Radio detection of air showers at the Pierre Auger Observatory

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Abstract. High-energy cosmic rays impinging onto the atmosphere of the Earth induce cascades of secondary particles: extensive air showers. Many of the particles in a shower are electrons and positrons. The electrons and positrons interact with the geomagnetic field and emit radiation. We detect such radiation at frequencies of tens to hundreds of MHz with the Auger Engineering Radio Array (AERA) at the Pierre Auger Observatory in Argentina. The objective is to investigate the properties of cosmic rays at the expected transition from Galactic to an extragalactic origin at energies around $10^{17}$ to $10^{18}$ eV. We discuss the recent progress in radio detection of ultra-high-energy cosmic rays with AERA. To this end, we elaborate on our measurements of shower properties, such as the lateral distribution of the radio emission at ground level. In addition, we present methods to reconstruct the properties of the primary particle from the radio data.

1. Introduction

The radio emission from cosmic-ray-induced air showers is dominated by two emission mechanisms, the geomagnetic effect [1] and the Askaryan effect [2]. The geomagnetic effect is caused by the transverse separation of the electrons and positrons due to the geomagnetic field. The Askaryan effect probes radio emission produced by the negative charge excess along the longitudinal development of the extensive air shower. The combination of both effects leads to radiation in a large frequency bandwidth of tens of MHz.

Radio detection of air showers benefits from a quasi-calorimetric measurement of the shower energy with a duty cycle of 100%. In addition, similar to fluorescence detectors, radio detectors are sensitive to the longitudinal air-shower development, thus can provide an estimate for the mass of the primary cosmic rays [3].

AERA [4] is located at the site of the Pierre Auger Observatory [5] in the province of Mendoza, Argentina. The current configuration of AERA, i.e. AERA-124, consists of 124 radio stations, covering an instrumented area of about 6 km$^2$. AERA is equipped with two types of radio stations: a) 24 radio stations equipped with Logarithmic Periodic Dipole Antennas (LPDA), which are deployed on a grid of 125 m. b) 100 radio stations using butterfly antennas (see figure [1]), which are placed on grids of 250 m and 375 m. Each radio station consists of two crossed antennas aligned in the geomagnetic North-South and East-West directions, recording radio signals in a frequency range of 30 to 80 MHz. AERA operates in self trigger and external
trigger modes. The external trigger exploits the surface detectors (SD) or fluorescence detectors (FD) of Auger for triggering.

Exploiting the proven techniques developed in previous radio detectors, such as LOPES [6] and CODALEMA [7], AERA aims to investigate the radio emission processes taking place in high-energy extensive air showers. In addition, AERA has been calibrated to provide the measurements of the fundamental parameters of extensive air showers, such as the direction, energy and mass of the primary cosmic rays that initiated the shower. AERA covers energies around and above $10^{17}$ eV.

This paper presents results obtained using the first set of externally triggered events which have been detected and reconstructed with AERA.

2. Measurement of the radio emission from air showers

In order to make use of the data measured by radio detectors, we need to understand the radio emission mechanisms taking place in air showers. As mentioned before, two radio emission mechanisms, i.e. the geomagnetic and Askaryan effects, contribute mainly to the radio emission of air showers. The electric field induced by the geomagnetic effect points to the direction defined by $\vec{v} \times \vec{B}$, where $\vec{v}$ is a vector denoting the axis of an air shower and $\vec{B}$ is the geomagnetic field vector. On the other hand, the electric field induced by the Askaryan effect has a radial direction pointing towards the shower axis [8].

One can consider total electric field as the linear contribution of electric fields induced by geomagnetic $\vec{E}^G(t)$ and Askaryan $\vec{E}^A(t)$ effects:

$$\vec{E}(t) = \vec{E}^G(t) + \vec{E}^A(t),$$  

(1)
where \( t \) is the time of the measurement of the electric field at a certain radio station. Each AERA station measures voltages in two polarisation directions, i.e. North-South and East-West. Using the information of the reconstructed direction of the event and correcting for the response pattern of the radio antennas, we transform the time traces of radio pulses measured in the two polarisation directions to the components of the electric field vector. Comparing the predicted azimuthal polarisation angle \( \Phi_{p(pr.)} \), as defined in equation (2), with the measured azimuthal polarisation angle \( \Phi_{p(me.)} \), one can quantify the contribution of each emission mechanism in the radiation of air showers.

\[
\Phi_{p(pr.)} = \tan^{-1}\left( \frac{E_{Gy}^G + E_{Ay}^A}{E_{Gx}^G + E_{Ax}^A} \right),
\]

(2)

where the subscripts \( x \) and \( y \) denote the geographic East and North directions, respectively. One can express the above equation in terms of azimuthal angles of geomagnetic \( \Phi^G \) and Askaryan \( \Phi^A \) contributions, in which the azimuthal angles can be calculated for a shower with a given direction (more details presented in [8]):

\[
\Phi_{p(pr.)} = \tan^{-1}\left( \frac{\sin \Phi^G + a' \sin \Phi^A}{\cos \Phi^G + a' \cos \Phi^A} \right),
\]

(3)

where the parameter \( a' = \left| \frac{E^A}{E^G} \right| \).

We estimate the most likely values of the \( a' \) parameter, by comparing the measured and predicted azimuthal polarisation angles. Since the strength of \( E^G \) depends only on the angle \( \alpha \) between the shower axis and the geomagnetic field, we scale \( E^G \), dividing it by \( \sin \alpha \). Thus we obtain the \( a = \sin(\alpha) a' \) parameter which is independent from the shower arrival direction. Therefore, we define the \( a \) parameter as the relative strength of the electric fields induced by the Askaryan emission processes.

Figure 2 (left) presents the distribution of the measured value of the \( a \) parameter and its estimated uncertainty (black error bars) for each measurement. The distribution has a mean value of \( a = (14 \pm 2)\% \) at 68% confidence level. Figure 2 (right) shows the distribution of the azimuthal polarisation angle as a function of the predicted azimuthal polarisation angle for the mean value of \( a = 14\% \). The value of the Pearson correlation coefficient, i.e. \( \rho_P = 0.93^{+0.04}_{-0.03} \) at 95% confidence level is at its maximum for the mean value of the \( a \) parameter.

A comparison between the simulation and measurement of the radio emission indicates that the general picture of the radio emission mechanisms agrees with the experimental measurements within the uncertainties (see [9]). Figure 3 shows the lateral distribution of a typical radio event measured by AERA (data points) compared with predictions from radio emission simulations (shaded areas). Two different radio emission codes, i.e. CoREAS version 1.0 [10] and ZHAireS beta v28 [11], have been applied for this comparison. There is a good agreement between the measured data and the simulation of the radio emission.

3. Event reconstruction

The measurement of the arrival time of the radio wavefront hitting the array of AERA-radio stations leads to the reconstruction of the arrival direction. When a radio event is externally triggered by the SD detector, all AERA stations equipped with buffering hardware are read out. This increases the probability of baring stations with pulses from radio frequency interferences (RFI). In order to suppress RFI pulses, we exploit the information of the event direction reconstructed by SD to impose a time window in which the radio signal is searched. The width of the signal search window is the quadratic sum of the uncertainties derived from the SD direction reconstruction and the AERA timing precision. Furthermore, we suppress the RFI
Figure 2. Left) Distribution of the $a$ parameter and its estimated uncertainty (black error bars) per measurement, where the solid line indicates the 68% confidence belt around the mean value of the $a$ parameter; the dashed line shows the value of $a = 0$. The orang boxes show the upper (lower) uncertainty bound when the mean value of $a$ is larger (smaller) than the measured $a$. Right) Distribution of the measured azimuthal polarisation angles as a function of the predicted azimuthal polarisation angles for the optimal value of $a = (14 \pm 2)\%$. The plots are taken from [8].

Figure 3. Lateral distribution of an event measured by AERA compared with COREAS (left) and ZHAires (right) simulation codes. Data points show the experimental data while the blue and red shaded areas show the proton and iron simulations, respectively. The smearing shown for simulations is the uncertainties of the input parameters, e.g. core location and energy, caused by shower-to-shower fluctuations. The plots are taken from [12].
Figure 4. Performance of the direction reconstruction of AERA. Shown are the difference between the AERA and SD reconstructed zenith angle (left) and azimuth angle (right). A Gaussian function is fitted on the distributions in order to obtain the spreads of the distributions.

pulses using a cluster algorithm which selects the cluster of stations associated with the event measured with the SD detector.

Figure 4 shows the performance of the direction reconstruction of AERA, which compares the shower directions measured experimentally by SD and AERA (RD). According to the figure, the direction reconstruction of AERA agrees with that of SD within 2.1°. The events used in this analysis include low-energy events which employ only a few stations per event. The deviation is expected to decrease for high-energy events.

We exploit the amplitude information of radio pulses to reconstruct the energy of the events [13]. As explained in section 2, we transform the time traces of radio pulses in the East-West and North-South polarisation directions to the components of the electric field vector (see figure 5). Then our energy reconstruction algorithm is defined as the strength of the electric field vector at the optimal distance $D_0$, which is scaled with the angular dependency of the geomagnetic emission mechanism. The value of $D_0$ is optimised to achieve the highest energy resolution for AERA [13].

Figure 5 (left) shows a typical measured time trace of an electric field vector for East-West, North-South and vertical directions. Figure 5 (right) overimposes the measured electric field vectors and the expected electric field induced by geomagnetic and Askaryan fields, for a subsample of the externally triggered events. There is a good agreement between the measured and expected electric fields.

4. Conclusion

AERA is the world’s largest cosmic-ray radio detector. It operates at the Pierre Auger Observatory, in Malargüe, Argentina. Taking advantage of measuring cosmic rays in coincidence with Auger’s surface and fluorescence detectors, AERA furnishes important cross-calibrations and comparisons with the other detection techniques employed at the Observatory. AERA primarily aims to investigate the radio emission mechanisms from air showers in an energy range between proximately $10^{16.9} - 10^{19}$ eV. In addition, operating with a duty cycle of nearly 100%, AERA intends to pursue the scientific goals of the Pierre Auger Observatory, by providing complementary information to Auger’s surface and fluorescence detectors.

We have summarised results which have been obtained using the first set of externally triggered events measured by AERA. The results show that radio emission from air showers consists of the contributions of two main effects: geomagnetic and Askaryan effects. The geomagnetic emission process is dominant, while the Askaryan effect contributes with about...
Figure 5. Left) Measured electric field vector for East-West (solid black line), North-South (solid dark grey line) and vertical (solid light grey line) polarisation components. The Hilbert transformation is applied to calculate the envelope of the time trace of the electric field vector. The dashed line shows the Hilbert envelope. The figure is adapted from [13]. Right) The measured comparison of electric field (dark black arrows) with the expected electric field (light red arrows). The figure is adapted from [14].

(14 ± 2)% to the radio emission of air showers measured of AERA. This is in good agreement with full Monte-Carlo simulations of radio emission in air shower for the location of the Pierre Auger Observatory. Furthermore, AERA has been optimised to contribute to the measurement of fundamental air-shower parameters, i.e. direction, energy and composition. The direction of events measured by AERA scatters by an angle of 2.1° from that measured by the SD, which is expected to improve for high-energy events for which the number of employed stations per event are higher. AERA has also been calibrated to measure the event energy. The AERA-reconstructed energy correlates with the SD-reconstructed energy.

5. References

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