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Radio Detection of Cosmic Ray Extensive Air Showers

Dallier R., Denis L., Gousset T., Haddad F., Lautridou P., Lecacheux A., Morteau E., Ravel O., Rosolen C., Roy C.

Abstract

At the Radio Observatory of Nançay we study the possibility of detecting extremely high energy cosmic rays by radio detection of the electromagnetic pulse radiated during the development of extensive air showers in the atmosphere. Details on the experimental setup and present results on the demonstrative experiment CODALEMA are given .

1 Motivation

In order to demonstrate the existence of radio emission by extensive air showers (EAS), various experiments have been led in the 60's (Linsley 1963, Jelley 1966, Weekes 2001). These investigations were almost completely withdrawn before the end of the 70's, due to the increase of anthropic radio emissions, difficulty of interpretation of recorded signals and poorly adapted electronics (see Allan (1971) for a review of this period). In the late 90's two experimental systems have again been developed (at the CASA-MIA site (Green et al. 2003) and at the KASCADE site (Falcke and Gorham 2003)). In both cases, the antennas are triggered by a particle detector array. No clear evidence for radiofrequencies transients associated with EAS was found by Green and collaborators, indicating that only primary particles above 10^{17} eV were detectable with their setup at CASA-MIA. First results of simultaneous detection on KASCADE and LOPES are expected for 2004 (Horneffer et al. 2003).

Different mechanisms of electromagnetic pulse generation have been identified (Allan 1971). Among them, though not dominant, is the negative charge excess in the shower. This contribution to the total electric field depends only from the charge distribution and can be easily estimated (Ravel et al. 2003). For instance, with a primary particle energy of 10^{20} eV, a vertical shower with an impact parameter of 1 km produces via this mechanism an electric field reaching $300 \mu\text{V}\times\text{m}^{-1}$, with a time width of about 300 ns. Such an electric pulse is potentially measurable on the ground with an antenna. Furthermore, a determination of the pulse waveform may enable one to unfold the charge profile of the shower, while triangulation using at least 3 antennas allows one to extract the location of the shower axis.

2 The CODALEMA demonstrative experiment

Taking into account the time characteristics of the electromagnetic signal, a high sensitivity, low directivity antenna with a frequency bandwidth extending from a few hundreds of kHz up to 100 MHz is the best choice. To deduce the primary particle energy and its trajectory from a radio air shower signal, a minimum of 3 antennas is required. Considering those specifications, the DecAMetric array of the Radio Observatory of Nançay (DAM, <http://www.obs-nancay.fr>) is very well suited. The DAM is made, on a 85 m side square, of 9×16 (144) log-periodic, spiral-shaped conic antennas, whose gain is + 3 dB in the band 1-100 MHz and over a wide directivity diagram (90° angle lobe).

CODALEMA (Cosmic Detection Array with Logarithmic ElectroMagnetic Antennas) is a demonstrative experiment which aims at studying whether a self-triggering radio detection system of cosmic ray air showers is possible. This means that no particle detector is used : one antenna equipped with a dedicated electronics is devoted to trig the signal in a pulse limited bandwidth with a threshold discriminator. We use the 4 corners antennas of the DAM and an additionnal one, installed in the middle of the northern side (Fig. 1). Signals from each antenna come through co-axial wires of equal lengths (150 m). At last, a distant antenna, located 1 km eastbound, and whose signal is transported via an optical fibre, have been installed to serve as a test for a future long-based array, and to check the capability of a fibre link.

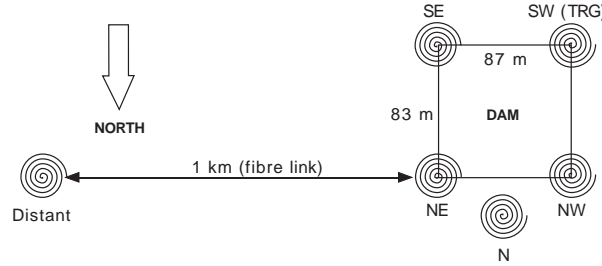


Figure 1: *Current CODALEMA setup.*

For each antenna, the electronic line is constituted by a high gain amplifier (+36 dB), a low loss 150 m wire, followed by a high-pass filter (above 400 kHz, filtering AM radio transmitters). On the distant antenna, an optical transceiver is added and acts as a high-pass filter above 10 MHz. Provided that an adapted bandpass filter (33-65 MHz) is added, any of the 5 DAM antennas may be chosen as the trigger. This filter band was chosen after a study of background noises (mainly, radio broadcasting stations and many other anthropic transmitters, either periodic or sporadic). After a trigger event, the signals of the antennas are recorded using 2 GHz digital oscilloscopes (8 bits ADC, 2 GS/s, 10 μ s long signal), and are stored on disk for off-line analysis.

3 First results

To discuss the analysis as it is presently envisaged, Fig. 2 displays a simulated particle signal with a duration of the order of 100 ns (Ravel et al. 2003) and the effect of filtering in the 0.5 - 9 MHz and 33 - 65 MHz bands. For the latter, one can see the highly oscillating response, due to the filter. Though filtering in this band allows one to cancel numerous radio noises, and thus increases overall dynamic of the signal, it appears impossible with these informations alone to infer the real shape of the original signal. However, this filter band is compatible with a correct time tagging for the event, while a lower band filtering could give informations on the received power.

A typical 6 antennas coincidence signal is shown Fig. 3. After an analysis of time delays, arrival direction can be reconstructed. This event comes from a clear E-SE direction, which is not compatible with identified sources of noise. Undoubtly, it presents a wide frequency spectrum, with components both in high (33-65 MHz) and low (0.5-9 MHz) frequency bands, as expected from an electromagnetic pulse (Ravel et al. 2003).

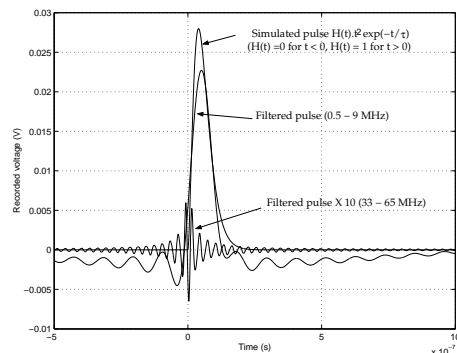


Figure 2: *0.5 - 9 MHz and 33 - 65 MHz filter responses for a simulated pulse.*

At last, the sensitivity of CODALEMA has been measured with the dedicated noise generation system of the DAM. This system delivers a signal whose level is similar to the sky background level on the instrument. This signal is injected in place of the trigger antenna's signal. In the 33-65 MHz band, such a signal produces a $500 \mu\text{V}$ rms signal on the oscilloscope, and can be easily digitalized by the ADC. This corresponds to an electric field amplitude of $2 \mu\text{V} \times \text{m}^{-1}$ in the trigger band. Thus, CODALEMA is sensitive to the sky background at these frequencies.

At this development stage, CODALEMA is able to detect any electric field transient above sky background level. We have also identified many anthropic noise sources, of which some can easily be removed. Main analysis investment is now put on wide band signal reconstruction, particularly by the use of an adaptive filter algorithm, and on the trajectory reconstruction.

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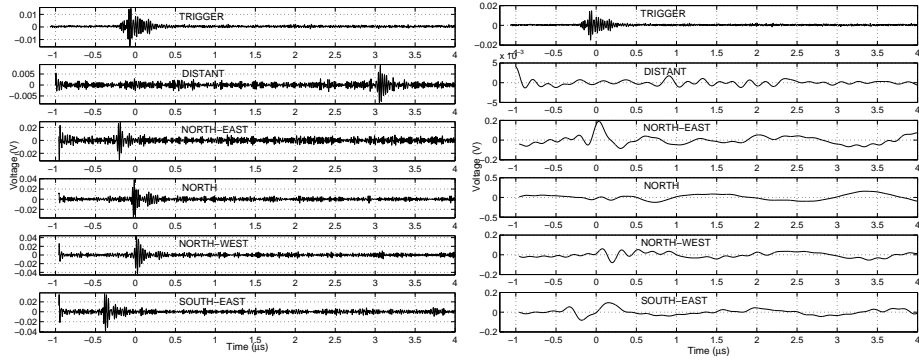


Figure 3: *Coincidence transients detected with CODALEMA. Left : signal after 33-65 MHz numerical filtering. Right : after 0.5-9 MHz numerical filtering. From Top to Bottom : trigger, distant (1 km), NE, N, NW and SW antennas respectively. No signal is expected in the 0.5-9 MHz band for the distant antenna, because of the cutting edge of the fibre optics transceiver at 10 MHz. No low frequency signal is observed here for the Northern antenna. Time delays are compatible with an E-SE direction of the event.*