplexers up to 64 analog signals with its internal ADC. The MSP430 also provides a USB interface and is tied via an I^2C-bus to an EEPROM and a pressure sensor. More than 90 monitoring variables - including currents and voltages of the power supply and the PMTs - are managed by the slow-control software.

The various functions (front-end, calibration, time tagging, trigger, monitoring) are implemented on a single board, the Upgraded Unified Board (UUB). An architecture with an FPGA containing an embedded ARM processor is used. The heart of the UUB is a Xilinx Zynq FPGA with two embedded ARM Cortex A9 333 MHz microprocessors. It is connected to a 4 Gbit LP-DDR2 memory and 2 Gbit Flash memory. The FPGA implements all basic digital functions like the read-out of the ADCs, the generation of triggers, the interface to LED flasher, GPS receiver, clock generator, and memories. High-level functions like the data handling and communications with the radio transmitter are implemented under LINUX. The trigger and time tagging functionalities are implemented in the FPGA. The current local triggers (threshold trigger, time-over-threshold trigger (ToT), the multiplicity of positive steps (MoPS-trigger), etc.) are currently run at a 40 MHz rate which will allow the detectors to be operated with the new electronics emulating the current system. This will enable the deployment of new electronics during the maintenance of the current system without disturbance to the data taking. The trigger can later be adapted to the 120 MHz sampling rate.

The UUB, together with the GPS-receiver board, is mounted inside an RF-enclosure. Two

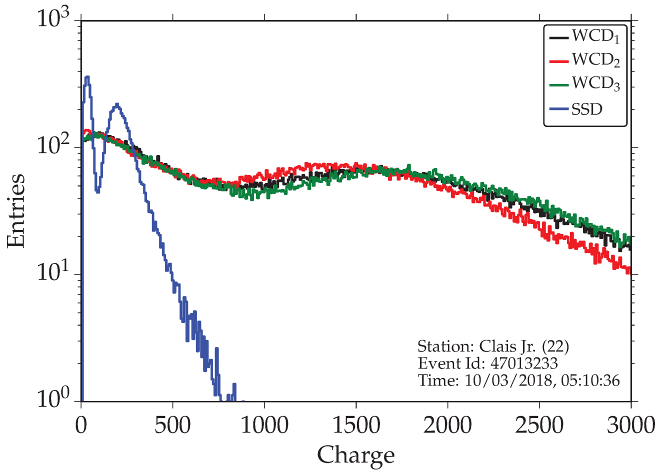

Figure 4. Calibration histograms for SSD and the three large PMTs of WCD.

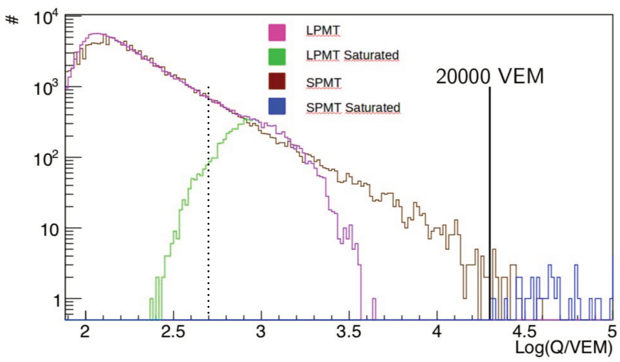

Figure 5. Extension of the dynamic range to 20 000 VEM using the small PMT. Here LPMT refers to the XP1805 PMTs, SPMT to the R8619 PMT, and “saturated” to signals which saturate the respective ADCs.

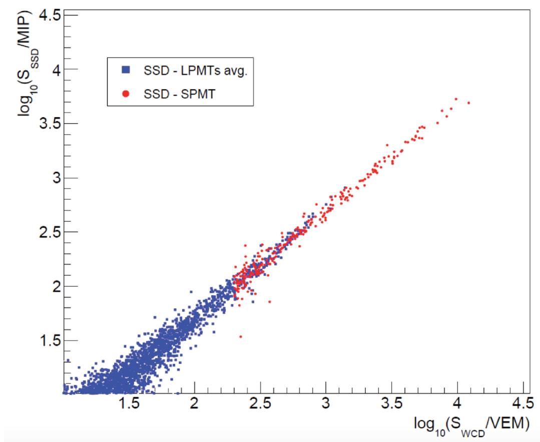

Figure 6. Correlation between SSD and WCD signals.

digital connectors are provided for additional detectors. The enclosure is the same as used for the current electronics, only the front panel is changed. This allows us to keep the current mechanical components of the SD detectors. The UUB is interfaced with the current communication system providing 1200 bits per second bandwidth for data transmission, and with the current power system providing 24V from the batteries. The current power budget of 10 W will be increased by installing new solar panels when RD antennas are installed. A more detailed description can be found in refs. [3], [8], [9], [10], and [11].

3. Calibration and dynamic range

The calibration of the large WCD PMTs is performed by using background muons. The VEM signal is the reference unit of the WCD high-gain calibrations and was previously determined on a test tank with an external trigger hodoscope to give on average 95 p.e. at the cathode of the XP1805 PMTs. This corresponds to ≈1500 integrated ADC counts above the pedestal after signal digitization on the UUB.

The SSD calibration is based on the charge of the MIP signal. About 40% of the calibration

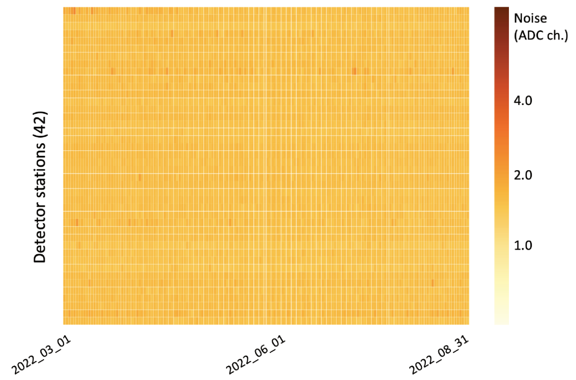

Figure 7. Noise of the LMPT1 high-gain channel for various WCD detectors as a function of time.

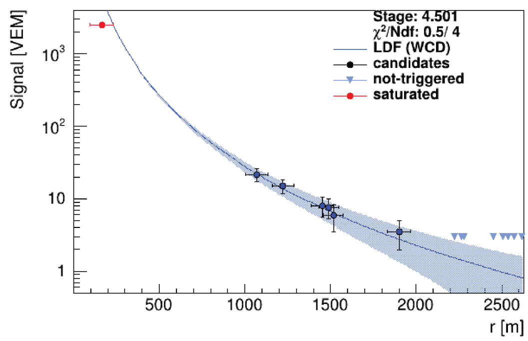

Figure 8. An example of the reconstructed LDF.

triggers of the WCD produce a MIP in the SSD. An example of the VEM and MIP calibration histograms is shown in Fig. 4. The muon calibration data is continuously recorded and allows us to compensate for the effect of outside temperature variations. The cross-calibration between high-gain and low-gain channels is obtained from electronics, about 32 in the case of WCD and 128 in the case of SSD. Due to its small area, the SPMT cannot be calibrated using atmospheric muons. A selection of small showers allows us to cross-calibrate it with the VEM signals of the large PMTs, as can be seen in Fig. 5.

The very good correlation between the calibrated signals of the WCD and SSD is shown in Fig. 6. Both detectors, WCD and SSD, allow us to reach 20,000 VEM/MIP. This corresponds to a distance of about 250 m from the shower core yielding a more accurate determination of the shower core position and the lateral distribution function (LDF) compared to the current SD array.

4. Current status and performance

Currently, all the SSD detectors have been installed atop WCDs. The deployment of UUBs, together with SPMTs and SSD PMTs, is in progress. As of today, more than 40 % of the surface detector area is already covered and the deployment will be completed by mid-2023. Data taking for commissioning is in progress since the end of 2020. In parallel, the central data-acquisition (CDAS) program, the monitoring program, and the data analysis pipeline are being updated for AugerPrime. The data from AugerPrime is continuously monitored and analyzed to obtain various resolutions and to assess the uniformity of detector stations and their long-term performance.

The noise for the high-gain channel of the WCD PMTs is below 2 ADC channels, meeting the requirements. The time resolution has been studied by using two twin detectors spaced about 11 m apart from each other. Measuring the fixed delay between these two stations with a mutual trigger, yielded a time resolution of ≈5.0 ns. The various performance parameters are continuously monitored. As an example, Fig. 7 shows the baseline rms-value for one of the LPMT high-gain channels measured for 40 detector stations over a period of six months. One can observe a very good uniformity as well as long-term stability. The yellow color corresponds to the rms-value slightly below 2 ADC channels.

The SD records the footprint of the air shower on the ground. After passing the event selection criteria, standard shower reconstruction methods are applied to estimate the intrinsic properties of the primary cosmic ray. In the SD event reconstruction, the information about start times is used to reconstruct the arrival direction of the primary using a spherical model of the shower front. After a first estimation of the arrival direction, a fit of the LDF of signals at the ground is performed. This distribution arises from a convolution of the energy spectrum and the incoming direction of shower particles with the detector response. Different functional forms are used to describe signals at the ground which generally follow a power law with changing index. For analysis of the first AugerPrime data, a modified Nishimura-Kamata-Greisen function is employed [12]. An example of an LDF function is shown in Fig. 8. Currently, work is in progress to include SPMT in the general data-analysis pipeline. A dedicated hexagon array of twin detectors having old and new electronics allows us to verify that the upgraded AugerPrime analysis programs yield similar results and have no biases compared to the current data.

5. Conclusions

The goal of AugerPrime upgrade is to disentangle the muonic and electromagnetic components of extensive air showers, thereby enhancing the ability to study UHECR composition, composition-assisted anisotropies, and hadronic interaction effects at the highest energies. This is achieved by complementing the existing WCD with an additional SSD for better identification of air-shower particles. An extra small PMT allows us also to extend the dynamic range of WCD. The upgraded surface detector electronics support additional detectors and enhance the performance of the surface detector. A Radio Detector array will complement with horizontal observations, and the implementation of a 23 km^2 Underground Muon Detector array will give a direct measurement of the shower muon content and its time structure.

Currently, all SSD detectors have been installed and about 40% of AugerPrime is already taking data. The plan is to complete the deployment by mid-2023. The results of the commissioning data analysis show good uniformity and long-term performance. The plan of the collaboration is to run AugerPrime until 2030. This would yield an additional vertical exposure of 40,000 km^2 sr yr. Furthermore, the Auger Collaboration plans to re-analyze also the current Phase I dataset by using machine learning techniques and taking advantage of the AugerPrime Phase II data.

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