Acta Polytechnica **53**(Supplement):825–828, 2013
doi:10.14311/AP.2013.53.0825

THE AUGER ENGINEERING RADIO ARRAY

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Abstract. The Auger Engineering Radio Array currently measures MHz radio emission from extensive air showers induced by high energy cosmic rays with 24 self-triggered radio detector stations. Its unique site, embedded into the baseline detectors and extensions of the Pierre Auger Observatory, allows to study air showers in great detail and to calibrate the radio emission. In its final stage AERA will expand to an area of approximately 20 km^2 to explore the feasibility of the radio-detection technique for future cosmic-ray detectors. The concept and hardware design of AERA as well as strategies to enable self-triggered radio detection are presented. Radio emission mechanisms are discussed based on polarization analysis of the first AERA data.

Keywords: AERA, radio detection, cosmic rays, air shower, Pierre Auger Observatory.

1. Introduction

During the last years significant progress has been made in radio detection of cosmic rays both in experiments and in theoretical calculations. Experiments such as LOPES [1] and CODALEMA [2] use arrays of radio antennas to detect coherent VHF (10 ÷ 100 MHz) radio emission from extensive air showers induced by cosmic rays. Geomagnetic radio emission has been identified as the dominating process, and subdominant effects are studied currently. By including information from particle detectors on the ground, the characteristics of the radio pulse are investigated with respect to the fundamental properties of the primary cosmic rays.

On the theoretical side, various approaches such as REAS [3] and MGMR [4] simulate the radio emission from air showers in detail. They predict a quadratic scaling of the emitted radio power with the energy of the primary cosmic ray. Furthermore, a sensitivity of the lateral distribution of the pulse amplitude to the chemical composition of the primary cosmic ray was found. Experimental evidence for this phenomenon has recently been observed by the LOPES collaboration [5].

These results suggest that the radio-detection technique, with its high duty cycle close to 100 %, is well suitable for measuring all relevant parameters of cosmic rays. As a next step, the Auger Engineering Radio Array (AERA) now explores radio detection at ultra-high energies ($E \geq 1 \cdot 10^{18}$ eV).

2. AERA

AERA is a radio extension of the Pierre Auger Observatory located in Argentina. The Pierre Auger Observatory follows a hybrid concept to detect ultra-high-energy cosmic rays via their induced air showers. An array of 1660 water-Cherenkov tanks covering an area of 3000 km^2 detects secondary shower particles at ground level. This surface detector array is overseen by 27 fluorescence telescopes at 4 sites which track the emission of fluorescence light during shower development in the atmosphere.

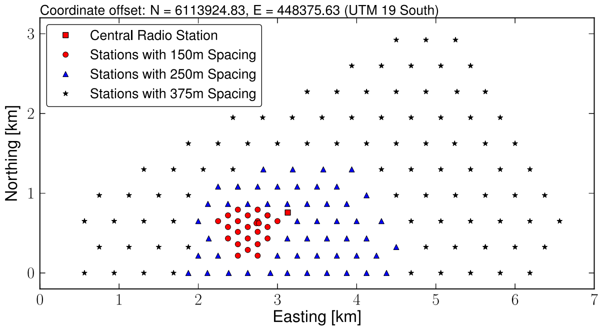

Figure 1. Layout of AERA. Each marker denotes the position of a radio detector station.

AERA is situated within the field of view of the fluorescence telescopes Coihueco and HEAT [6] and co-located within the extension AMIGA [7], a combination of muon detectors and additional water-Cherenkov tanks. Thus, a unique environment is formed to study air showers with complementing detection techniques and to calibrate the radio detectors.

The deployment of AERA started in 2010 with a dense core of 24 radio detector stations arranged on a triangular grid with a spacing of 150 m (Fig. 1). Since spring 2011, these stations are operational and successfully measure the radio emission from air showers in a self-trigger mode. More than 100 cosmic-ray events have been recorded in coincidence with the surface detector, and several "super-hybrid" events have been observed with the fluorescence detector of the Pierre Auger Observatory as well. In its final stage AERA will consist of 161 radio-detector stations with a spacing of 150 m (the deployed 24 stations), 250 m (52 stations) and 375 m (85 stations), covering nearly 20 km^2. For the final layout, several thousand cosmic-ray events per year with energies above 10^{17} eV are expected [8].

The layout of AERA aims to fulfill the following scientific goals:

- Calibration of the radio emission from air showers by super-hybrid measurements. This includes the understanding of underlying dominant and subdominant emission mechanisms.
- Exploring the feasibility of radio detection for future cosmic-ray experiments. Evaluating the quality of the angular, energy and primary mass measurements.
- Composition measurements in the transition region of galactic to extragalactic cosmic rays.

2.1. Radio detector stations and calibration

The hardware design of the autonomous radio-detector stations (RDSs) evolves from various prototype setups at the Pierre Auger Observatory. These allowed us to define the technical requirements for successful self-triggering and to examine the environmental demands at the site in the Argentinean pampas.

The stations of the dense core (Fig. 2) utilize dual-polarized log-periodic-dipole antennas, aligned north-south and east-west. The bandwidth from 30 to 80 MHz corresponds to the relatively radio-quiet region between the short-wave and FM bands. The received signals pass a two-stage amplification chain and band-pass filters before they are digitized. The custom-built digitizers are based on 12-bit ADC units at a 200 MHz sampling rate. The data is transmitted via optical fibers or a wireless link to the central radio station which hosts the DAQ system. The stations are powered by a photovoltaic system. To prevent triggering on noise generated by the station electronics itself, all critical components are shielded by a radio-frequency tight chamber.

The physical quantity of interest, the time dependent electric field emitted by the air shower, has to be reconstructed from the voltage traces measured by the RDSs. This requires end-to-end calibration of the entire signal chain including the antenna. All relevant electronic components of the AERA stations: amplifiers, cables and digitizers were calibrated by individual measurements. The antenna gain has been measured as a function of the zenith angle at the AERA site. Therefore, a calibrated signal source attached to a helium balloon has been used in the far-field region of the antenna. The results are in fair agreement with the corresponding simulations.

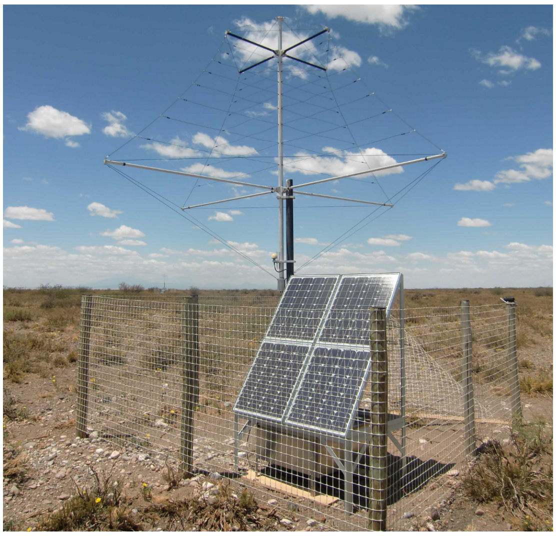

Figure 2. Photograph of an AERA radio-detector station.

2.2. Self-triggering

To demonstrate the feasibility of radio detection as a stand-alone technique, AERA is capable of self-triggering on the measured voltage traces. This is a technical challenge as one has to deal with various man-made noise sources. Even in the relatively radio quiet environment in Argentina, sources of transient noise have been discovered. By assuming that signals propagate as spherical waves, the location of the sources can be reconstructed by a spherical wave fit if the signal was measured at least at four different positions. The reconstructed source positions of self-triggered radio events are plotted in a map of the AERA site in Fig. 3. Various hot spots are visible. Coincidences with the positions of potential man-made noise sources such as transformer stations can be observed.

Various methods have been developed for rejecting these noise sources. The RDS electronics host a field-programmable gate array (FPGA) where sophisticated real-time algorithms can be implemented.

Before triggering on a radio pulse, the signal-to--noise ratio is increased by filtering out narrow band transmitters with digital notch filters. The trigger itself consists of a threshold in the time-domain and also considers various quantities which are sensitive to the shape of the pulse expected from cosmic-ray induced air showers [10]. Events often occur with a certain periodicity, e.g. with a frequency of 100 Hz, matching twice the frequency of the power grid in Argentina. These events are rejected directly at the station level by an algorithm which dynamically adjusts to the phase drift of these periodic pulses.

At the central radio station a fast plane wave fit is performed to reconstruct the arrival direction of events. Events coming from known hot spots can then be excluded.

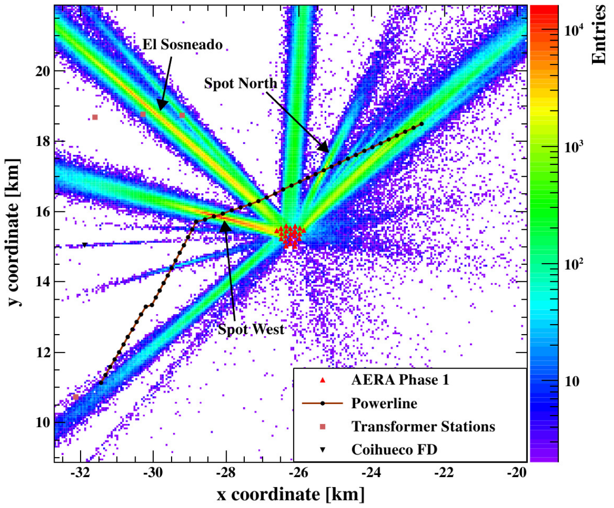

Figure 3. Map of the AERA site (the stations of the dense core are in the center) with directions of 2.35×10^6 reconstructed radio events. Each symbol represents the reconstructed source point of a self-triggered radio event with a zenith angle larger than 60°. Color-coded is the density of events. In addition suspected sources of the transient radio pulses are marked. From [9].

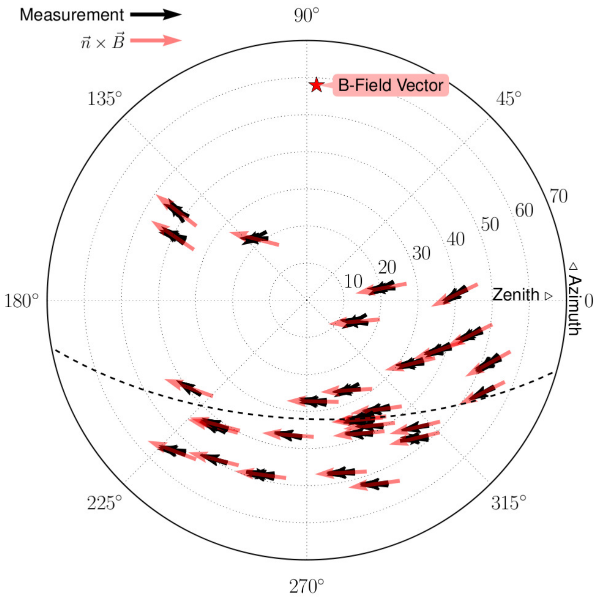

Figure 4. Polar skyplot of measured polarizations in comparison to the $\mathbf{n} \times \mathbf{B}$ calculation. All vectors are normalized to unity. Note that at least 3 black vectors are plotted on top of each other for a specific incoming direction according to the multiple measurements of the electric field vector at the different RDSs triggered in the event. The dashed line indicates incoming directions perpendicular to the magnetic field vector (red star) at the AERA site.

3. Polarization Studies

Although the emission of MHz radiation from air showers is not fully understood yet, two different emission mechanisms are currently considered: geomagnetic emission and emission due to the charge-excess effect. A robust observable for investigating different emission mechanisms is the polarization signature of the electric field emitted by air showers. Due to its dual-polarized antennas and extensive calibration, AERA is a suitable tool for measuring these observables with high precision.

3.1. Geomagnetic Emission

Charged secondary shower particles are deflected in the earth's magnetic field by the Lorentz force, which causes emission of electromagnetic radiation. The superposition of radiation from single shower particles produces an electromagnetic pulse which appears to be coherent in the radio frequency region. The polarization of the electric field $\mathbf{E}$ is then given by the direction of the Lorentz force:

$$\mathbf{E} \propto \mathbf{n} \times \mathbf{B} \tag{1}$$

where $\mathbf{n}$ is the direction of the shower axis and $\mathbf{B}$ is the local magnetic field vector.

The polarization signature of AERA data has been investigated based on radio events measured in coincidence with the surface detector, as these events likely result from cosmic-ray induced air showers. By cutting on at least three triggered RDSs and on zenith angles smaller than 55°, 29 events were selected. The electric field traces were reconstructed at each triggered RDS with the radio extension of the standard Auger reconstruction framework Offline [11]. Afterwards, the electric field vector was extracted at the pulse position.

In Fig. 4, east-west and north-south components of the measured electric field vectors are plotted in a skyplot corresponding to their arrival direction given by the surface detector. All measured electric field vectors corresponding to one cosmic-ray event are pointing essentially in the same direction. This implies that all stations measure approximately the same linear polarization. Furthermore, the measured polarization is in good agreement with the predictions by the calculation following Eq. 1. This gives evidence that, for those air-shower events and within the bandwidth of our setup, the radio emission is mainly of geomagnetic origin.

The angular distribution of radio events shown in Fig. 4 supports this conclusion. Equation 1 implies that the strongest radio pulses are emitted if the shower axis is perpendicular to the earth's magnetic field vector. If the radio detector triggers above a threshold for the pulse amplitudes, an anisotropy in the arrival directions is expected. This anisotropy is clearly observed in Fig. 4. The dominant role of geomagnetic emission is well known and has recently been observed at AERA prototype setups [12], and by LOPES [1] and CODALEMA [2].

As for the measured events and the present setup, the geomagnetic emission dominates the emitted signal strength, an estimator for the primary cosmic ray's energy can be formulated by correcting for the arrival direction using Eq. 1 and taking into account an exponential lateral distribution function. A calibration of this radio-energy estimator versus the energy given by the surface detector was recently presented at the ARENA conference [13].

3.2. Charge-excess emission

Askaryan first predicted that a negative net charge in the air shower can also lead to a coherent emission of MHz radiation [14]. This emission mechanism implies an essentially different polarization signature compared to the geomagnetic emission. The electric field is polarized radially with respect to the shower axis. Observers placed at different positions with respect to the shower core thus would measure different polarization.

In a polarization analysis of data from an AERA prototype setup experimental evidence was found that the charge-excess effect contributes to the total radio emission [12]. Similar analysis are being performed with AERA data and will be presented in a forthcoming publication.

4. Conclusions

In its initial stage, AERA has successfully detected cosmic rays by self-triggering on MHz radio emission. Various strategies have been implemented to reject the background of transient man-made noise and to enable a stable data taking. The end-to-end calibrated detector stations allow for precise polarization-sensitive measurements of the radio emission. Analyses of the first AERA data provide an insight into the underlying emission mechanisms and support the dominating role of geomagnetic emission. Super-hybrid measurements in coincidence with the baseline detectors and extensions of the Pierre Auger Observatory provide the calibration of the radio emission and will determine the sensitivity of radio detection to the primary energy and mass composition. In its final stage AERA will expand the energy range of radio detection and will provide new access to air shower physics and fundamental parameters of cosmic rays.

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Discussion

Peter Grieder — How problematic is the contribution from transition radiation?

Klaus Weidenhaupt — This has not been studied with AERA data yet. As the antennas of the dense core are essentially insensitive to the ground it should be a second-order effect.