Status of the AugerPrime upgrade of the Pierre Auger Observatory

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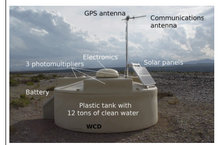
Introduction:

Cosmic particles with the energies above 10^{18} eV are known as the ultra-high energy cosmic rays. These particles are extremely rare: the particles with the energy about 10^{20} eV have an estimated arrival rate of just 1 particle per km^2 per millennium. The Pierre Auger Observatory is a detector with the area 3000 km^2, situated in Malargue, Argentina. It was built for the detection of the rare cosmic rays by recording extensive air showers, cascades of secondary particles, induced by cosmic ray particles in the atmosphere. Such a huge detector is aimed to answer the questions of the origin of the cosmic rays of the highest energies, their composition, source distribution and propagation. The observatory already largely contributed to our understanding of these puzzles. At the same time the results obtained by the Pierre Auger Observatory indicate the need of an improvement of the measuring capabilities of existing detectors, where the key feature to be improved is a method of separation of the muonic and electromagnetic components of air showers. AugerPrime is the ongoing upgrade of the Pierre Auger Observatory, which has been designed for this purpose.

Basic instruments of the Pierre Auger Observatory [1]:

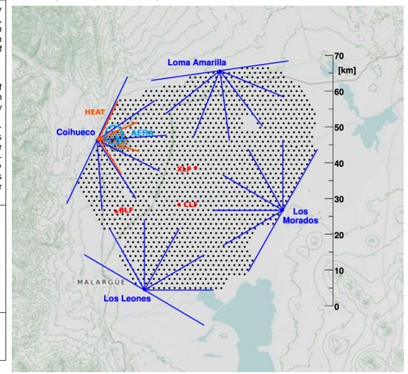
Surface Detector (SD) with **Water-Cherenkov Detector (WCD)** stations.



The principle of operation of the SD station is based on Cherenkov light emission in water.

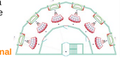
The WCD stations are sensitive to secondary particles of extensive air showers (muons, electrons, positrons and photons) as they reach the surface of the Earth, providing information on their arrival times and lateral distribution of extensive air shower.

The SD consists of:
→ **SD 1500** (black dots on a map) – an array of 1600 stations, placed in a grid with 1500 m between adjacent detectors on the Observatory area of 3000 km^2.
→ **SD 750** (gray dots near Coihueco FD) is a so-called **Infill array** – an array of 61 stations covering an area of 23.5 km^2 , composed of the regular array stations and added detectors at half-spacing between them, and so forming an array with 750 m distance between detectors. This denser array enables triggering on smaller showers, caused by lower energy cosmic rays.



4 Fluorescence Detector (FD) Sites, overlooking the atmosphere above the SD array. FD telescopes record the fluorescence light emitted by the atmospheric nitrogen molecules excited by the particles of the shower as they traverse the atmosphere. The FD provides data on the longitudinal development of the extensive air shower.
The FD consists of:
→ **24 FD telescopes**, located in 4 FD buildings, each telescope has a field of view 1-30° in elevation.

Schematic view of a single FD Site: there are 6 telescopes inside one building.

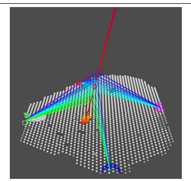


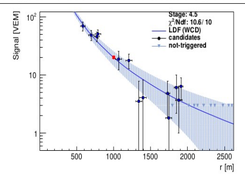
→ **HEAT - 3 additional high-elevation FD telescopes**, with field of view: 30-60°, installed to observe lower energy showers.

Other instruments:
AERA radio antennas (blue circle at the map): 153 radio antennas over 17 km^2;
UMD - Underground Muon Detectors - about 70 prototype UMD (located near Coihueco FD site);
+Atmospheric monitoring tools (red dots at the map): CLF, XLF, Lidars, …

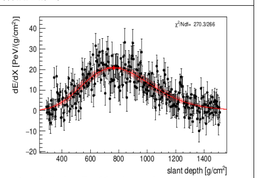
Hybrid detection concept of the Observatory:

The combination of the SD and FD detection systems enhances the reconstruction capability of the Observatory, and enables measurements in the "hybrid mode" – the extensive air showers are simultaneously detected by the FD and the SD detectors. At the figure below you can see the Auger hybrid event recorded simultaneously by SD stations at the ground and all 4 FD telescopes. In addition, the profiles of the shower, lateral (reconstructed by SD) and longitudinal (obtained from one of triggered FD), are shown. The reconstructed energy of this event is about 1.1 × 10^{19} eV.





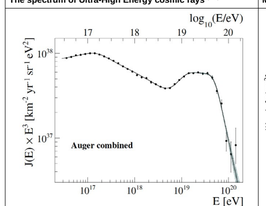
Lateral profile of the shower shown on the left.



Longitudinal profile of the shower shown on the left.

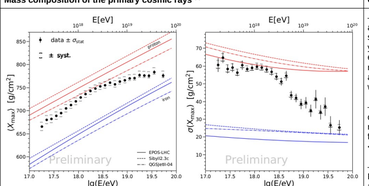
Main scientific results of the Pierre Auger Observatory

The spectrum of Ultra-High Energy cosmic rays [2, 3]



Several spectrum features:
• the high-energy suppression was identified above an energy of 5 × 10^{19} eV,
• the "ankle" - a known spectral feature at energy 5 × 10^{18} eV,
• clear observation of the second knee above 10^{17} eV.

Mass composition of the primary cosmic rays [8]



The atmospheric depth at which the shower exhibits its maximum development Xmax and σ(Xmax) as functions of primary energy are displayed at the figure. The data points are compared to the expectations from simulated showers with different hadronic models for proton (red) and iron (blue) primaries. Lighter composition is observed up to ~2 EeV, heavier above this energy.

Other important results

– **Arrival direction anisotropies** - searches for anisotropies on small and intermediate angular scales have been performed by exploiting 15 years of data, reaching an unprecedented exposure of ~100,000 km^2 sr yr in a declination range between −90 ° and +45 °. Large-scale anisotropy in the arrival directions of cosmic rays was discovered above 4 × 10^{18} eV [4].

– **Hadronic interactions** - a deficit in the number of muons predicted by the hadronic models was reported by the Auger Collaboration. Simulations fail to reproduce muon densities: 38% increase in <Nμ> at 1 EeV needed for EPOS-LHC model [5].

– **Search for neutrinos and photons** [6]. The Pierre Auger Observatory is capable of recording and identifying extensive air showers initiated by ultra-hight energy neutrinos or photons.

– **Study of atmospheric phenomena: ELVES** [7] - transient luminous events produced at the base of the ionosphere by the intense electromagnetic pulses emitted during lightning discharges.

* AugerPrime: The Upgrade of the Pierre Auger Observatory[8]

Motivation for the Upgrade

- **The determination of the mass composition of the primary cosmic rays** is a major experimental challenge to be performed in AugerPrime. A more precise determination of the mass composition on an event-by-event basis is required to be done with high statistics to reach the upper end of the spectrum. It is important to study the number of muons N_μ in the shower, which is a good indicator of the composition. To perform this task disentangling of the muonic and electromagnetic component of the extensive air shower at the ground is needed. This can be achieved either with a muon detector or a detector which has different sensitivity to both shower components.

- **Origin of the suppression** above an energy of 5 × 10^{19} eV: determining whether the suppression is a GZK-like effect arising from the propagation of cosmic rays from their sources in the intergalactic medium, or it is due to an exhaustion of the injection power of the astrophysical sources. For a full understanding of the observations, a combined analysis of the spectrum and the composition is required. AugerPrime will allow us to measure the composition-discriminated flux in the range from about 10^{18} eV up to the highest energies.

- **Search for the sources:** although anisotropies in the arrival directions have been found, the search for the sources is still not concluded. AugerPrime will allow us to carry out composition-enhanced anisotropy searches based on event-by-event estimates of the primary mass.

- **Hadronic interactions:** it is expected that it will be possible to understand the muon deficit in shower simulations using the new data from AugerPrime. Test of our understanding of hadronic interactions at c.m.s. energies near and beyond 60 TeV also will be possible with the AugerPrime data.

- Other important analyses based on AugerPrime data: search for GZK secondaries as tracers of proton primaries, search for ultra-high energy secondary photons produced in or near cosmic ray sources, etc.

Components of AugerPrime

• **Surface Scintillator Detectors (SSD)** – new detectors, placed above the existing 1660 water-Cherenkov Detectors (WCD), will be used for a complementary measurement of the shower particles.

• **New electronics** [9] - The surface detector stations will be upgraded with new electronics that will process both WCD and SSD signals. The new electronics will also provide faster sampling of ADC traces, better timing accuracy, increased dynamic range, and enhanced triggers.

• **small PMT** - To increase the dynamic range, each WCD will be equipped with an additional "small PMT", i.e., a smaller low gain photomultiplier tube, to register large pulses from very close showers that saturate the signal of the large PMTs.

• **Underground Muon Detector**[9] **(UMD)** will provide important direct measurements of the shower muon content and its time structure, while serving as verification and fine-tuning of the methods used to extract muon information with the SSD and WCD measurements.

• **Extended FD operation mode** - The operation mode of the Fluorescence Detector (FD) will be changed to extend measurements into periods with higher night sky background and twilight. This will allow an increase in the current ~15% duty cycle of the FD to over ~20%.

• **Radio detection array**[10] **-** Each Surface Detector station will be complemented with an antenna – radio detector **(RD) –** for radio detection of cosmic ray showers.

Surface Scintillator Detector (SSD)

The key element of the upgrade is the installation of a new Surface Scintillator Detector (SSD) on top of each of the existing WCD detectors.

SSD will provide a complementary measurement of the shower particles. As the SSD and the WCD have different responses to muons and electromagnetic particles, this allows for the disentangling of the different shower components.

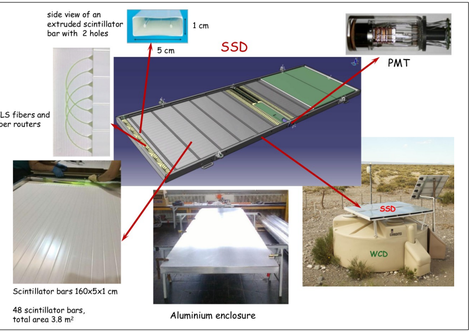
The SSD unit consists of a box of 3.8 m × 1.3 m, housing two scintillator panels, each covering an area of 1.9 m^2 . Each panel is composed of 24 bars of 10 mm thick, 50 mm wide and 1.6 m long scintillator made of extruded polystyrene. The bars have two holes in which the wavelength-shifting fibres can be inserted. The fibres are 1 mm in diameter and are used in a "U" configuration that maximizes light yield and uniformity. All ends of the fibres are bundled towards a single photomultiplier in the centre of the module.

The SSD modules are fixed to an aluminium frame mounted on top of the WCD tanks of the SD.

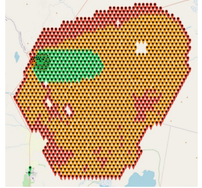
The triggering of the SSDs is done in slave mode: the SSD data is read out every time the corresponding WCD reports a trigger.

SSD detector and its components are shown on the right.

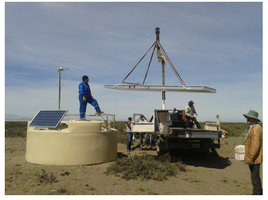
All of the 1500 SSDs for the Upgrade have already been built at laboratories in Germany, Italy, Poland, Netherlands and France. They have already been shipped to Malargue, where they are being assembled and installed in the field, awaiting the delivery of the optical modules and electronics.



Status of the deployment



The larger fraction of the SD array is orange on the map, that means that 1212 WCD have already SSD installed and 153 (green area) are equipped with PMTs and are in acquisition.

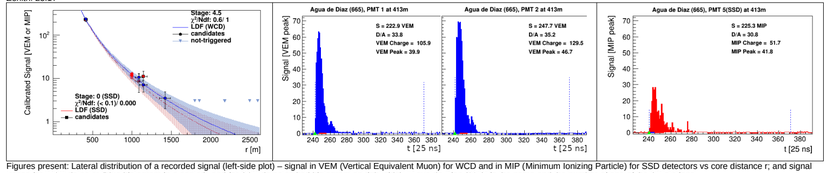


The SSD modules are deployed in the field with a truck and crane.

The detector in the field with the SSD and RD installed on top.

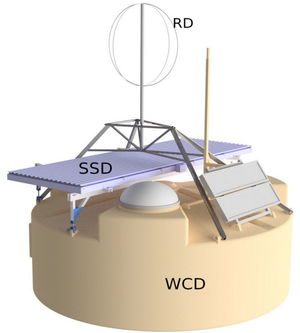
AugerPrime: first data from SSD – example of real WCD-SSD event

Energy: 2.20 EeV
Zenith: 25.17 °



Figures present: Lateral distribution of a recorded signal (left-side plot) – signal in VEM (Vertical Equivalent Muon) for WCD and in MIP (Minimum Ionizing Particle) for SSD detectors vs core distance r; and signal traces for WCD detector (blue histogram in a center), and for SSD detector (red histogram on right side). "Agua de Diaz (665)" is the name and the number of one of the SD stations.

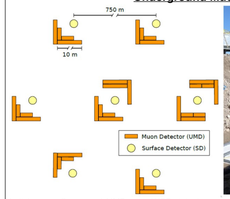
A prototype of an upgraded Auger Surface Detector

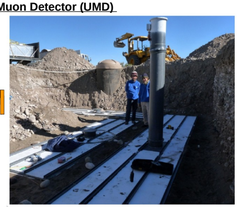


Both the scintillator planes, the new electronics and the radio antennas will be deployed over the full 3000 km^2 area of the Pierre Auger Surface Detector, with minimal impact on the continuous data taking and maintenance of the existing detectors.

Several WCD stations equipped with SSD and RD. Also UMD are shown.

Underground Muon Detector (UMD)





Left figure – Scheme of UMD and WCD detectors during the prototyping phase. For the final design, the 30 m^2 detection area will be reached with three 10 m^2 units with 64 segments each, totaling 192 channels. Right figure - UMD during installation.

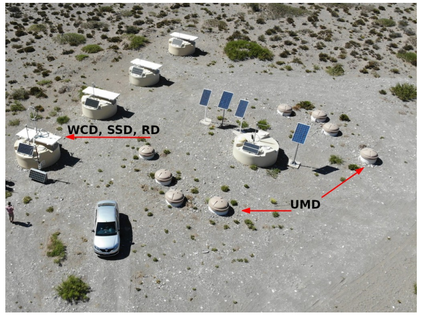
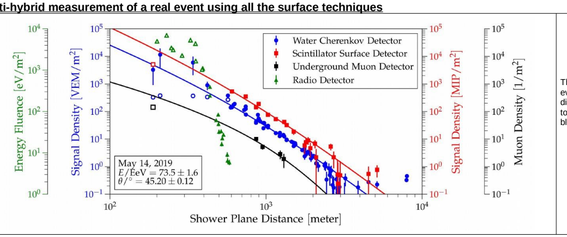


Figure similar to that on the left side, but taken from above during summer time. Both surface and underground detectors are shown in their arrangement.

Multi-hybrid measurement of a real event using all the surface techniques



The plot on the left illustrates the measured signals of a real event from SD, SSD, UMD and RD detectors. The lateral distribution of a signal is shown as a function of the distance to the reconstructed shower core. Fits (solid red, blue and black lines) to the measured data are also included.

Conclusions

The Pierre Auger Observatory has been running smoothly with nearly full aperture, and has now accumulated more than 12 years of data with the full-size observatory. It has also contributed to the understanding of cosmic ray shower physics, high-energy particle interactions, atmospheric phenomena and instrumentation development.

A major upgrade of the Auger Observatory is now underway. Presently, 100% of the SSD modules (1500 units) have already been built, and 80% of the SSD have been installed in the field, most of the remaining ones are already in Malargüe awaiting deployment. Their PMTs are being fabricated and tested in Europe and will soon be shipped to the site for installation.

Small PMTs for increased dynamic range of the WCDs are ready to be deployed together with the new electronics. An engineering array of more than 150 SSD is running in the field, using the original electronics kits. Their performance indicates that they respond according to design. The first batch of the preproduction series of upgraded electronics is being tested and will be installed at the site in the coming months. The upgrade of the Pierre Auger Observatory is expected to be completed in 2022.

The AugerPrime upgrade of the Pierre Auger Observatory will provide a multi-hybrid cosmic ray detection, that will allow simultaneous measurement of a shower with water-Cherenkov detectors, surface scintillator detectors, radio detectors, muon counters and fluorescence detectors. Operation of the upgraded Observatory is expected for at least 10 years, nearly doubling the statistics with respect to the presently available one.

References

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