Measuring cosmic ray radio signals at the Pierre Auger Observatory

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Abstract

The recent results of the LOPES and CODALEMA experiments open the door to a renewal of the radio technique for cosmic ray induced shower measurements. The demonstration has been done of its potential and performances at energies below 10^{18} eV, this upper limit being due to the small scale of the current experiments. A natural stage toward the improvement of the method is thus to install radio detectors in association with a large cosmic ray detector such as Auger. Besides surface and fluorescence detection, radio detection could be an alternative method, providing a complementary information. The Pierre Auger collaboration has thus engaged a R&D effort which will led to the installation of a radio engineering array covering 20 km^2 on its southern site. Outline of the technique, results of the first phase of the tests and current plans for the future engineering array will be presented.

Key words: cosmic rays, extensive air showers, antennas, Auger, AERA project
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1. Introduction

Since 2002, radiodetection of cosmic ray induced air showers has been successfully implemented on two sites in Europe, the LOPES [1] and CODALEMA [2] experiments. Both setups are made of a ground particle detector array triggering a slave cabled antenna array, and have roughly the same size ($\simeq 0.3$km^2) and thus the same energy threshold ($\simeq 10^{17}$ eV) and accessible energy range (up to $\simeq$ 2-3.10^{18} eV). Although their results are hampered by threshold effects due to the poor statistics at high energy, LOPES and CODALEMA have firmly proved the possibility of detecting radio signals emitted by the air showers. Among the most illustrative results obtained (see for example [3] for a comparative review):

- the geomagnetic origin of the electric field produced in the shower has been demonstrated;
- it has been shown that the electric field strength scales mostly linearly with primary energy;
- empirical parameterizations of the electric field, based on an exponential decay, have been obtained in both experiments;
- the technics has proved its ability to accurately reconstruct the arrival direction of the shower.

Those remarkable results, obtained in few years only, have been accompanied by strong theoretical developements [4, 5, 6, 7], which have in common a primary asumption on the influence of the geomagnetic field on the production of the shower's electric field. However, a lack of statistics and the energy threshold effects does not allow distinguishing precisely between the proposed models. Although it has been clearly demonstrated that a simplified view based on the Lorentz force reproduces the data [8], further works - both experimental and theoretical - are required to establish the fine behaviour of the electric field in the shower. From the experimental point of view, a gain of statistics well above the energy detection threshold and a sensible increase of the density of detection antennas are required to get a fine map of the electric field profile over the shower footprint for a large set of shower energies (for polarization studies for example). In the same time, crossed analyses of radio signal with other shower observables such as ground particle signals and, if possible, fluorescence detector signals should allow accurate calibration of the radio signal in various shower geometries. To reach those objectives, it is necessary to cover a wider area and to take benefit of a performing cosmic ray detector, such as the Pierre Auger Observatory southern site in Malargüe, Argentina [9]. Today, the radio technique has been judged mature enough to authorize the construction of such an hybrid detector combining surface detection (SD), fluorescence detection (FD) and radio detection (RD) at Auger: it is the goal of the AERA (Auger Engineering Radio Array) project.

2. Scientific goals and technical needs

Two majors scientific goals are defined for AERA before producing the cosmic ray science results in which radio detection associated to other techniques can clearly contribute:

- To accumulate enough statistics at energies around and specially above 10^{18} eV, and to derive all the dependencies of the radio signal with other shower parameters obtained with SD and FD. This will help determining more precisely the underlying emission mechanism and choosing between various scenarii;

- by comparison with the other techniques, to find the radio observables related to the most important quantities of the cosmic rays: primary energy, primary mass and arrival direction determination.

Once the above challenges will have been achieved, the technique should give important results on the cosmic ray energy spectrum and their mass composition in the region of energies between $10^{17.4}$ and $10^{18.7}$ eV (the so-called "ankle", supposed to be due to the transition between galactic and extra-galactic sources of cosmic rays).

To reach these goals, it is mandatory to achieve a change of scale, from the area covered by current experiments (less than 1 km^2) to several km^2: an area of 20 km^2 covered with some 150 antennas, disposed on a variable spacing grid would allow to expect more than 1000 events above 10^{18} eV per year. This will fulfill the statistical needs. Moreover, we will take advantage of two current Auger enhancements, the so-called "infill" (increasing of Auger SD density to lower the energy threshold) and two new fluorescence telescopes observing at low elevation and also detecting fluorescence traces at lower energy. Those two projects, respectively named AMIGA and HEAT, are located in the same area of the Auger field, near the existing fluorescence building of Coihueco in the North-West of the field. By building the AERA array at the same place, the hybrid setup AMIGA-HEAT-AERA will give an uncomparable and complete view on the cosmic rays in the ankle region of energy.

One major technological challenge has also to be solved: covering a large array implies using autonomous, self powered and self triggered radio stations, and to set up an array of stations communicating through wireless data link. Autonomous radio detection of cosmic ray signals has never been made before in existing experiments and constitutes by itself the first exciting challenge of this project.

3. Present status of radiodetection at Auger

At the end of 2006, two preliminary sites have been equipped on the Auger array (Ballon Launching Station, BLS, and Central Laser Facility, CLF), in order to test various concepts of antennas, triggering systems and acquisition electronics (see Fig. 1). One of the objectives was also to get a better understanding of the radio sky over Auger, and to evaluate the discrepancies between various sites that could as well be encountered over a large area of 20 km^2. A complete description of the different setups used is presented in ref. [10].

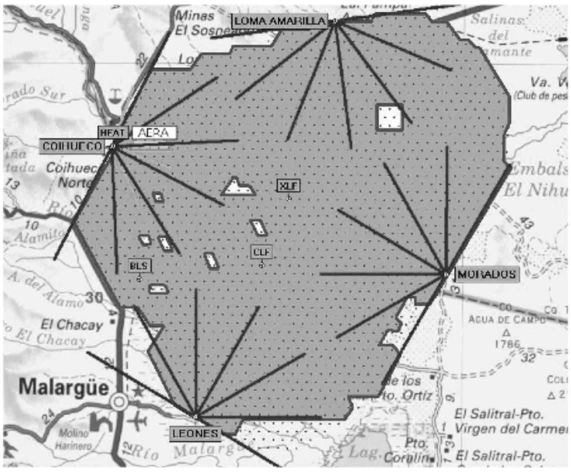

Figure 1: Map of the Auger South array. Existing radio setups are located at the BLS and the CLF, the future AERA array will be build at the East of Coihueco.

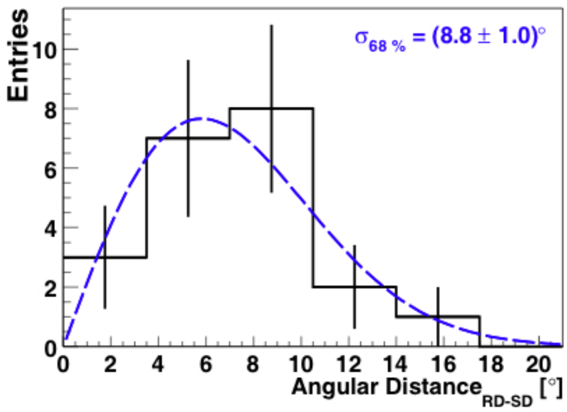

Figure 2: The angular difference between the reconstructed arrival directions of radio detectors at the BLS (RD) and the Auger SD, for 27 coincident events at 3 antennas externally triggered. The dashed line is a Rayleigh function fit through the data.

One of the setups installed at the BLS is composed of 3 poles equipped with logarithmic periodic dipole antennas (LPDA) in both North-South (NS) and East-West (EW) polarizations, mounted on a triangular base of 100 m side. They are triggered externally using two particle detectors (plastic scintillators). Several hundred of events have been recorded in time coincidence between these externally triggered stations and Auger SD events. Among them, 27 have been seen by the 3 poles, allowing the reconstruction of the arrival direction of the shower by the radio stations. The comparison with the direction reconstructed by the SD is presented Fig. 2. Considering an angular resolution of $\simeq 2°$ for the SD events (mostly 3 or 4 SD tanks involved in coincident events), the major contribution to the angular uncertainty of 8.8° seen on this distribution can be attributed to the radio, mainly because of the small distance (100 m) between the radio detectors.

Noise and sensitivity studies have also been performed with the LPDA at the BLS. They show that these anten-

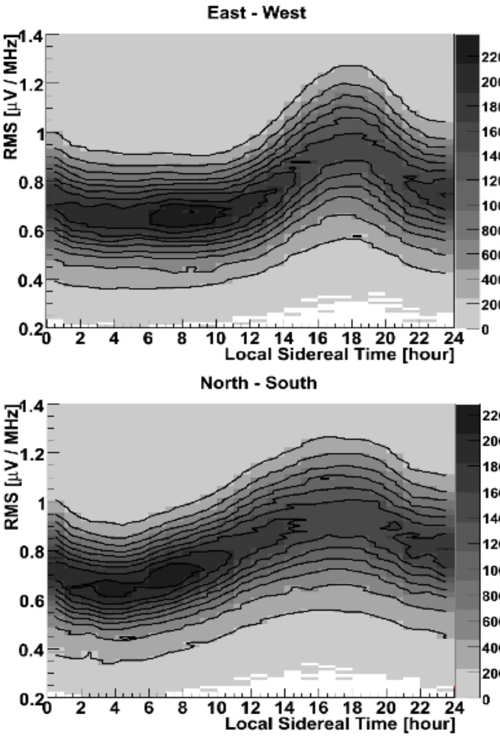

Figure 3: RMS noise level as a function of LST in EW (top) and NS (bottom) polarizations for the LPDA, over a one year period. The passage of the galactic plane over the array is clearly visible around 18:00. The gray scale indicates the number of counts per hour and per 0.012 μV.MHz^{-1}.

nas are sensitive to the galactic noise, which constitutes the absolute noise limitation in any radio experiment. Fig. 3 represents the root mean square (RMS) value of the noise (out of any transient signal) seen by the antennas in a 50-55 MHz band, recorded over a period of almost one year, in both NS and EW polarizations. Plotted against local sidereal time (LST), this RMS value shows in both polarizations the same trend, *i.e* an increase around 18:00 LST (see also [11, 12]). This corresponds to the LST of the transit of the galactic plane in the Auger sky, which could help to calibrate the radio antennas.

On the CLF site, studies with 3 solitary systems have been performed, in self triggered mode. Those radio detection stations are completely autonomous in terms of power (solar energy), triggering and data transfert (WiFi). Similar systems have also been installed at the BLS but in externally triggered mode. In both cases, special care has been taken to reduce the self-induced noise generated by the station electronics itself, which constitutes a technical challenge in terms of electromagnetic interference (EMI) mitigation. In purely autonomous mode, radio triggered events are recorded and time-stamped by GPS, and an offline comparison is made between these arrival times and Auger SD event arrival times for tanks around the antenna array. At the CLF setup, 36 radio events have then been observed in time coincidence with Auger SD events

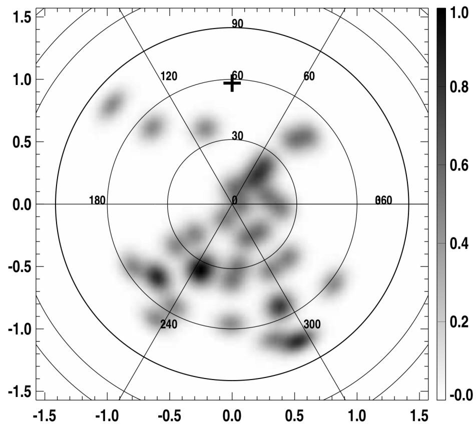

Figure 4: Sky map of the 36 radio events recorded with the autonomous system at the CLF in coincidence with Auger SD, in local spherical coordinates. The zenith is at the center, East at 0°. The Earth magnetic field vector at the site of the Pierre Auger Observatory makes an angle of about 60° with respect to the zenith and its azimuthal angle is 90° (i.e. North), indicated by the cross.

within 400 ns (the time corresponding to the maximal distance between the closest tank and the farest antenna at the speed of light): this unambiguously demonstrates the air shower origin of these radio signals. Unfortunately, for technical reasons no event has been recorded on more than 2 radio stations at each time, and thus the arrival direction could not be compared with that of the SD. However, this is the first time ever that such an indepedent detection has been achieved using radio detection stations [13].

The sky distribution of radio events observed with this setup in coincidence with the SD Array is presented Fig. 4. It is well known that the efficiency for the observation of cosmic rays with the SD array does not depend on the azimuth angle. The sky plot of the observed radio events, however, is highly asymmetric with a large excess (more than 70%) of events arriving from the South. This observed asymmetry provides further support for the geomagnetic origin of radio emission by air showers, as it has been observed before in the northern hemisphere [8]. In the geomagnetic model, electric pulses will be strongest if the shower axis is perpendicular to the magnetic eld vector. The observed asymmetry can however be considered as a threshold effect, disappearing when full detection efficiency is reached for radio: here the energy of the detected showers is close to the radio detection threshold and the statistics at higher energies (*i.e* higher radio signal) is still poor due to the small extent of the CLF radio array (139 m side triangle).

4. The AERA 20km^2 project

Those promising results opened the door to the AERA project, which is now considered as a new task in Auger. The final configuration of AERA will cover an area of 20 km^2 with 150 autonomous radio detectors set up in a

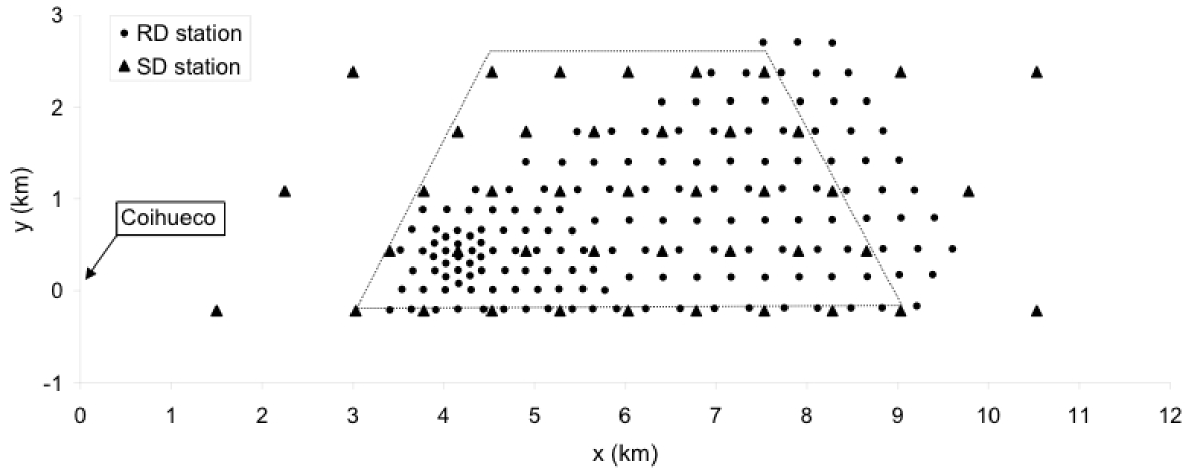

Figure 5: Layout of AERA within the infill region of Auger. Radio detection stations are figured as dots, SD stations as triangles. All the coordinates are relative to the Coihueco fluorescence building.

multi-scalar layout (see Fig. 5), based on triangular grids. The core of the array will have 24 stations with a dense pitch of 150 m, and will be encompassed by 60 antennas with a pitch of 250 m and at last an outer region of 72 stations on a 375 m pitch grid. The radio detectors are optimized for a frequency window of 30 to 80 MHz, performing self triggering on radio pulses thanks to a smart trigger and sampling the data at 200 MS.s^{-1} on 4 channels of 12 bit ADC. A Central Radio Station (CRS) will receive the data of each radio detection station through a wireless link, and will be connected to the central Auger campus by the mean of another wireless link.

Calculations of the expected event rate for AERA have been performed on the basis of LOPES data [14], CODALEMA data [15] and REAS2 simulations [16]. The expected rate is obtained by multiplying the effective AERA area with the cosmic ray flux derived from the spectrum obtained by Auger [9]. The expected number of events per year is depicted on Fig. 6, which shows some differences in the threshold region, where large uncertainties come from the extrapolation of Auger flux spectrum to lower energies. With a conservative approach, the lower energy threshold for AERA is estimated to $10^{17.2}$ eV, and roughly 5000 events per year are expected to be measured, $\simeq 1000$ being above 10^{18} eV.

By itself, AERA will provide worldwide the only possibility to study in details the radio signals emitted by the air showers. Co-located with AMIGA and HEAT, it will be part of a super-hybrid cosmic ray detector which should greatly contribute to the study of the galactic/extragalactic transition region of the cosmic ray energy spectrum.

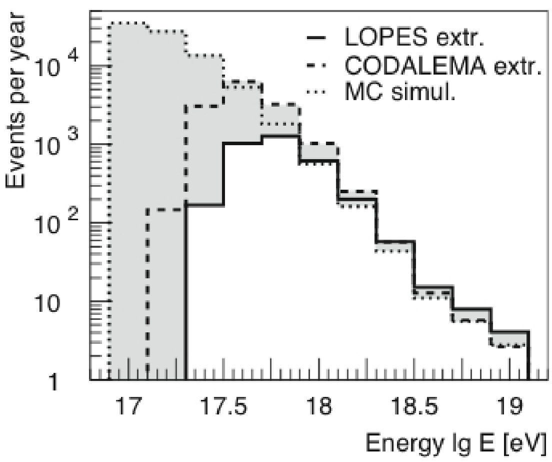

Figure 6: Expected number of event per year, based on extraoplations from CODALEMA and LOPES data and simulations with the REAS2 radio emission code.

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