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Radio detection of extensive air showers at the Pierre Auger Observatory

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ABSTRACT

Deployed at the end of 2010 at the Pierre Auger Observatory, the first stage of the Auger Engineering Radio Array, AERA24, consists of 24 radio stations covering an area of 0.5 km^2. AERA measures the radio emission from cosmic-ray induced air showers. The amplitude of this radio emission is used to constrain the characteristics of the primary particle: arrival direction, energy and nature. These studies are possible thanks to an instrumentation development allowing self-triggered and externally triggered measurements in the MHz domain and an improved understanding of radio emission processes. In May 2013, 100 new stations were installed to cover an area of $\simeq 6$ km^2, for a total of 124 stations. This stage 2 will provide higher statistics and will enhance both the estimate of the nature of the primary cosmic ray and the energy resolution above 10^{17} eV as an addition to detectors such as the Auger fluorescence telescopes and particle detectors. We will present the main results obtained with the stage 1 of AERA and the current status of the experiment. We will end with a brief overview of the GHz-experiments installed at the Pierre Auger Observatory.

1. Introduction

One of the challenging questions related to cosmic rays concerns their nature. Improving our knowledge about the composition of cosmic rays allows us to constrain the models concerning their origins and their production mechanisms in the astrophysical sources. The electric field of radio emission induced by the shower is sensitive to the whole shower development and can be measured with a high duty cycle, and thus is a promising technique to identify observables sensitive to the nature of the primary cosmic ray.

In Europe two experiments have given the first modern results concerning the study of extensive air showers at low energy (because of their small area: less than 1 km^2): CODALEMA [1] in France and LOPES [2] in Germany.

The *A*uger *E*ngineering *R*adio *A*rray installed at the Pierre Auger Observatory has recently been extended and covers, with its stage 2 installed since the beginning of May 2013, approximately 6 km^2 with 124 radio stations. AERA allows the study of the radio emission during the development of the shower in the MHz domain. In this frequency range, two mechanisms lead to a polarized coherent radio signal.

The first one, *the geomagnetic effect* is due to the action of the geomagnetic field on the charged particles of the shower and leads to the creation of a linearly polarized electric field along the vector $-\mathbf{v} \times \mathbf{B}$. This phenomenon was described by Kahn and Lerche in 1966 [3] and has been confirmed by several experiments.

The second one, *the charge excess effect*, was predicted by Askaryan in 1962 [4] and is due to the annihilation of positrons in the shower and to the Compton effect leading to a negative charge excess in the shower front. It leads to the creation of a signal which is radially polarized with respect to the shower axis.

The main objective of AERA is to characterize the primary cosmic ray: nature, energy and arrival direction. For this it is necessary to disentangle the mechanisms responsible for the radio emission occurring during the development of the shower. This can be done by analyzing the polarization of the measured electric field as presented in Section 3.2. AERA will also permit one to test the performances of a large radio array compared to the other techniques.

2. The Pierre Auger Observatory

The Pierre Auger Observatory is the largest air shower detector in the world. Its 1660 Cherenkov detectors, which compose the surface detector array (SD), cover 3000 km^2, and four fluorescence sites (FD) surround the Observatory. The experiment reaches its maximum of efficiency at 3 EeV and is thus dedicated to the study of ultra-high energy cosmic rays.

In recent years, new equipment has been installed at the observatory to lower this energy threshold in order to increase the statistics. This low energy extension is sensitive to energies

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from 0.1 to 10 EeV and is composed of an infill array of Cherenkov detectors with a reduced grid size (750 m instead of 1.5 km for the regular array), three high elevation fluorescence telescopes (HEAT) and a muon detector array (AMIGA).

The composition of cosmic rays is at the heart of the studies, especially with the FD which allows the study of the whole shower development. However, the telescopes can be used only during dark nights with a reduced duty cycle around 14% [5]. That is why the radio detection technique is promising. It allows the measurement of the whole shower development but with a duty cycle close to 100% and using inexpensive detectors.

3. AERA—1st stage

AERA is deployed in the low energy extension of the Pierre Auger Observatory in order to have a large statistics and high-quality super-hybrid measurements. It enables the comparison of radio observables with those obtained with the SD (regular and infill array) and the nine fluorescence telescopes close to AERA installed on both the HEAT and Coihueco sites.

The stage 1 of AERA has operated at the observatory since 2010 and is taking data since 2011 with 24 stations spaced by 144 m and covering 0.5 km^2. Each station is equipped with

- a *L*og *P*eriodic *D*ipole *A*ntenna measuring both EW and NS polarizations between 30 and 80 MHz;
- an electromagnetic compatibility box containing the electronics to prevent for the triggering of the station by itself; and
- solar panels, batteries and GPS.

Thanks to this equipment AERA is completely autonomous in power supply and can also be used in a self-trigger mode for which the measured signal triggers the station if its level exceeds a predefined threshold. This defines the first level trigger T1. After a pulse-shape analysis performed directly at the station level, each station sends on average 500 level 2 triggers per second (T2). The corresponding timestamps are sent to the central data acquisition system. All T2s coming from all AERA stations are treated in real time to search for cosmic ray candidates studying the time difference between several pair of AERA stations event by event to check the compatibility of this event with the arrival of an air shower on the array. This is the level 3 trigger (T3).

AERA can also be externally triggered by the SD stations close to the array, and very soon by the fluorescence telescopes HEAT and Coihueco.

3.1. Proposed rejection algorithm

In the self-trigger mode the stations are mostly triggered by anthropic background and thunderstorms sending a huge number of T2s, occupying a large fraction of the bandwidth and saturating the disks. The background transients lower the detection efficiency of cosmic rays. To use this technique we must develop efficient rejection algorithms at level 1 or 2 of the trigger to increase the purity of the recorded signals.

We present here an example of such an algorithm which was developed for RAuger [6], a prototype radio-detection experiment which was one of the pathfinders for AERA. The results of this prototype are described in Ref. [7]. The study presented here was performed using the data of the upgraded version of RAuger which was composed of three autonomous radio stations located near the *C*entral *L*aser *F*acility at the center of the SD. These stations were equipped with Butterfly [8] antennas developed for CODALEMA and are now equipping the stage 2 of AERA. The proposed

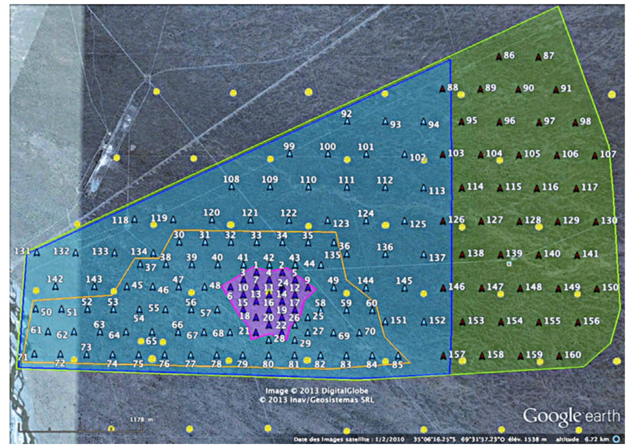

Fig. 1. AERA—in purple is shown the 1st stage with 24 stations, in blue are shown the 100 new stations of the 2nd stage installed since May 2013 and in green the last stations scheduled for 2014. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

selection algorithm has been established using two different data sets:

- air-shower events detected in coincidences between the RAuger stations and the SD stations close to the array and
- background events.

We study the time evolution of the filtered signal in a short time window containing the main pulse as illustrated in Fig. 2. In this time window and for each trace we sum up bin after bin the square of the amplitude of the signal to compute a normalized cumulative function. This cumulative function is defined as follows:

$$C(i) = \frac{\sum_{k=b_{\text{start}}}^{b_{\text{start}}+i} s_{\text{EW}}(k)^2}{\sum_{k=b_{\text{start}}}^{b_{\text{end}}} s_{\text{EW}}(k)^2} \quad \text{with } 0 \le i \le b_{\text{end}} - b_{\text{start}}. \tag{1}$$

We have observed that, in most cases, a background trace has a longer duration than a cosmic ray trace. We define the rise time of the signal as the time needed for the cumulative function to rise from 10% to 70%. We observe (Fig. 3) that the rise time for cosmic rays (red triangles) is significantly smaller than the rise time of the background transients (black diamonds). The values 10% and 70% and the frequency range for the filtering (30–60 MHz) have been optimized for this experiment.

This rejection method has an efficiency of approximately 90% on the RAuger2 data (cut at 30 ns, orange line in Fig. 3). One cosmic ray trace is rejected by this method (isolated red triangle above 100 ns in Fig. 3). This signal is of very bad quality and is thus probably a random coincidence. The algorithm has been installed on CODALEMA since the beginning of 2013 with an efficiency of approximately 94% [9] and is currently being tested on the AERA data.

3.2. Polarization studies

As discussed previously, the study of the polarization of the measured electric field allows a better understanding of the emission processes: several studies have confirmed the dominance of the geomagnetic effect [7,10,11]. These experiments have shown an excess of events coming from directions far from the direction of the geomagnetic field, which is a signature of the geomagnetic effect. When comparing the direction of the measured electric field with the expected direction due to this dominant mechanism ($-\mathbf{v} \times \mathbf{B}$) [12], we observe some