SOME RECENT RESULTS OF THE CODALEMA EXPERIMENT

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Abstract. Codalema is one of the experiments devoted to the detection of ultra high energy cosmic rays by the radio method. The main objective is to study the features of the radio signal induced by the development in the atmosphere of extensive air showers (EAS) generated by cosmic rays in the energy range of 10^{16}-10^{18} eV. After a brief presentation of the detector features, the main results obtained are reported (emission mechanism, lateral distribution of the electric field, energy calibration, etc.). The first studies of the radio wave front curvature are discussed as new preliminary results.

Keywords: UHECR, radiodetection, antennas, radio emission mechanism, EAS

1 Introduction

A century after the discovery of cosmic rays, several fundamental issues related to the nature and the origin of ultra high energy cosmic rays (UHECR) remain unanswered, despite intensive experimental efforts. The main difficulty opposing the progress is due to the extremely low flux of UHECR (1 particle/km^2/century at 10^{20} eV) and the present performances of particle detectors arrays and fluorescence telescopes (Abraham et al. 2010; Abbasi et al. 2010). In the recent decade, the measurement of the radio counterparty of EAS becomes a promising technique. Many scientific collaborations like CODALEMA in France (Ardouin et al. 2009) and LOPES in Germany (Apel et al. 2010) have demonstrated the feasibility of this method to deduce the EAS features. The potentialities of the radiodetection resides in several avantages, among them may be mentioned: the operating duty cycle close to 100%, the sensitivity to the shower longitudinal development in the atmosphere and the mechanical robustness, the simplicity and the low cost of the antennas. The CODALEMA experiment is installed at the radio observatory site (Nançay, 47.3°N, 2.1°E and 137 m above sea level). Its main goal is to improve the pioneer experimental results (Allan 1971), taking avantage of ultrafast electronic devices and a quiet radio environment from anthropic transmitters in the detection bandwidth (Ardouin et al. 2006). From the phenomenological point of view, CODALEMA has made progress in the understanding of radio signal origin, showing that the geomagnetic field is the main actor in radio signal emission via the geomagnetic mechanism (Ardouin et al. 2009), and showing recently the contribution of a second emission mechanism due to the shower negative charge excess (Marin 2011). This contribution reports on the last results of the experiment CODALEMA with updated data set, recalling the observations of the north-south asymmetry and of the energy correlation. Finally the reconstruction method of the radio wavefront radius of curvature is presented.

2 Experimental situation

The CODALEMA experiment is made of two main arrays of detectors. The first array is built with 24 short active dipoles antennas distributed on a cross geometry with dimensions 400 m by 600 m. This apparatus is used to study the EAS radio counterpart. The dipole antenna is made by two radiator arms each 60 cm long at a height of 1.2 m. The antenna design was optimized to reach an almost isotropic pattern. Low noise amplifier (LNA) is used to amplify the electric signal. It is conceived to be sensitive to the radio galactic background and is linear over a wide frequency band from 0.1 MHz up to 230 MHz. The second apparutus is a ground-based particle detector array formed by 17 plastic scintillators placed on a square with 340 m side. It measures the primary particle energy and provides the trigger signal to the other detector arrays. The entire acquisition system (DAQ) is trigged by the passage of secondary particles in coincidence through each of the five central scintillators.

3 A North-South asymmetry: a geomagnetic effect signature in the production of the radio signal

CODALEMA is the first experience which has reported a large and stable assymetry in counting rates between showers coming from north and south (Ardouin et al. 2009; Ravel 2010). This asymmetry has been interpreted as a signature of the geomagnetic field effect in the radio signal emission process. The local geomagnetic field $\vec{B}$ is the main cause of this assymmetry through the action of Lorentz force on the secondary charged particles via the $\vec{v} \wedge \vec{B}$ term. We find that among the 2030 events detected in coincidences with the two arrays: 1708 events coming from the north and 322 coming from the south (see Fig. 1, left). The respective ratio equal to 0.188 is consistent with the value of 0.17 obtained with a previous statistic used in (Ardouin et al. 2009). A pure statistical effect is excluded with 15 σ. One can enhance here on the fact that this asymmetry is stable over time and with different data samples.
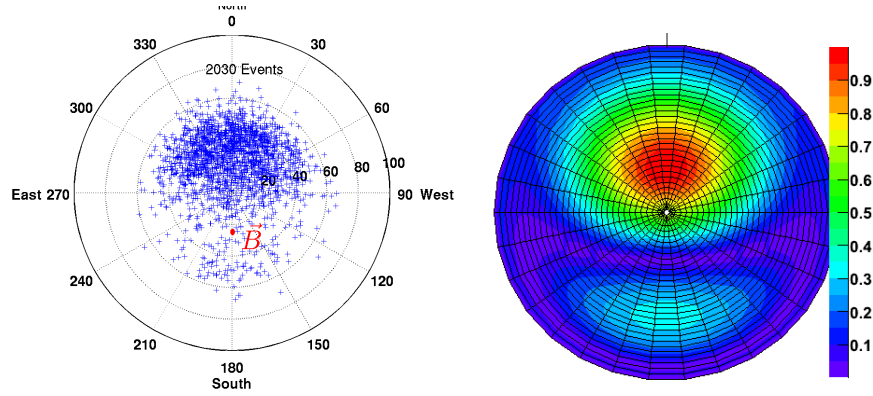

Fig. 1. Left: A plot sky showed the arrival directions distribution of detected EAS events. The red dot indicates the local geomagnetic field ($\theta = 27°$, $\phi = 0°$). **Right:** Sky map of the geomagnetic model theoritical prediction based on the projection of the product $\vec{v} \wedge \vec{B}$ on the East-West direction multiplied by the trigger coverage map. The colormap is normalized to 1.

4 Energy calibration of the Codalema antenna array

The energy of the primary particle E_p is one of the most important parameters for studying EAS. To avoid the use of the particles detectors array, the radio technique must demonstrate its ability to estimate the primary particle energy with the information given by the radio signal alone. In this perspective, a study of the correlation between the shower energy and the electric field created at the shower axis E_0 is the natural way to determine the energy calibration response of the antenna array. In this goal, after sampling the particules density at ground a NKG lateral distribution is deduced to measure the total number of charged paticles N_e (mostly electrons and positrons) in the shower front. The energy E_p is deduced from the constant intensity cuts method (CIC). The procedure gives a relative error equal to 30%. The electric field E_0 is determined by the lateral distribution function (LDF). The Allan formula has been used to fit the radio LDF with an exponential law (Fig. 2) following this formula:

$$E_i = E_0 \exp\left(-\frac{\sqrt{(x_i - x_c)^2 + (y_i - y_c)^2 - ((x_i - x_c)\cos(\phi)\sin(\theta) + (y_i - y_c)\sin(\phi)\sin(\theta))^2}}{d_0}\right) ,$$

where, θ and ϕ are respectivly zenithal and azimuthal angles reconstructed by a planar fit. This fit has four free parameters E_0, the LDF decay distance d_0 and the radio-shower core coordinates on the ground (x_c, y_c), providing the antennas coordinates (x_i, y_i) and the radio filtered pulse amplitude E_i for each antennas. The error on E_0 has been estimated through a Monte Carlo analysis. It consist of repeating the LDF fit with E_i values, randomly selected from gaussian probability density function centred on the measured values E_i and a gaussian standard deviation σ_i took as the RMS of measured radio noise on the antenna. This Monte Carlo method enables to explore the entire phase space and thus to estimate the E_0 error on a by event basis. At the end of the procedure a statistical error less than 22 % is deduced. A linear regression is then used to deduce the

correlation coefficients in the (E_p, E_0) plan, assuming some hypothesis: (i) The two variables are represented on a linear scale. (ii) Gaussian errors are used on both observables. (iii) The two observables E_p and E_0 are assumed to be independent, to cancel the nonlinear covariance term. Results of this procedure is presented on Fig. 3.
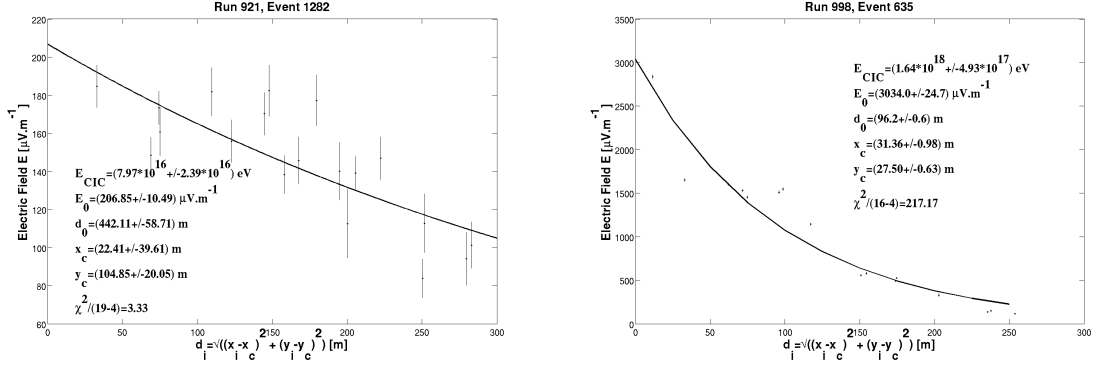

Fig. 2. Radio lateral distributions reconstructed from antenna signals. The full line show the result of an exponential law fit (Allan formula). **Left:** We show the lateral distribution of an event detected by 19 antennas. The primary particle energy is estimated to $E_p = 7.97 \ 10^{16}$ eV. Error bars correspond to the radio galactic background. In this example, the signal amplitudes are close to the noise level. **Right:** We show the lateral distribution of an other event ,detected by 16 antennas, with larger energy $E_p = 1.64 \ 10^{18}$ eV. In this case, error bars are small compared to signals.
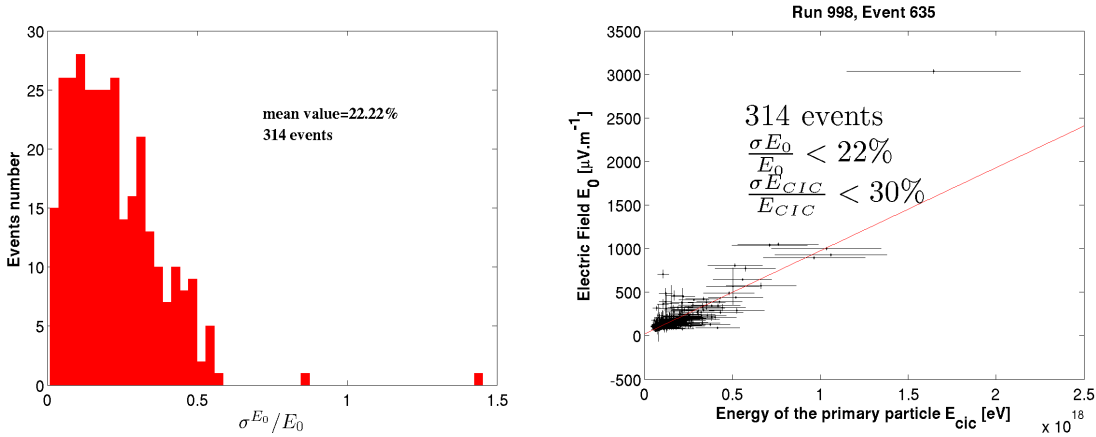

Fig. 3. Left: E_0 statistical errors $\frac{\sigma_{E_0}}{E_0}$ histogram of the LDF fit method. **Right:** Fit of the correlation between the primary particle energy E_p and the electric field at the shower axis E_0. This study strongly depends on both E_p and E_0 errors.

It shows that the electric field created at the shower axis E_0 is clearly correlated with the primary particle energy E_p following the relationship $E_0 = a \, E_p + b$. This correlation shows that the radio signal emitted by EAS seems coherent. An energy calibration relationship can be deduced, with the following form $E_R = (1/a) \, E_0 - (b/a)$ which allows to have a radio estimation E_R of the energy through the radio method once we have measured E_0. It is conceivable that for a future autonomous antennas array, we can measure the primary particle energy only with a pure radio observable.

5 Radius of curvature reconstruction with CODALEMA

Because theoritical developments indicate that the radio signal shape depends on the shower longitudinal development, it is waited that the wavefront shape provides information on the nature of the primary particle. In the first step of the CODALEMA's analysis, the wavefront was assimilated to a plan determined by a simple planar fit using the arrival times and locations of each tagged antenna. More detailed studies indicates today (Fig. 4.

Left) that the measured wavefront differs slightly from the plan in most cases and that it exhibits a curved geometry, favoring the idea of a privileged center for the radio emission during the shower development (Rebai 2010; Schroder 2011). To take into account of these experimental observations, one of the simplest hypothesis is to assume that the maximum of the filtered pulse is linked to a radio signal emission center located along the shower axis. This leads to define a curvature radius R_c. Several modelisations suggest that this observable could then be related to the shower maximum, X_{max}, which is directly correlated to the UHECR chemical composition. This possibility has been investigated using the present data. Our fitting method is based on the fit of the residue between the real wavefront determined by arrivals times distribution and the planar wavefront. A parabolic dependence is used to account for the difference. Results of the calculations are presented in Fig. 4. The distribution of the R_c presents a maximum at 4 km in global aggrement with the waited characteristic altitude of the emission maximum. However, the tail of the distribution extends up to 20 km. A present time, the physical interpretation of this long tail is not well understood. This may be due both to a poor estimate of arrival time and to a biased assessment of the estimated error on its time measurement, an arrival time error of 10 ns is used. Improvement of these points are underway.
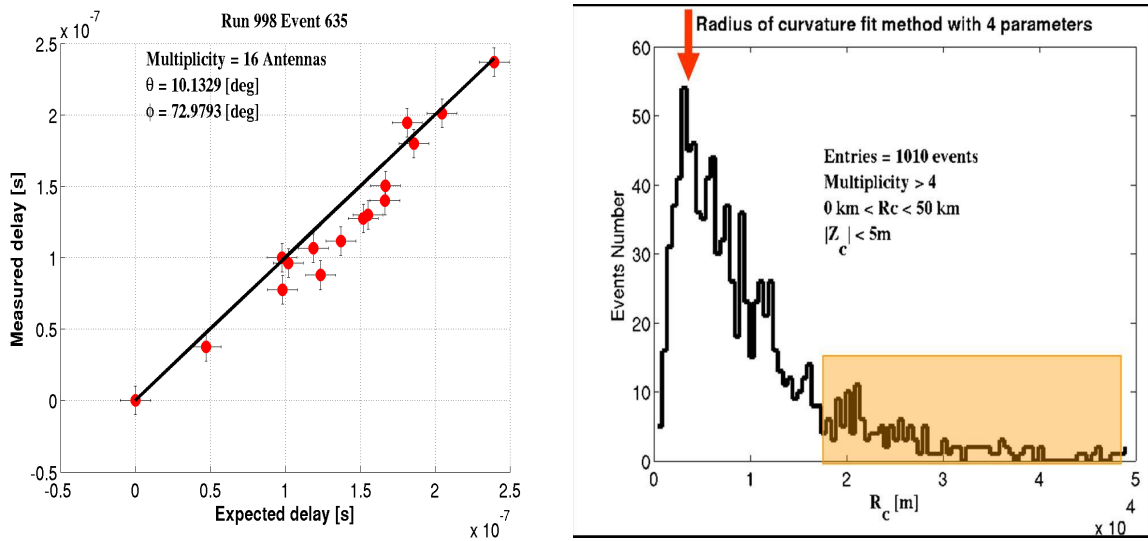

Fig. 4. Left: Expected delay versus measured delay. The black line presents the plane wave fit, Despite the 10 ns error bars on both axes, many points are located far from the line, which shows that the wavefront differs from a plane. **Right:** The histogram of the radius of curvature R_c distribution for 1010 selected events. The distribution maximum is located at 4 km.

6   Conclusions

Codalema is installed in a radio quiet environment. This advantage has enabled very high accuracy radio signal measurements and several progress in the understanding of the radio emission mechanisms like the geomagnetic field effect or the energy calibration method. A method for the wavefront radius of curvature reconstruction has been presented. The first analysis of the radius of curvature presented shows extremely interesting perspectives with the aim of determining the cosmic rays nature. The deduced location of the emission point are in a satisfactory agreement (for radii less than 10 km) with the waited values, but for the larger curvatures the values remain poorly understood. Unfortunately the low timing accuracy (<10 ns) may limit the analysis with current data. The current array extension which uses standalone radio stations to reach a larger array (1.5 km²) will increased the available statistic and improve our interpretations.

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