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Overview of radio detection of cosmic ray air showers in the MHz range, and prospects for a large scale experiment

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Abstract. Since its revival in the last decade, radio detection of cosmic ray air showers has made tremendous progress. Today, several experiments are routinely detecting radio signals associated with air showers. Large cosmic ray observatories such as the Pierre Auger Observatory are also pursuing radio detection activities.

As an introduction, in this article we will summarize the main results from the first generation of radio detection experiments: LOPES and CODALEMA. Then, we will show which questions concerning the radio emission mechanisms can be answered from larger-scale experiments like the Auger Engineering Radio Array (AERA), which is a 20 km^2 antenna array under construction close to other enhancement devices at the Pierre Auger Observatory.

1 Introduction

radio detection of atmospheric cosmic ray air showers has made significant progress in the last few years. The story began 40 years ago with the first detection of radio signals associated with cosmic ray air showers was published (Jelley, 1965).

However, due to technical limitations at that time, radio-detection projects faded out until the last decade, when several small sized experiments showed that radio detection is now technically feasible. New projects under construction include a 10 to 20 km^2 array at the Pierre Auger Observatory, AERA.

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2 Radio emission mechanism

From the beginning of the radio detection adventure, there were controversial discussions on the emission mechanisms. First, coherent emission was proposed (Askaryan, 1962). Askaryan considered radio emission in presence of a charge excess, due to annihilation of secondary positrons during the air shower development. In addition, an alternative scenario based on the charge separation, induced during the shower development by the geomagnetic field, was proposed (Kahn and Lerche, 1965). Quite early, the latter model was already favoured by experimental observations. But since the experiments came to a stop, the theoretical investigations of these effects also ceased. Only recently, updated versions of the geomagnetic emission mechanism have been developed, either based on a microscopic model, summing the contributions due to the acceleration of each particle during the shower evolution (Huege and Falcke, 2005; Huege et al., 2007) or by a macroscopic description of the charge evolution in the shower (Werner and Scholten, 2008; de Vries et al., 2010).

3 Small size experiments

In recent years, the progress made on digital electronics has facilitated a rebirth of radio detection. Since 2004, radio detection is conducted at the KASCADE site using LOFAR (LOFAR) prototype antennas, which became the LOPES experiment (LOPES; Schroeder et al., 2011). At the Nançay observatory, similar activities started, becoming the CODALEMA experiment (Codalema). Both experiments published their first radio signals in 2005 (Falcke et al., 2005; Ardouin et al., 2005), and are still taking data and evolving.

These experiments have proven the feasibility of radio detection for primary particles with an energy above 10^{16} eV and are now improving their instruments. LOPES has been

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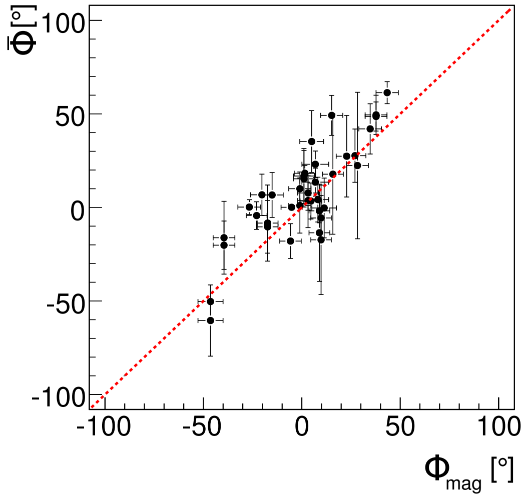

Fig. 1. Measured polarization angle ϕ_{mag} vs calculated polarization angle for a pure geomagnetic model ϕ, the dashed line being $\phi_{\text{mag}} = \phi$. This figure shows that the recorded data are compatible with a geomagnetic mechanism.

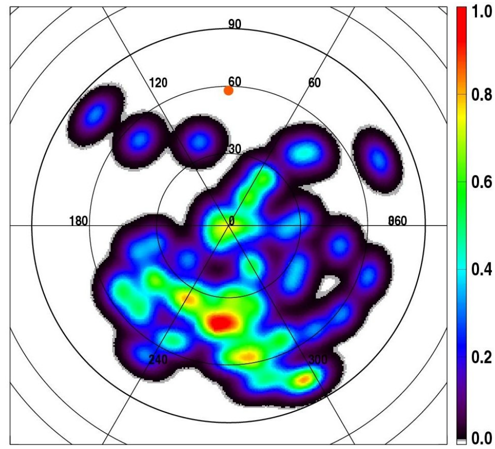

Fig. 2. Angular distribution of events recorded by the CLF setup. The geomagnetic field direction in Malargüe is marked with the red dot.

reconfigured recently and now includes measurements with tripole antennas in order to measure the full electric field vector (Huege et al., 2011). At CODALEMA, new developments include research and development (R&D) on optimizing the antenna. The low-noise environment at Nançay also provides the opportunity to perform self-triggering tests (Ravel et al., 2011).

Both experiments have studied the influence of several parameters on the radio signal and have shown that :

– the amplitude of the radio signal scales linearly with the primary CR energy;

– the amplitude of the radio signal drops exponentially with the distance to the shower axis; and

– the amplitude of the radio signal depends on the angle between the shower axis and the direction of the geomagnetic field;

These results prove the feasibility of radio detection with modern instrumentation. Consequently, new projects are starting such as within Icecube / Icetop (Boeser, 2011), or in Tian Shan using a radio astronomy antenna array (Martineau-Huynh et al., 2011). Unfortunately, small experiments like LOPES and CODALEMA run out of statistics above 10^{18} eV, making larger experiments necessary to improve statistics at high energies.

4 Large scale experiment at Auger

The Pierre Auger Observatory southern site (Auger Coll.; Caruso et al., 2011), located in Argentina, is the largest cosmic ray observatory worldwide. Ultra-high energy cosmic rays are measured in an environment with little human activity, thus this is a natural location for a large-scale radio-detection experiment. Since 2006, radio detection tests at Auger were conducted with small setups close to existing infrastructure, the balloon launching station (BLS) and the central laser facility (CLF).

At the BLS, there is an externally triggered test-setup. Among all recorded events, 494 were in coincidence with the surface detector in 2007–2008. Of these events, 40 could be reconstructed with an arrival direction within 20° of that determined by the surface detector. In the case of a purely geomagnetic emission mechanism, the signal should be linearly polarized in the direction given by the cross product of the shower axis vector and the magnetic field. The predicted polarization angle (ϕ_{mag}) is compared with the average polarization angle in the signal region ($\bar{\phi}$) in Fig. 1. It clearly shows that the recorded data are – to first order – consistent with a geomagnetic emission mechanism (Schoorlemmer et al., 2011).

At the CLF, self-triggering tests have been conducted and 65 recorded events were associated with cosmic ray events. The setup has proven the possibility of self-triggered radio measurements. As in the BLS setup,the recorded events are distributed with an incoming direction mainly opposed to the geomagnetic field, which is consistent with a geomagnetic emission mechanism as shown by Fig. 2 (Revenu et al., 2011)

The BLS also provides meteorological instrumentation, including an electric-field meter which can be used for thunderstorm detection. Five events with the highest signal-to-noise ratio have been compared with the environmental electric field. It has been shown that 3 of 5 events have been recorded during thunderstorms. These events are compared with simulations in Fig. 3 which shows that the events recorded during thunderstorms show an amplitude significantly higher than predicted by REAS3 simulations for a

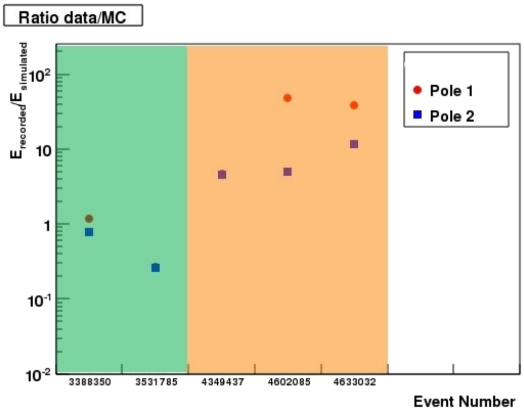

Fig. 3. Ratio between simulated and measured events, for events with an amplitude with signal to noise ratio > 20, events recorded during fair weather (in green) fit the simulation while events recorded during thunderstorm (in orange) have stronger pulses.

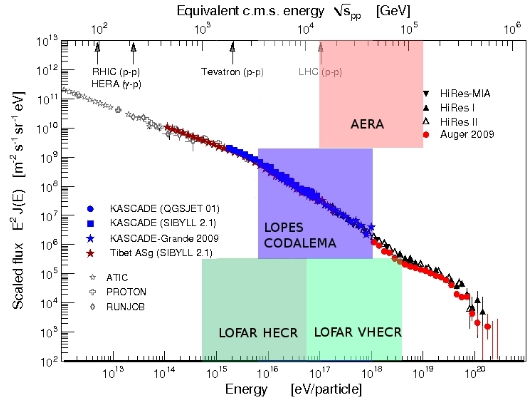

Fig. 4. The measured cosmic ray spectrum. The color background indicates the energy range of various experiments: at the lowest energy LOFAR; at energies above the knee (LOPES, CODALEMA); and at high energies (AERA at the Pierre-Auger observatory).

quiet atmosphere (Ludwig and Huege, 2011a,b). Similar behavior was also observed by the LOPES experiment (Buitink et al., 2007). This amplification is likely related to the acceleration of charged particles within the air shower by the atmospheric electric field, as predicted by CORSIKA and REAS simulations(Buitink et al., 2010).

The tests are based on small arrays of antennas per setup and have still very low statistics, but they proved the possibility to do such detection within the Auger Observatory and gave the necessary input on the design of a larger array.

Such a detector will address the following questions:

– What is the exact radio emission mechanism?
  To answer this question high statistics are necessary. An advanced polarization analysis can be used to discriminate contributions of different emission mechanisms e.g. coherent Cerenkov, charge excess, and geomagnetic.

– Can the radio technique improve cosmic ray measurements, and find the nature of cosmic ray in the transition region ?
  Currently, the best estimate of the primary mass is given by the fluorescence technique, but this technique is effective only 10% of the time due to its limited duty cycle, If radio detection can give a good estimation on the primary mass with a better duty cycle it would be a clear improvement. According to theoritical models, such an estimate is possible by studying the lateral distribution of the radio signal (Huege et al., 2008).

A large scale radio detection experiment should ideally have a common measurement range with current experiments, allowing for cross-checks. Thus it needs to be sensitive around 10^{17} eV. Consequently, the ideal energy range for a large scale experiment corresponds to the red underlayed part of Fig. 4, with sufficient overlap between different experiments.

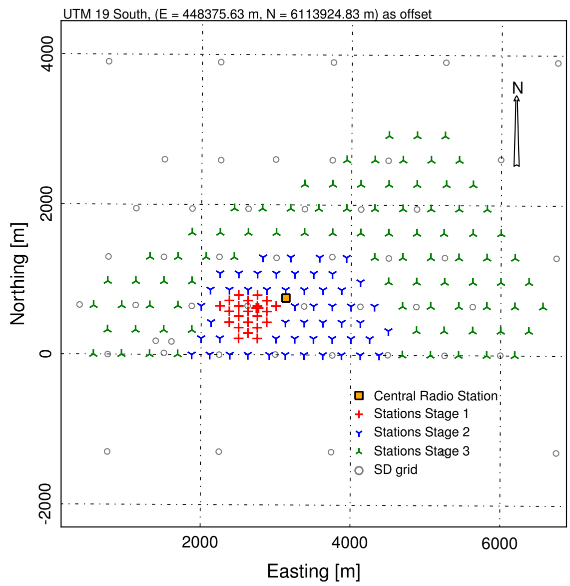

Fig. 5. Layout of AERA array, showing the 3 planned phases. For stage I, the grid size of 150 m; for stage II, the grid size will be 250 m; and for stage III, the grid size will be 350 m

These constraints have guided the design of the **A**uger **E**ngineering **R**adio **A**rray (AERA). It will be a 10 to 20 km^2 array located at the site of the Pierre Auger Observatory. AERA will consist of 161 antennas, deployed in three different grid sizes. The layout of the detector array is shown in Fig. 5. At the time of writing, the first 21 stations are connected and under commissioning.

The full AERA will provide around 3000 events between $0.1 - 10$ EeV per year. Moreover, the AERA site is built in a region where several other Auger enhancements are operating. AMIGA includes an infill array of surface detectors which will reduce the energy threshold down to $10^{17.2}$ eV, and additional buried muon detectors also improve the measurement's quality. This extended region is located close to the Coihueco fluorescence detector, which has also been upgraded with a low energy extension: HEAT (Meurer et al., 2011). The reduced trigger threshold provided by the infill array will guarantee that most of the events recorded by AERA are also recorded by the surface array.

5 Conclusions

Small arrays have demonstrated the feasibility of radio detection. This technique is now in transition between R&D and physics. Among the new projects, we have focused on the Auger Engineering Radio Array, which is under construction and recording its first commissioning data. When completed, AERA will provide 3000 radio air shower events per year. As a first step, it is being used to investigate radio-emission mechanisms, and in a second step it will be used to explore cosmic ray physics around the ankle.

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