# RADIO DETECTION OF COSMIC RAY AIR SHOWERS WITH CODALEMA 

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#### Abstract

Studies of the radio detection of Extensive Air Showers (EAS) is the goal of the demonstrative experiment CODALEMA. Previous analysis have demonstrated that detection around $5.10^{16} \mathrm{eV}$ was achieved with this set-up. New results allow for the first time to study the topology of the electric field associated to EAS events on a event by event basis.


## 1 Introduction

Large experiments, like Agasa ${ }^{1}$ or Hires ${ }^{2}$, have brought into light difficulties concerning the determination of the origin and energy of the Ultra High Energy Cosmic Rays (UHECR). In a near future, the giant hybrid experiment $\mathrm{PAO}^{3}$ could be in situation to enlighten this problem by furnishing a larger set of events, using both particle and fluorescence detectors.

Beside this, some experiments ${ }^{4,5,6}$ have recently started to detect Extensive Air Showers (EAS), taking advantage of the radio emission associated to their development. Actually, the radio detection was proposed in the 1960's ${ }^{7}$ and gave birth to several experimental investigations ${ }^{8}$ but this effort was quickly abandoned. Thanks to technical improvements, recent results ${ }^{9}, 10$ demonstrate that EAS radio detection is now feasible. Furthermore, advantages of this method ( $100 \%$ duty cycle, low cost of the detector, etc...) make it a promising tool for future detectors. The CODALEMA experiment is a part of this demonstrative effort. Despite measurement of UHECR around $10^{20} \mathrm{eV}$ is the admitted goal of such a method, a proof-principle demonstration at this energy would suffer of a lack of statistic. This can be avoided by working around $10^{17} \mathrm{eV}$ with a much lower signal amplitude, specially far from the shower core. Nevertheless, this signal should remain measurable ${ }^{10}$. Considering a vertical shower falling upon the detector, the predicted transient should reach $150 \mu \mathrm{~V} / \mathrm{m}$ with a 10 ns FWHM duration ${ }^{4,6}$. Transposed in the frequency domain, the corresponding pulse spectrum should extend from 1 to 100 MHz . Thus, a broad frequency bandwidth antenna should permit to recover the original pulse shape, allowing to determine the energy


Figure 1: Display of the CODALEMA set-up with a superposed transient EAS event. The squares indicate the location of the particle stations. Each cross corresponds to one antenna and the size and color of the circles superposed are proportional to the measured voltage. The arrival direction and elevation angle of the event are mentioned. The star indicates the reconstructed shower core location from the radio signal.
and nature of the primary with minimal assumptions concerning its electromagnetic shower signature.

## 2 Principle of the experiment

The CODALEMA experiment ${ }^{11}$ takes place at the radio observatory of Nançay (France). The present related setup (see Fig. 1) uses 11 log-spiral antennas (originally part of the DecAMetric array ${ }^{12}$ ) and 4 particle scintillator stations acting as a trigger (originally designed as prototypes for the PAO array ${ }^{13}$ ).

Broadband antenna signals (frequency bandwidth of $1-100 \mathrm{MHz}$ ) are amplified ( 35 dB ) and recorded in a waveform mode ( $8 \mathrm{bits} \mathrm{ADC}, 500 \mathrm{MHz}$ sampling frequency, $10 \mu$ s recording time) using a common time reference given by the trigger. Due to sensitivity considerations with those ADCs, antenna signals are band-pass filtered (24-82 MHz). Particle stations are made up of two $2.3 \mathrm{~m}^{2}$ layers of acrylic scintillator, each being read out by a photomultiplier. Signals from upper layers of each station are digitized (8 bits ADC, 100 MHz sampling frequency, $10 \mu \mathrm{~s}$ recording time). The coincidence between top and bottom layers is obtained within a 60 ns time interval with a counting rate of 200 Hz per station. The whole experiment is triggered by a fourfold coincidence from those particle stations in a 600 ns time window. The corresponding rate is around 0.7 event per minute. Considering the active area of the particle detector array of $7.10^{3} \mathrm{~m}^{2}$ and the arrival direction distribution of the particle pancake, a value of $16.10^{3} \mathrm{~m}^{2} . \mathrm{sr}$ is obtained for the acceptance, which corresponds to a trigger energy threshold of about $1.10^{15} \mathrm{eV}$.

The recognition of the radio transients is made during an offline analysis (see also Ref. ${ }^{14,} 15,16$ ). Radio signals are first $37-70 \mathrm{MHz}$ numerically filtered to detect radio transient. The maximum voltage is searched in a given time window, correlated to the trigger time, and compared to a threshold based on the noise level estimation outside this window. If the threshold condition is fulfilled, the arrival time is set at the maximum voltage and the antenna is flagged 'fired'. When at least 3 antennas are flagged a triangulation procedure calculates the arrival direction of the radio wave using a plane front. To avoid fortuitous events, a cut is applied on the arrival time difference between the radio wave front and the particle front (obtained with particle detectors) that is within 100 ns for an EAS event. Finally, true radio-particle coincidences are selected by requiring that the arrival directions obtained by both particles and radio signals are the same within 15 degrees.

Due to the low trigger threshold, only a fraction of those air shower events goes with significant radio signal. After the previous sorting, the EAS radio event rate is 0.9 per day. Assuming that the acceptance of both, particle detector and antenna array, are the same, the energy threshold of the radio events has been estimated around $5.10^{16} \mathrm{eV}$.

At the end of these analysis procedures, physical characteristics of the radio EAS events can be extracted.

## 3 Illustrative EAS event

With our limited array of antennas, the number of tagged antennas per event is highly variable, depending on the shower energy and core position. Thus, only events falling inside the surface delimited by the extremities of our antenna array can be unambiguously analyzed. The EAS event example shown on Fig. 1 is one of those. It exhibits a 11 antennas multiplicity with the associated signal amplitude measured on each antenna (depicted by the circle size). The arrival direction has been reconstructed from both scintillator and antenna data (discrepancy of 1.6 deg. between both estimations for this event) and indicates that it corresponds to a shower with a zenith angle of 51 degrees.

The electric field distribution for the above mentioned EAS event (full line) and a fortuitous one (dashed line) are shown Fig. 2, for East-West (left) and North-South (right), antenna axis. The fortuitous event belongs to a set of events identified as resulting from a single polluting source (constant arrival direction from one event to another) and rejected from EAS candidate status using the procedure described in Ref. ${ }^{6}$. The dotted line indicates the noise level of our setup and illustrate the amount of useful signal received. Antenna responses were cross calibrated and gains adjusted within a few \%.

It appears that topologies are clearly different between EAS and anthropic events. On the one side, the anthropic event (dashed line) presents an electric field topology with a soft linear decrease of the amplitude which is not expected for an EAS candidate falling in the vicinity of the array. On the other side, the EAS event (full line) shows a highly variable field amplitude depending on the position on the axis. This allows to estimate the projected core location using first barycenter calculations, then, by fitting Gaussian model. The resulting core position, similar with a relative location error of a few meters on each axis for both estimations, is pointed by a star on Fig 1.

This margin between electric field topologies depending on its origin (EAS or anthropic) could constitute one decisive criterion of selection as it comes from the antenna array only and not from a comparison to the particle detectors. In other words, it means that a radiodetection of cosmic rays experiment should be able to discriminate EAS event by itself.



Figure 2: Sampling of the electric spread. Left : Profile of the maximum voltage recorded on the antennas in the East-West direction. Right : Profile of the maximum voltage recorded on the antennas in the North-South direction. Both for an EAS event (full line) and an anthropic transient (dashed line). The dot line correspond to the noise level of the antennas.

Once the core position and the arrival direction of the shower are known, the measured electric field can be plotted in a shower-based coordinate system (instead of a ground-based one) to look at the radio signal behavior with an increasing distance from the core such as shown Fig. 3. The above event fits an exponential decay given Eq. $1^{8}$.

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\begin{equation*}
E(d)=E_{0} \cdot \exp \left[\frac{-d}{d_{0}}\right] . \tag{1}
\end{equation*}
$$



Figure 3: The electric field measured on antennas for the presented EAS event as a function of the distance between the detector and the estimated shower core location. The full line corresponds to an exponential fit of the data.
with $d$ the distance between the shower core and the detector, $d_{0}$ and $E_{0}$ the fit parameters. The result gives values for those two parameters, $d_{0}=215 \mathrm{~m}$ and $E_{0}=14 \mu \mathrm{~V} / \mathrm{m} / \mathrm{MHz}$ at 37 MHz .

## 4 Conclusion

CODALEMA is already an operating tool to detect EAS associated radio emission. It is also able to determine its arrival direction using triangulation and core position by fitting a Gaussian profile over two axis. More data and upgradings are needed to enhance the knowledge of the electric field over long distances and to calibrate the experiment in energy using additional particle detectors. Nevertheless, it is now possible to discriminate an EAS event electric field from a fortuitous one using only antennas and no particle detector. Considering the low trigger rate ( $\leq 1 \mathrm{evt} / \mathrm{s}$ ) obtained during the first phase of CODALEMA ${ }^{6}$ where the system was self-triggered using a devoted antenna, this is one further step toward a stand-alone system that could be deployed over a large area.

## References

1. N. Hayashida et al, Phys. Rev. Lett. 73, 3491 (1994); M. Takeda et al., Phys. Rev. Lett. 81, 1163 (1998).
2. D.J. Bird et al, Phys. Rev. Lett. 71, 3401 (1993); Astro-phys. J. 441, 144 (1995).
3. Auger Collaboration, Nucl. Instrum. Meth. A 523 (2004) 50-95
4. K. Green et al, Nucl. Instrum. Meth. A498, 256 (2003).
5. A. Badea et al, Proceedings of CRIS2004, Nucl. Phys. Proc. Suppl. 136, 384 (2004); astro-ph/0409319.
6. D. Ardouin et al, submitted to Nucl. Instrum. Meth. A, Astro-ph/0504297.
7. G.A. Askar'yan, Soviet Physics, J.E.T.P., 14, (2) 441 (1962)
8. H.R. Allan, in: Progress in elementary particle and cosmic ray physics, ed. by J.G. Wilson and S.A. Wouthuysen (North Holland, 1971), p. 169.
9. D. Ardouin et al, submitted to Phys. Rev. Lett., Astro-ph/0504240.
10. T. Huege and H. Falcke, astro-ph/0501580.
11. O. Ravel et al, Proceedings of the 8th Pisa Meeting on Advanced Detectors "Frontiers Detectors for Frontier Physics", Nucl. Instr. Meth. A518, 213 (2004).
12. http://www.obs-nancay.fr/ (2005)
13. M. Boratav, et al, Proceedings of the 24th ICRC, Rome, 954(1995).
14. R. Dallier et al, SF2A 2003 Scientific Highlights, ed. F. Combes, et al. (EDP Sciences, 2003).
15. A. Bellétoile et al, SF2A 2004 Scientific Highlights, ed. F. Combes et al. (EDP Sciences, 2004), astro-ph/0409039.
16. D. Ardouin, et al, Proceedings of the 19th European Cosmic Ray Symposium, Florence, 2004, astro-ph/0412211.
