PROCEEDINGS OF SCIENCE

Status and prospects of the Pierre Auger Radio Detector

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The Pierre Auger Observatory is presently undergoing a major upgrade to improve its detection capabilities for ultra-high-energy cosmic rays. Part of the upgrade is the installation of radio antennas at each position of the Surface Detector array, forming a 3000 km^2 antenna array for the detection of air showers – the Radio Detector. The status and prospects of the Radio Detector are discussed.

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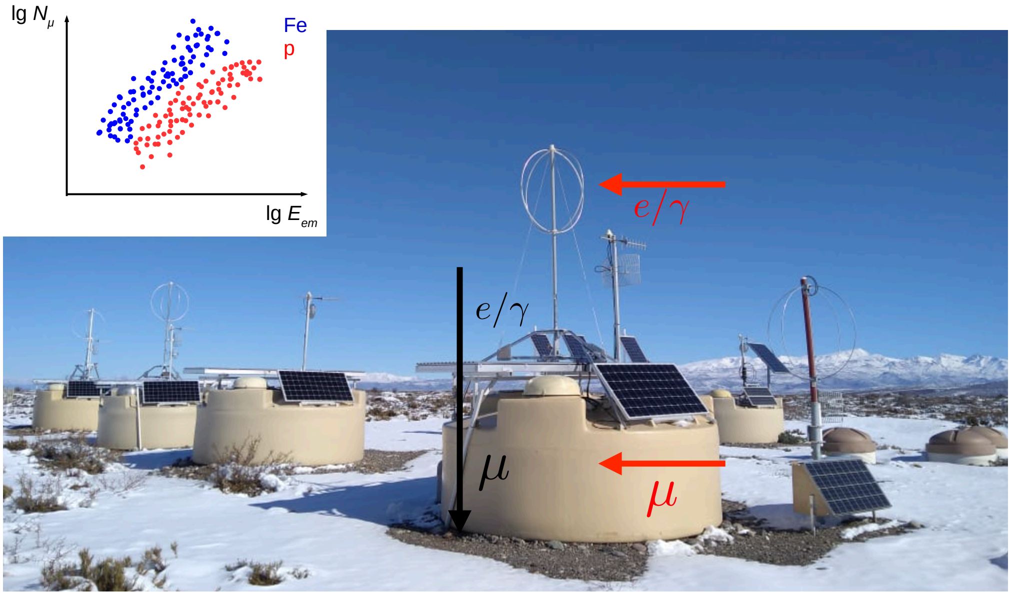

Figure 1: Prototype Surface Detector stations of the upgraded Pierre Auger Observatory. The hybrid detection capabilities are illustrated: the muonic component is measured with the water-Cherenkov detectors, while the electromagnetic component is measured with the Scintillator Surface Detector (installed above the water-Cherenkov detector) for vertical showers and with the radio antennas for inclined showers.

1. Introduction

The Pierre Auger Observatory [1] is investigating the properties of ultra-high-energy particles with unprecedented precision [2] with the objective to reveal the physics and origin of the highest-energy particles in Nature. At present, the Observatory is undergoing a major upgrade [3] to increase the sensitivity and quality of the measurements, in particular to improve the capabilities to identify the particle type (mass of the incoming cosmic ray) at the highest energies. To identify the atomic mass and, thus, indirectly the charge of the incoming cosmic rays is a key observable, which will allow, together with the established energy measurement, the exploration of today unknown regions of the parameter space, such as rigidity-dependent energy spectra or sky maps. Questions we seek to address with the upgraded Observatory include [4]:

– What are the sources and acceleration mechanisms of ultra-high-energy cosmic rays?

– Do we understand particle acceleration and physics at energies well beyond the LHC (Large Hadron Collider) scale?

– What is the fraction of protons, photons, and neutrinos in cosmic rays at the highest energies?

A major component of the upgrade is the installation of radio antennas at all positions of the Surface Detector – the Radio Detector [5]. Covering an area of 3000 km^2 equipped with almost 1700 detection units, the Radio Detector will be the largest radio detector for extensive air showers. The upgraded Observatory will allow studying extensive air showers with unique hybrid capabilities, observing simultaneously fluorescence light, particles arriving on the ground, muons underground, and radio emission.

The basic concept of the upgraded Surface Detector array is illustrated in Fig. 1. It shows a test field where several Surface Detector stations are placed next to each other. In the main Surface Detector array they are spaced on a triangular grid with 1500 m spacing. To identify the type of the incoming cosmic ray (i.e. to determine the atomic mass of the nucleus) the electromagnetic and muonic components of the air showers are measured simultaneously. The muonic component is detected with the water-Cherenkov detectors (ocher colored plastic tanks in the photograph) where 12 m^3 distilled water serve as detection medium, being observed by three photomultiplier tubes. To increase the dynamic range, a fourth (smaller) PMT is added as part of the upgrade. The water volume has a height of 120 cm and is therefore sensitive to air showers arriving from the upper hemisphere, with arrival directions from the zenith to the horizon. A layer of scintillation detectors, the Scintillator Surface Detector, is installed above the water-Cherenkov detector [6]. In a simplified picture, the Scintillator Surface Detector is mainly sensitive to the electromagnetic component, while the water-Cherenkov detector is mostly sensitive to muons. Unfolding techniques (also including machine learning algorithms) will be applied in order to unfold the mass information from the measured detector responses.

The aperture of the flat scintillator decreases as a function of the zenith angle $\propto \cos(\theta)$, thus vanishing towards the horizon. The electromagnetic component of air showers is probed with the radio antennas, mounted on top of the water-Cherenkov detectors and the Scintillator Surface Detector. This is in particular interesting for inclined air showers, with zenith angles above 60°. Inclined air showers have large radio footprints on the ground [7]. This has been verified experimentally with the Auger Engineering Radio Array (AERA) [8]. The measurements indicate that for large zenith angles the radio footprint covers several tens of square kilometers, illuminating dozens of radio antennas above the threshold on the standard 1500 m grid. In our frequency range of interest (30 to 80 MHz) the atmosphere is transparent. Thus, the radio antennas provide a clean measurement of the electromagnetic shower component. Combining the signals from the water-Cherenkov detectors and the radio antennas, again unfolding methods will be applied in order to unfold information from the electromagnetic and muonic shower components to determine the atomic mass of the incoming particle. The upgraded observatory will have unique mass sensitivity for air showers arriving from the zenith to the horizon.

2. The Radio Detector

A schematic view of an upgraded Surface Detector station is shown in Fig. 2. The main components of the Radio Detector are visible. Two aluminum rings, forming the dual-polarized antenna are mounted on a fiberglass mast. One antenna ring is oriented parallel to the Earth magnetic field and the second one perpendicular to it. Thus, the electric field of air showers is probed in two polarization directions, north-south and east-west. The mast is fixed by an aluminum frame directly connected to the structure of the water-Cherenkov detector (not touching the Scintillator Surface Detector beneath). Guy wires additionally support the mast and reduce vibrations that could otherwise be induced by strong winds.

The antenna is a Short Aperiodic Loaded Loop Antenna (SALLA). It is based on a simple mechanical design, minimizing cost and easing handling and maintenance. With its diameter of 122 cm, it is tailored at the frequency range of interest of $30 - 80$ MHz, for which it delivers a virtually uniform response with very little dispersion. The antenna arms are held in place by

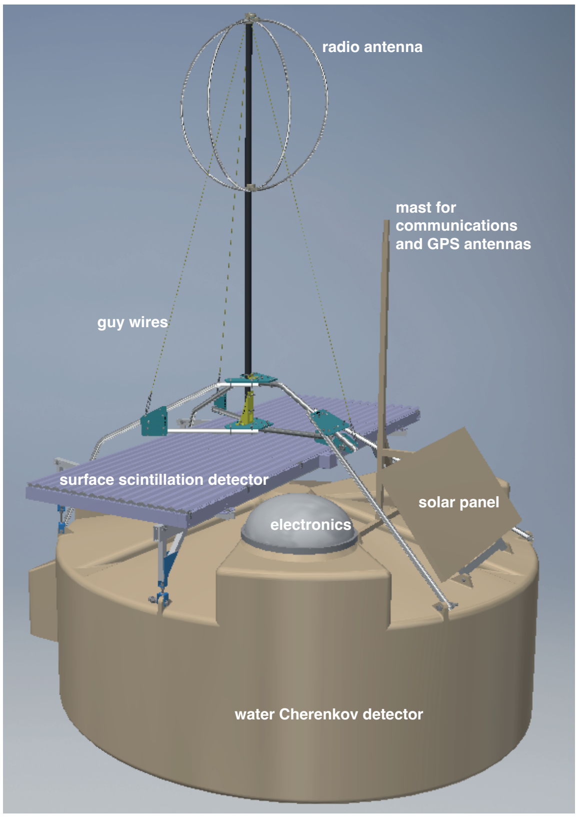

Figure 2: Schematic view of an upgraded station of the Surface Detector array. The main components are indicated: the water-Cherenkov detector, the Scintillator Surface Detector, and a radio antenna. A solar panel provides energy for the local electronics. Time synchronization is obtained via the GPS antenna and communications to the central data acquisition system is conducted via wireless communication.

injection-molded plastic housings, which also contain the pre-amplifier at the top and the load resistor at the bottom. Non-conductive plastic material has been chosen for the housings in order to reduce parasitic capacities (which negatively influence the antenna performance). A schematic illustration is given in Fig. 3.

The antenna features a 392 Ω resistor at the bottom which suppresses dependence on structures below the antenna, in particular the Scintillator Surface Detector, the water-Cherenkov detector and potentially variable ground conditions. Two coaxial cables, routed inside the glass fiber mast connect the low-noise amplifiers at the top of the antenna with the main electronics inside the "dome". Inside the mast the cables are run through four ferrites in order to minimize the effect of the cables on the antenna pattern.

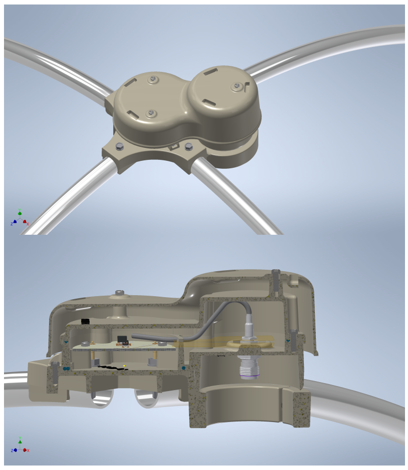

Figure 3: Schematic illustration of the top of the SALLA antenna.

The Radio Detector front-end electronics, often called in short "the digitizer" is located inside the "dome". It has two parallel input channels for the signals from the two polarization directions, see Fig. 4. The signals are being amplified in total by 36 dB and a band pass filter limits the signals to the frequency range of interest 30 – 80 MHz. The signals are processed by an analog-to-digital converter with a sampling rate of 250 MHz and a dynamic range of 12 bits. A Field Programmable Gate Array (FPGA)

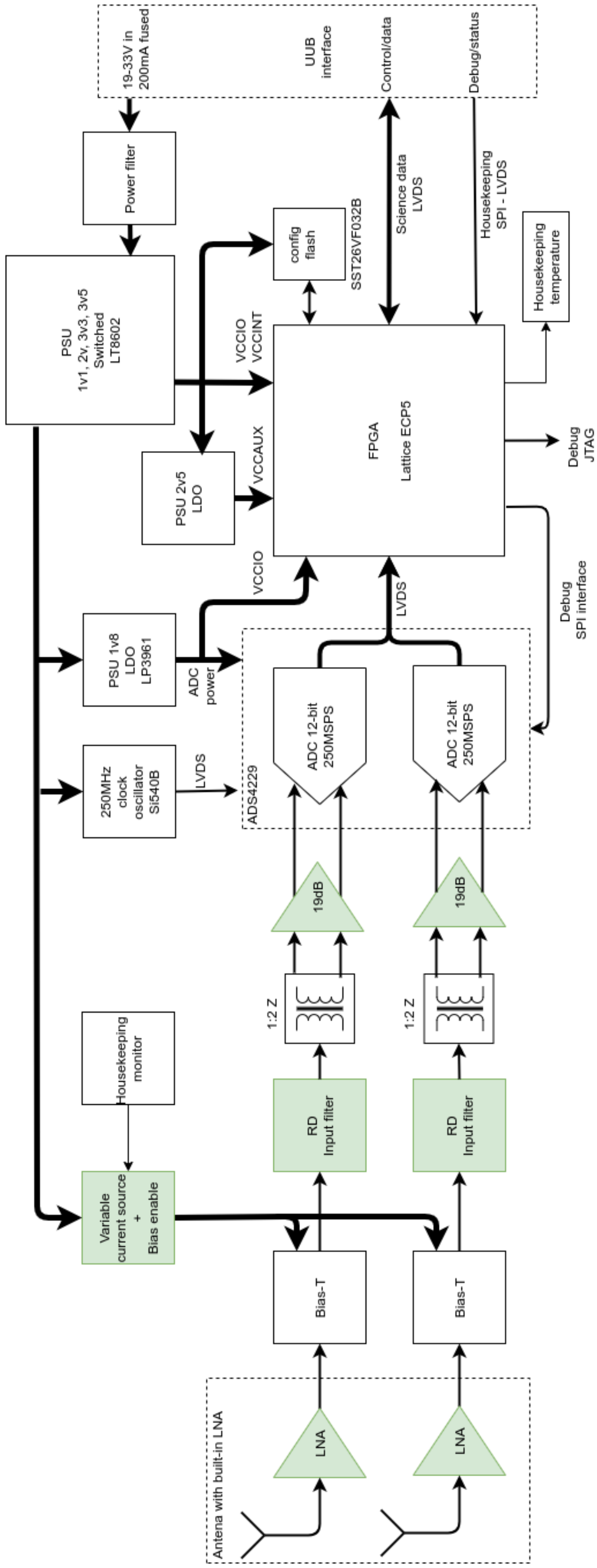

Figure 4: Schematic view of the Radio Detector front-end electronics.

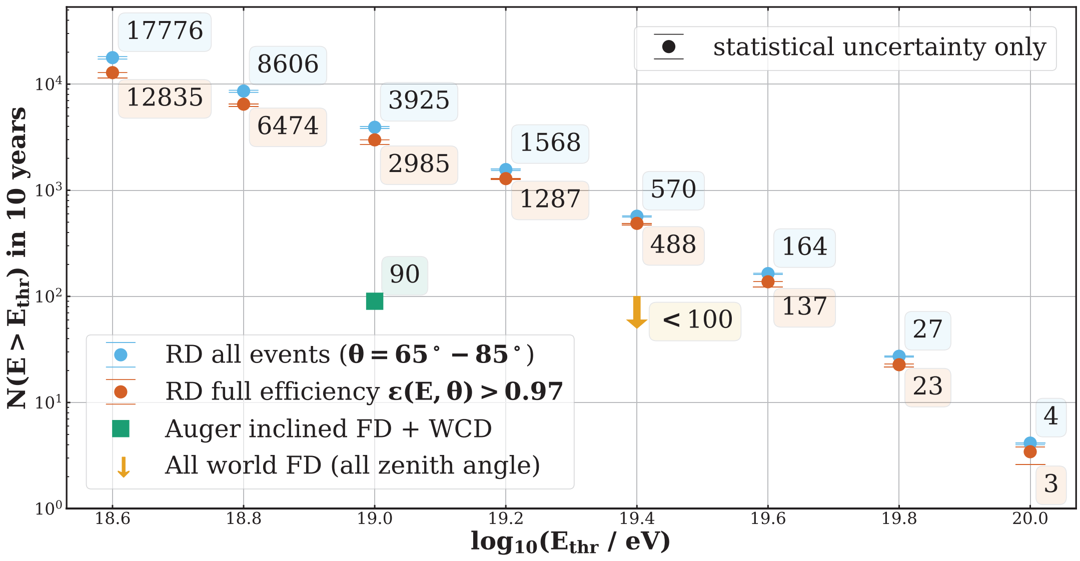

Figure 5: Integral number of cosmic rays expected to be detected by the Auger Radio Detector for a measurement period of ten years. See [9] for details. Blue points denote all detected events, red points only those in bins of energy and zenith angle for which the detection efficiency is at least 97%. For comparison, the number of inclined air showers measured with both the Auger Surface and Fluorescence Detectors is shown in green, and the total number of air showers measured with fluorescence detectors worldwide at energies of $10^{19.4}$ eV or higher is shown in yellow.

coordinates data exchange with the Upgraded Unified Board which queries 2048 samples of the radio data whenever a trigger was received from the water-Cherenkov detector. In the future, we plan to include information from the radio detector in the trigger decision, which would be useful in particular for the detection of photon-induced air showers. In addition, the frontend board features auxilliary circuits to provide power.

The data are sent via the existing wireless communications system as part of the regular Surface Detector data stream. Further monitoring information, such as a regular characterisation of the Galactic radio signal, will in addition be transmitted as part of a monitoring data stream.

3. Performance

The expected performance of the Radio Detector for the measurement of hadronic cosmic rays has been investigated extensively with end-to-end Monte Carlo simulations [9]. The study includes a detailed description of the development of air showers with the CORSIKA code, the accompanying radio emission is modeled with the CoREAS code. Realistic models of the antenna response, the environmental noise, and the electronics performance have been taken into account. The reader is pointed to [9] for further details.

Based on the measured flux of cosmic rays the expected number of particles to be detected with the Radio Detector have been calculated. The expected numbers as a function of energy for an operation period of ten years are shown in Fig. 5. The reader should take notice of the yellow/brown

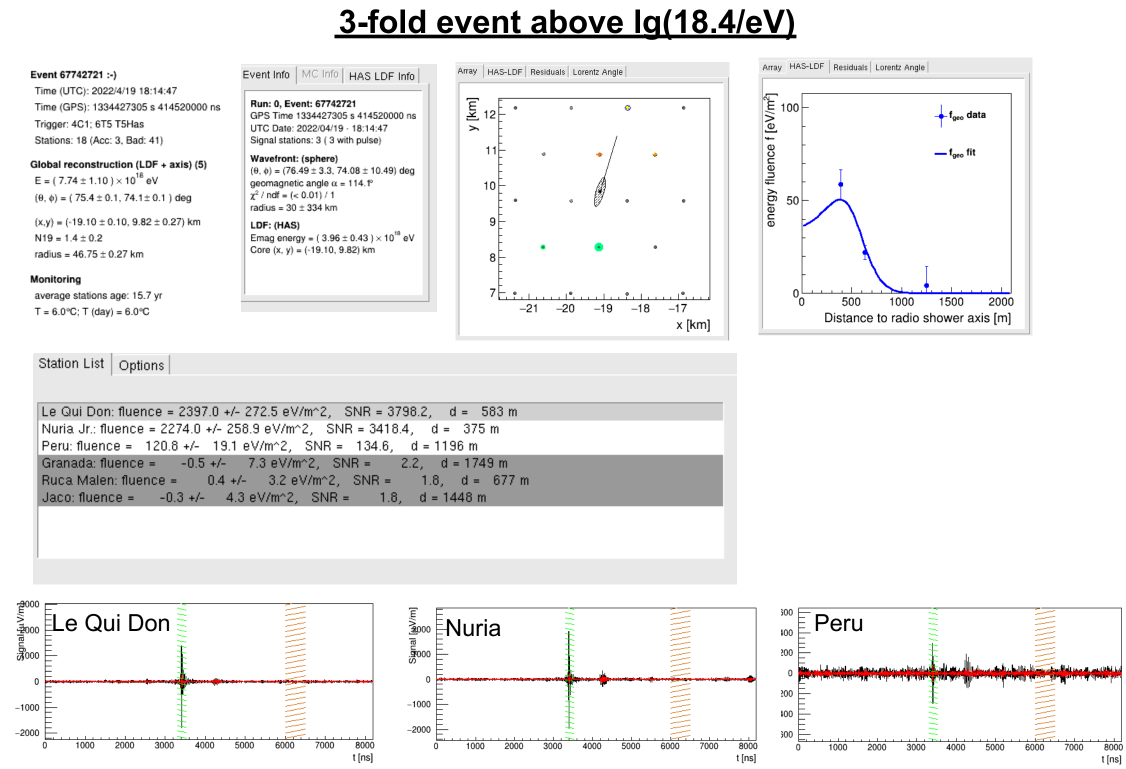

Figure 6: Event display of a measured air shower with an energy of about 8×10^{18} eV in the Engineering Array.

arrow, which symbolizes the combined number of cosmic rays measured with fluorescence detectors to date. This illustrates the potential of the Radio Detector for inclined air showers.

In addition to the reconstruction of hadronic particles, at present reconstruction algorithms for photons and neutrinos are being prepared. The Radio Detector, providing a clean measurement of the electromagnetic component is, in particular interesting for the reconstruction of gamma-induced showers, with a high fraction of the electromagnetic shower component.

4. First data

An Engineering Array has been set up in 2019 to verify the detection concept, see Fig. 1. In addition to the stations shown in the photograph a hexagon of the Surface Detector array has been equipped with radio antennas. Air showers are routinely detected with the Engineering Array [10]. A measured air shower is illustrated exemplary in Fig. 6. A cosmic ray with an energy of about 8×10^{18} eV has induced radio signals above threshold in three stations of the Radio Detector. Fig. 7 illustrates the center of gravities of recorded air showers, located around the Engineering Array. A sky map of the arrival directions of the air showers with radio signals above the threshold is depicted in Fig. 8. The Radio Detector is optimized for inclined showers with zenith angles above 60°. The sky plot also exhibits a north-south asymmetry, this is expected from the main emission mechanism,

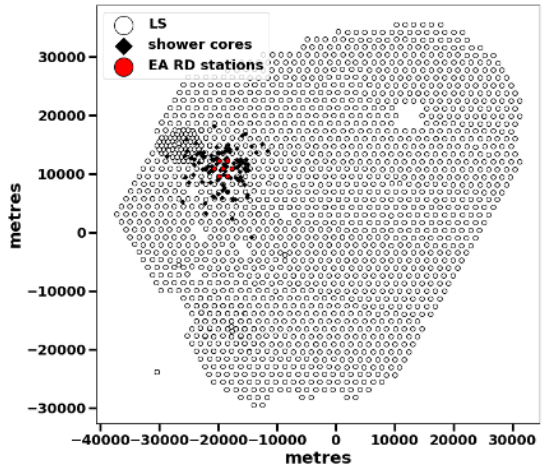

Figure 7: Location of centers of gravity for air showers detected with the Engineering Array.

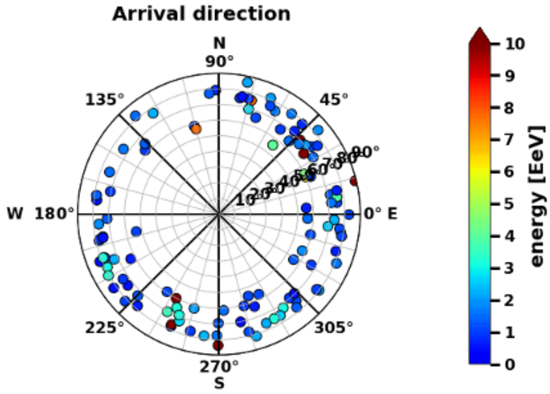

Figure 8: Sky plot indicating the arrival direction of air showers recorded with the Radio Detector.

the charge separation of electrons and positrons in the geomagnetic field, which is proportional to the vector cross product of the Earth magnetic field $\vec{B}$ and the shower direction $\vec{v}$: $\vec{v} \times \vec{B}$.

5. Deployment and commissioning

Deployment of the Radio Detector components has been started in austral autumn 2023. Except for the digitizers, all components are available presently at the Observatory. Installing radio detectors at all (almost 1700) positions of the Surface Detector array will take several months. The digitizers are being manufactured at present in Europe. After thermal cycling and calibration they will be delivered to the Observatory. Installation at the stations is expected to start in austral winter 2023. We aim to complete the installation of the Radio Detector in early 2024. Commissioning will be conducted partly in parallel to the installation. We aim to take air shower data as soon as possible with a partially operating Radio Detector, which will grow in size as a function of time. We expect the commissioning of the full Radio Detector to be completed in 2024.

6. Acknowledgements

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