Characteristics of radioelectric fields from air showers induced by UHECR measured with CODALEMA

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D.Ardouin [a] and the CODALEMA collaboration [a, b]

***Abstract*—The CODALEMA detection array, triggered by 4 particle detectors, has been used for the detection of high energy cosmic rays at an energy threshold equivalent to 5x 10^{16} eV. Radio measurements of electric field profiles are presented for the first time on an event-by-event basis. Amplitude and slope variations with impact parameters and zenith angles of the air showers have been observed over large distances due to the large acceptance of the detection array.**

I. General outlines of the CODALEMA experiment

The CODALEMA (COsmic ray Detection Array with Logarithmic Electro-Magnetic Antennas) experiment, located at the Nançay radio observatory [1] , has been designed to study the radio emission generated by ultra high energy cosmic rays (UHECR) with an energy threshold equivalent to 5x 10^{16} eV. In order to investigate the electric field spread and the impact parameter dependencies of field amplitudes, long baselines (608 m long in the East-West direction, 120 m for the South-North direction) have been equipped [2] with 11 log-periodic antennas (Fig. 1).Four coincident particle detectors, complement this set-up. All the antennas are band-pass filtered (24-82 MHz)and linked, after radio frequency (RF) signal wide band amplification (35 dB), to digital oscilloscopes (500 MHz sampling frequency, 10 μs recording time). After offline analysis using a 37-70 MHz digital filter, short transient signals appear with a time ordering reflecting the wavefront propagation times. The maximum voltage is then searched for in a 2 μs wide time window correlated to the trigger time. The average noise and its standard deviation are calculated, for each antenna and each event, in a 7.2 μs wide time-window out of the signal one [3]. When at least, three antennas are flagged, a triangulation procedure calculates the arrival direction of the radio wave using a plane wavefront assumption.

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Each of the 4 particle detector station consists of a 2.3 m^2 double layer of scintillator. The whole experiment is triggered by a four-fold coincidence between these particle detectors.

II. Identification of cosmic-rays

Our characterization of extended air-showers (EAS) radio signals is based on a double selection of arrival time and direction differences issued from the antennas and the particle detectors. The radio wave arrival time, at a given reference location, is first extracted from an off-line triangulation of multi-antenna events. The corresponding time is then compared with the particle front time supplied by the scintillator signals. The time difference distribution obtained by this procedure is shown in Fig. 2. The observation of a sharp peak, a few tens of nanoseconds wide, shows an unambiguous correlation between some radio events and particle triggers. The flat distribution which is visible on both sides of the coincidence peak corresponds to accidental radio transients which occur in the 2 μs coincidence window. These events mostly originate from directions close to the horizon associated with human activities or distant storms. Being not correlated with particles associated with air showers, they present a uniform arrival time distribution. We select the EAS candidate events by setting a time difference selection ($\Delta t < 100$ ns) between the two detection systems.

In order to eliminate the remaining chance coincidences in this selected time window , we take advantage of the large angular difference between the corresponding reconstructed arrival directions as determined from particle detectors and antennas (grey histograms - Fig. 3) for these chance events. On the contrary, events resulting from the above time cut present a small angular direction difference (black histograms - Fig. 3). An angular cutoff ($\Delta\theta < 15°$) of this difference is thus set to characterize true EAS. In the next section, we will present an analysis of events obtained from a set of 2314 hours data-taking from which 1151 coincidences (with at least 3-antennas tagged) were observed in the 2 μs trigger coincidence time-window. From the above time cut and angular cutoff, 112 true EAS and 52 chance coincidence events were determined.

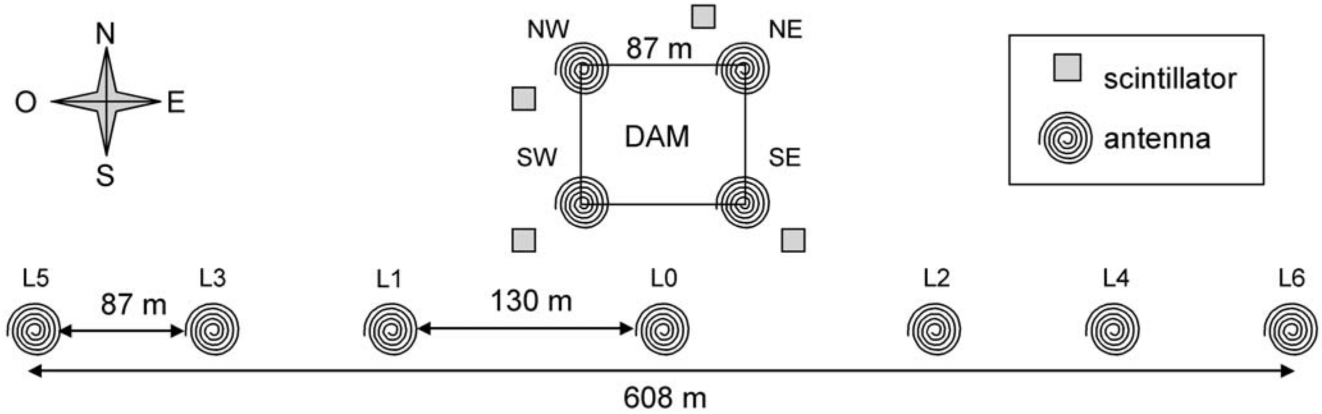

Figure 1. *Layout of the CODALEMA set-up*

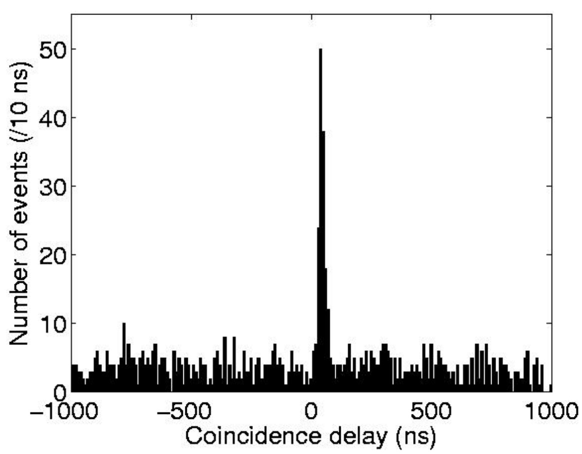

Figure 2. *Distribution of time delays between the radio plane front and the particle plane front.*

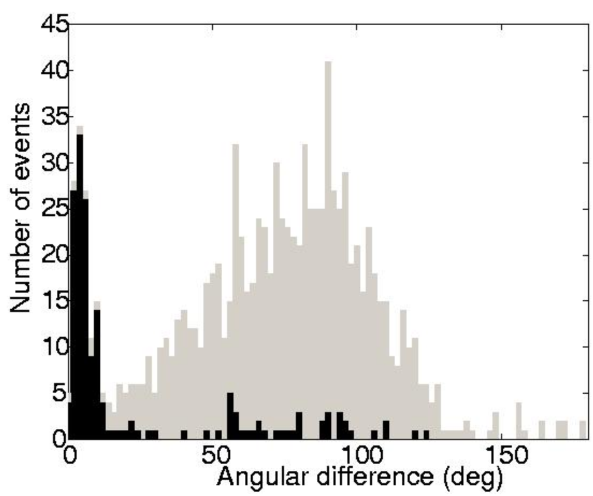

Figure 3. *Distribution of relative angles between particles and radio-pulses without time cut (grey histogram) and with a time-cut around the coincident peak of the time difference distribution (black histogram).*

The resulting counting rate of EAS events with a radio signal counterpart is thus close to one per-day. The corresponding signal directions reconstructed as explained above, are displayed in Fig.4.

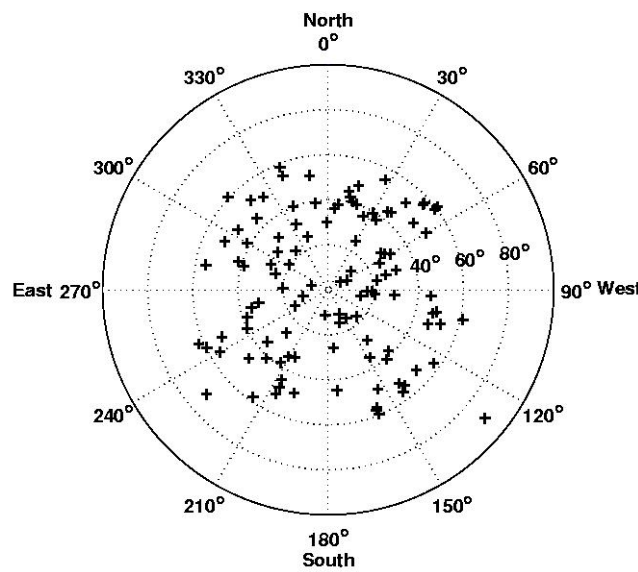

Figure 4. *Sky map of the reconstructed directions of 112 air-showers coincidences (with at least 3 antennas tagged). Dotted internal large circles refer to indicated values of zenith angles up to the horizon while the external numbers stand for azimuthal angle values.*

I. EAS ELECTRIC FIELD CHARACTERISTICS

A. Field profiles

Each tagged antenna of the CODALEMA array provides a measured voltage associated with its specific location with respect to the shower impact. Thus, depending on the antenna multiplicity, a sampling of the electric field amplitude over the area covered by the array is possible on an event-by-event basis. An example of measured electric field distributions along the East-West antenna axis for an EAS event is shown in Fig. 5 (squares), together with a chance event (triangles). The chance event belongs to the set of accidental coincidences described in the previous section while circles indicate the threshold level of detection [3]. These distributions demonstrate that the topologies are clearly distinct between EAS and RFI events. Contrary to chance events where a quasi uniform amplitude is observed, the EAS event falling in the vicinity of the array shows a large field amplitude variation with the position of the antenna along the line of detection. This may constitute a criteria of selection of EAS from others fortuitous RF sources.

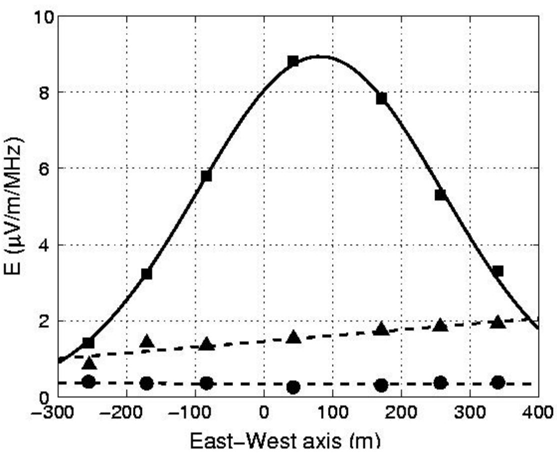

Figure 5. *Electric field variations recorded on different antennas along the East-West line for an EAS event (squares, full line) and an anthropic transient (triangles, dashed line). Circles-dashed line indicates the averaged threshold level. Lines between data points are just a guide for the eye.*

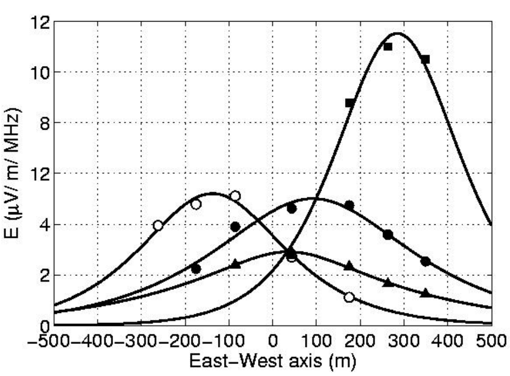

Figure 6. *Electric field variations recorded on the different antennas in the East-West direction for four EAS events (squares) with antenna multiplicity ≥ 4. The full lines result from the exponential fits of Fig. 5, discussed in the text.*

Other typical field patterns measured for 4 radio EAS events (out of 64 with antenna multiplicity > 3) along the East-West axis are presented in Fig. 6. The characteristic bell-shaped pattern which is observed indeed appears as a genuine radio signature of EAS and may be used by itself in a stand-alone triggering system.

The (amplitude and slope) differences from one event to the other observed for these characteristic patterns result from several geometrical and physical properties of the EAS such as its direction or core impact, energy or depth respectively. In order to disentangle their respective role , it is thus preferable to reformulate the lateral dependence of the electric field profile in the shower-based coordinate system deduced from the reconstructed arrival direction. This is presented in Fig. 7 for the same set of events as those shown in Fig. 6. In this representation, data are well reproduced by a 4-parameters fit (full lines) consisting of the E-W and S-N coordinates of the impact point on the ground, plus the amplitude E_0 and slope d_0 of an exponential profile description : . The latter corresponds to the radio data fit earlier discussed by Allan [4]. From our set of fitted widths (parameter d_0 above) , the mean extension of the field is found to be around 250 m FWHM, to be compared with a 100 m estimated value from the earlier work of Allan. This result provides an interesting determination for the spacing design of a large radio array.

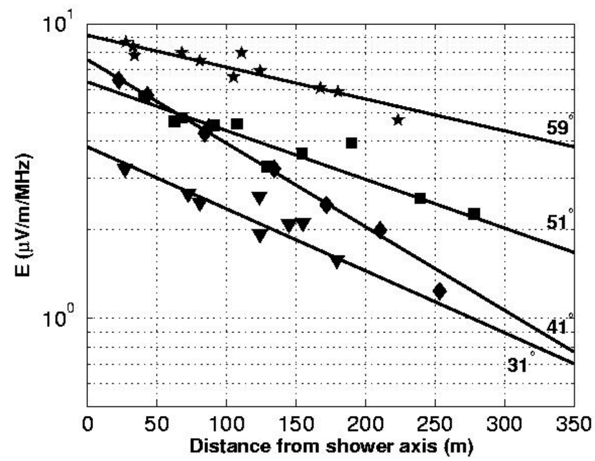

Figure 7. *Electric field profiles on a logarithmic scale for a set of radio EAS events recorded on CODALEMA. The measured amplitude in µV/m/MHz is plotted versus the distance from the antenna to the shower axis (in meters). The associated reconstructed zenith angle is indicated on each plot.*

The present analysis and results thus demonstrate the sensitivity of the radio array to the overall development of an EAS as well as its consistent description by an exponential law over several hundreds meters. More generally, this shows the feasibility of long distance and inclined shower measurements.

Various amplitudes and slopes of the field are observed in

Fig. 7. A dependence of the electric field amplitude on the energy and the nature of the primary particle is clearly expected. In the same way, the slope of the exponential fit should vary with the shower zenith angle and the shower longitudinal development related to various possible charge generation mechanisms. To our knowledge, no such simple correlations have been measured yet. Our preliminary measurements thus reveal very promising features for a more thorough characterization of the radio events associated with EAS.

B. Frequency dependence

Using the Fourier transform of the stronger observed signals from our data sample, the frequency dependence of the electric field spectrum has been also studied on an event-by-event basis. Fig. 8 shows one event (straight crosses) measured on one antenna as a typical example of the general feature observed in the 30-70 MHz frequency range. In addition to a clear separation from the background (slanted crosses), the observed fall-off of the voltage signal with frequency is well accounted for by a power-law : $v \sim K.\nu^{-a}$. The index *a* which can be estimated for each relevant signal is found to vary slightly from one event to the other.

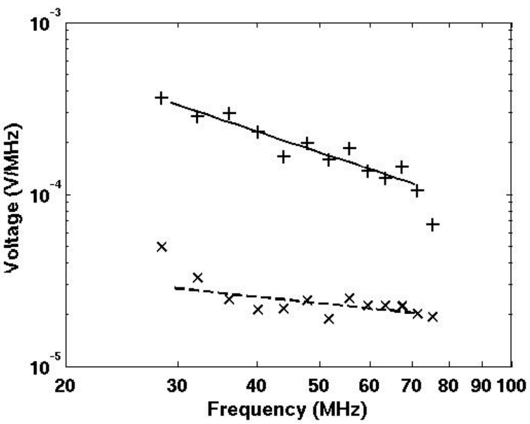

Figure 8. *Voltage frequency spectra of both the signal and the background. Full and dashed lines correspond to least square fits.*

These characteristics are comparable with those expected [4] from the dependences on impact parameter and extension characteristics of the shower associated with the loss of coherence at high frequency. Although the data collected is too sparse to draw any conclusion at that time, these observations open very interesting perspectives to characterize the radio emission associated with EAS and bring specific and complementary information to ground detector data.

II. CONCLUSIONS

Although with a limited sample of events resulting from the radio detection of air-showers in the 10^{17} eV energy domain, we have shown, for the first time on an event-by-event basis, the feasibility of electric field characteristics measurements. New and interesting features are observed such as an amplitude variation measured over long distances, the description of the field profile by an exponential law, and a slight radio frequency dependence. The determination of the shower core locations is deduced from the multi-antenna field profiles.

More generally, the large azimuthal acceptance which is clearly observed allows the study of very inclined showers. These appear as unique probes for the detection of ultra high energy events such as showers generated by UHE neutrinos. Through the current evolution and an upgrade of the CODALEMA set-up, more thorough studies with higher statistics will become possible to establish the exact nature of the specific physical correlations detectable by measurements of the radioelectric fields .

REFERENCES

[1] A. Lecacheux, ``The Nançay Decameter Array: a useful step towards giant, new generation radio telescopes for long wavelength radio astronomy", in Radio Astronomy at Long Wavelengths, *AGU monograph*, 119 (2000) 321.

[2] D.Ardouin *et al*, *Astroparticle Physics*, 26 (2006), to be published

[3] D. Ardouin *et al*, *Nuclear. Instruments & Meth*. A 555 (2005) 148.

[4] H.R. Allan, in: *Progress in elementary particle and cosmic ray physics*, ed. by J.G. Wilson and S.A. Wouthuysen (North Holland, 1971) 169.

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