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Toward the autonomous radio-detection of ultra high energy cosmic rays with CODALEMA

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ABSTRACT

The CODALEMA experiment aims to study the radio-detection of Ultra High Energy Cosmic Rays in the energy range of 10^{17} eV. Spread over an area of 0.25 km^2, the original device hosted at Nançay (France) has mainly benefited of an array of short dipoles, connected by cables up to a centralized acquisition room. Since 2010, a major evolution has been initiated to add 60 autonomous radio-detection stations, covering a surface of 1.5 km^2. This enlarged configuration should help refine the studies and serve as a bench test for the mastery of autonomous detection. The main characteristics of this new mode of operation is presented in the light of recent results obtained by the original CODALEMA setup.

1. Introduction

Despite intense experimental efforts in the last decades, the origin and nature of Ultra High Energy Cosmic Rays (UHECR above 10^{19} eV) are not firmly elucidated. Uncertainties remain, in part related to the extremely low radiation flux (around 1 particle/century/km^2 at 10^{20} eV) and in part to the incomplete experimental measurements [1]. One of the today considered tracks of progress consists to supplement the conventional measures of the Extensive Air Showers (EAS) by the radio method which based on the detection of the radio transient signal induced by the movement of secondary charged particles in the shower. This halfway idea, between the approach of particles physics and astronomy, emerged first in the early 60s [2], was abandoned in the mid-70s [3] then re-launched in early 2000. At that time, several small-scale experiments (as Lopes [4] and CODALEMA [5]), supported by renewed theoretical foundations [6–9] have tried to remake significant advances in this field. In recent years, this method comes to the forefront of the activities and several new experimental variations appeared [10] which greatly expands the prospects for the study of EAS using the radio-detection.

The present article reports on the contributions of the experiment CODALEMA to this effort in term of latest results and technical developments.

2. The original CODALEMA experiment

2.1. Detection method

The original experimental setup CODALEMA (sensors wired to the central acquisition room) consists mainly of two arrays of detectors (Fig. 1): an antenna array of 24 short active dipoles (including 3 in a N-S polarization) distributed on cross of 600×500 m; a particle detector array of 17 plastic scintillators located on a grid of 340×340 m (full descriptions of instrument and analysis methods can be found in [11,12]). The trigger of the system is provided by the coincident detection of the five central particles detectors leading to a detection threshold in energy around 5×10^{15} eV.

The off-line analysis is conducted independently for both arrays. The radio transients are searched in the antenna waveform through a 23–83 MHz frequency bandwidth were the maximum electric field value and the arrival time are extracted. If more than 3 radio transients are detected in coincidence, the arrival direction of the electric field is reconstructed by considering a planar wave front. Assuming a decrease of the electric field profile of the form: $E_0 \exp(-d/d_0)$, four new observables can be introduced: The radio-estimator of the energy of the primary inferred the electric field magnitude at the shower core, E_0 [13], the slope

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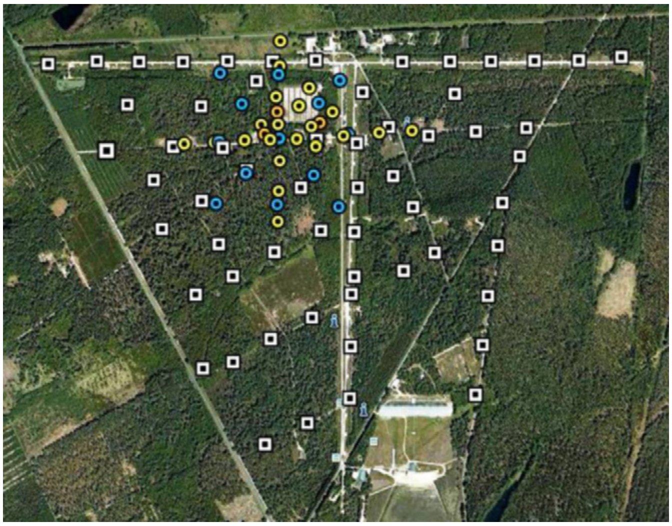

Fig. 1. $1.5 \times 1.5\ \mathrm{km}^2$ aerial view of the new foreseen CODALEMA setup. The white squares show the locations of the autonomous stations of the new multi-scale array in deployment. Related to original system, the plastic scintillators are depicted with blue circles when yellow and orange circles represent dipole antennas oriented, respectively, in the E–W and N–S directions; the gray square surface is the Decameter array. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

parameter of the electric field, d_0, and the impact location of the shower at the ground (x_0, y_0).

Meanwhile, the arrival direction of the particle front (assumed planar) is estimated from the relative arrival time in each particle detectors and an analytical NKG lateral distribution [14] is adjusted on the measured particle densities in the shower frame. If the shower core position stands inside the particle detector array, the event is referred to as internal and the fitted NKG distribution is used to estimate the energy of the primary using the constant intensity cut (CIC) method [15].

A coincidence below 100 ns in time and 20° in arrival direction with the event "particles" labels the radio event as an EAS.

Finally, for the antennas, the error in arrival direction is estimated below the degree of angle, and the error on the electric field resolution is of the order of the galactic signal [16,17]. For the particles shower, an energy resolution of the order of 30% at 10^{17} eV is estimated.

2.2. Results

Two of the most appealing observations, obtained with the original CODALEMA setup, have found their explanation in the mechanisms of radio emission.

On one hand, depending of the polarization and polarity of the detected electric field [18,19], the distribution of the arrival directions reveals a strong asymmetry in the detection of the radio events (Fig. 2). This pattern is reproduced assuming, at first order, an emission process proportional to the Lorentz force $\mathbf{F} = q\mathbf{v} \times \mathbf{B}$, with $\mathbf{v}$ the arrival direction vector of the shower and $\mathbf{B}$ the geomagnetic vector. The present theoretical understanding attributes a dominant contribution to this geomagnetic effect.

The second was deduced from the experimental observation of shower core positions. As shown on Fig. 3, the radio-shower core positions are, on average, sharply shifted toward the East direction, when compared to those obtained from the scintillator array. This marked difference was first mentioned in [20], but it is only very recently that this observation found a very likely interpretation as a convincing indication of a second order emission mechanism due to the charge excess [21].

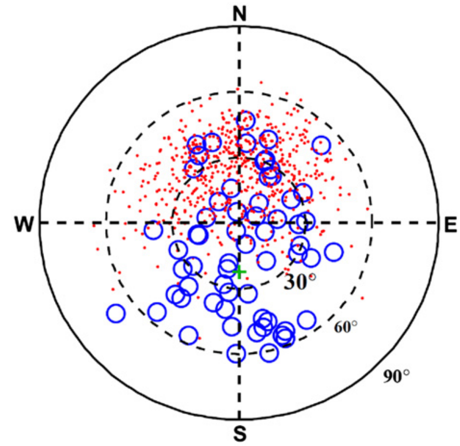

Fig. 2. Distribution of the arrival directions and opposite polarities of the radio signal (red points and blue circles) observed in East-West polarization at Nançay. The green cross indicates the geomagnetic vector. The concentric dashed circles indicate zenith angles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

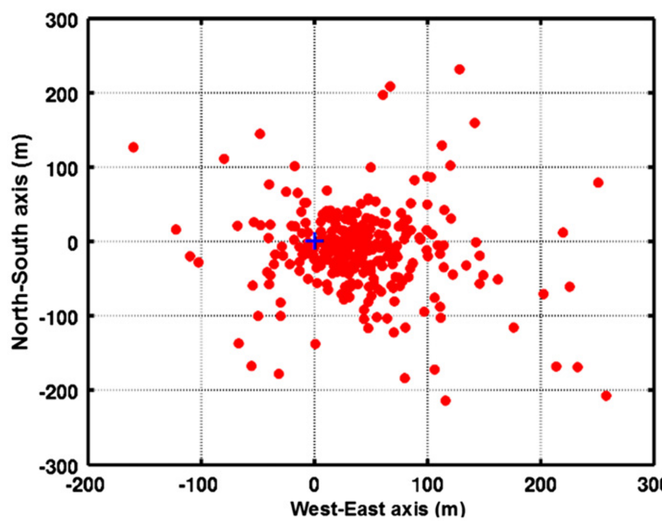

Fig. 3. Distribution of the radio shower footprints for the particles footprints re-shifted towards the origin.

Despite these breakthroughs, some experimental facts remain without satisfactory explanations. For example, the slope parameter d_0 of the lateral electric field distribution is usually marked as one of the keys for the identification of the primary [22]. About 15% of the events exhibit a flat behavior ($d_0 > 500$ m). The systematic analysis has not revealed, nor a perfectible detection, or that the near environment of the sensors would be more the main cause of signal interference by trees, buildings [17,23]. It is suspected that the exponential shape, although predicted in many theoretical developments, do not include yet full details at the smaller impact parameters [24–26].

Analogous disagreements in the interpretations are also encountered in the studies of the curvature of the radio wave which is usually linked to the same topic.

3. The new array of autonomous antenna of CODALEMA

3.1. Motivations

As suggested in the previous section, a qualitative gain in our understanding requires finer measurements of the electric field,