



## CODALEMA : A Cosmic Ray Radio Detection Array

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**Abstract:** Extensive air showers are associated with transient radio emission, which could provide a new mode of detection of UHECR with an important target volume and a high duty cycle. The Codalema experiment has been set up and is running in the Radio Observatory in Nançay, France, to investigate this possibility. The apparatus is composed of an antenna array overlapped by a ground particle array. A set of 16 wide band active dipoles are aligned on two 600 meter long baselines in the North-South and East-West directions. This radio array is triggered by a ground detector of 240 meters square containing 13 plastic scintillator stations. The antennas and scintillators are wired to a central data acquisition system where all the signals are processed. Radio signals are recorded in a large 1-200 MHz bandwidth, while favorable signal to background ratio is looked for in a narrower band around 50 MHz. In this band, the natural sky background on site almost free from anthropogenic radio frequency interferences allows a sensitivity to showers with energy around  $10^{17}$  eV. In this paper we shall present the set-up, simulation, calibration, sensitivity and performance of both arrays, and some illustrative coincidence events will be discussed.

## Introduction

Radio emission of cosmic ray air shower was predicted and observed almost fifty years ago [1]. In recent years, investigations in radio detection was revived by technological developments in electronics and computer sciences allowing the onset of fast digital radio astronomy. Large detection volume, high duty cycle, calorimetric information, together with the expected low cost per detection unit, are the main potentialities in radio observation of High Energy Cosmic Rays in very large array observatories. The Codalema research program aims to the characterization of the Extensive Air Shower radio profile, by measuring simultaneously the particle and radio contents of the EAS in a hybrid mode. EAS can be described as a rapidly evolving bulk of charges dominated by its electron-positron content. According to Lienardt-Wiechert theory, the delayed potential created at an observation distance  $R$  from the moving source, and after proper Lorentz transformation, gener-

ates a strongly focused electromagnetic field. The main contribution to this field comes from geosynchrotron emission from particles propagating in the earth magnetic field. In the time domain, the observed signal at  $R$  should behave like a pulse whose duration and amplitude are governed by the size and location of the shower. In the frequency domain it should behave as a decreasing frequency spectrum from few MHz to hundreds depending upon the degree of coherence of the source. The field polarization is dependent on the topological aspect of the shower, seen by the receiver. Its intensity, to be determined, should lie around  $2\mu V/m.MHz$  at 50 MHz for a  $10^{17}eV$  shower. The present objective of radio detection is to obtain the most achievable characterization of the shower radio emission content with shower location, direction and size. For this purpose two sets of overlapping detection arrays were deployed on the site of the Radio Observatory in Nançay, France. The radio detection array consists in 16 dipole antennas deployed on two half kilometer

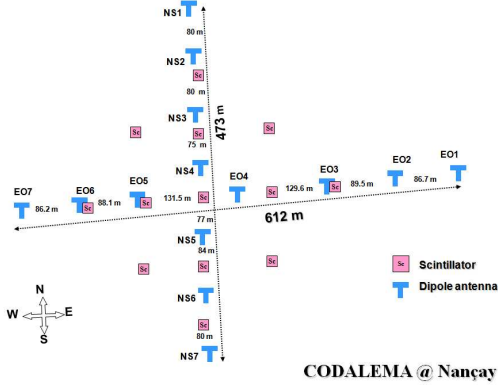


Figure 1: Codalema Array Lay-Out in Nancy

long arms , it is associated with 13 Scintillation detectors filling a  $240 \times 240$  meter square array to measure the ground particle content of EAS.

## The Ground Particle Detector

Each station includes a thick plastic scintillator seen by two photomultipliers all inserted in stainless steel box, finally housed in a  $1m^3$  plastic container for weather protection. The two photomultipliers XP3462 have their high voltage supply set to work at different gains (high gain (HG) and low gain (LG)). in such a way to have an overall dynamics of the order of 400 VEM, switching the signal analysis from HG to LG when the HG is near saturation. The trigger logic signal is taken from the discriminated HG photomultiplier with a threshold corresponding to 0.3 VEM. The information on charge and timing are extracted from the digitalized signal by fitting the recorded pulse shape. EAS arrival direction is obtained using the time of flight between different stations, after signal transit time correction and assuming a plane shower front. Shower size and core position are calculated from the measured particle densities in detectors whose positions are projected in the plane perpendicular to the arrival direction. This lateral distribution is fitted and compared to the theoretical NKG lateral distribution via a minimization algorithm. Core position and shower size are extracted, then back projected in the detection plane and stored for further use. Simulations show

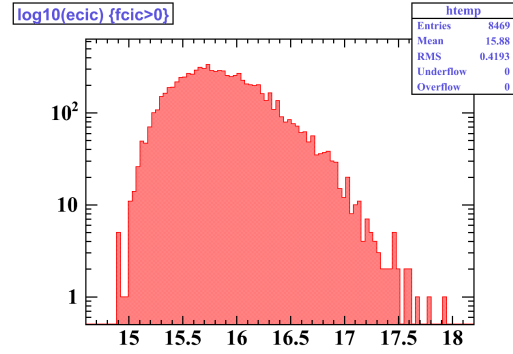


Figure 2: Energy spectrum for internal events

that a reasonable precision on both core and size is obtained mainly for internal events; external ones are overestimated.

Only internal events will be used as reference events for comparison with the Radio signal content of the shower. These internal events are selected by asking for a larger particle density in internal detectors than in surrounding ones. The estimation of the shower energy is simulation-dependent due to internal fluctuations. We used the Constant Intensity Cut (CIC) method to define a Vertical Equivalent Shower Size  $N_0 = N(\theta = 0, E)$  with an experimental attenuation length close to  $190g/cm^2$ . From Aires simulations the energy is related to  $N_0$  by  $E = 2.14 \times 10^{10} \times N_0^{0.9}$ , with a resolution of  $\frac{\Delta E}{E} \approx 32\%$  at  $E = 10^{17} eV$ .

## The radio antennas

In Nancy the first attempt to detect radio signals in coincidence with ground detectors was realized successfully by using few of the conic logarithmic antennas taken away from the 144 phased antennas of the Decametric Instrument [2]. However their huge size (6m high, 5m wide) prevented any further utilization as a fast and cheap element to be deployed later on in an open field array dedicated to UHECR detection. Emphasis on simplicity, size, cost and performance was used as guidelines to develop a new broadband antenna concept. A short active dipole was designed under these prescriptions [3]. It is made of two 0.6 meter long and

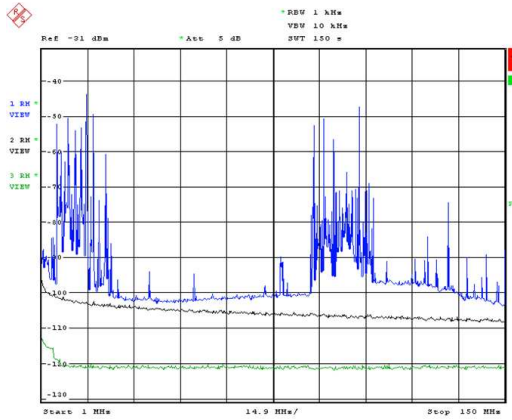


Figure 3: 1-150 MHz Radio frequency spectrum (dB/Hz) measured on site with dipole antenna. The amplifier electronic noise is superimposed together with the spectrum analyzer noise (green).

0.1 wide aluminium slats, separated by a 10 mm gap. It is held horizontally at 1m above ground by a plastic mast. This antenna is loaded by a high input impedance dedicated low noise 34 dB amplifier whose 3dB bandwidth is 100kHz-220 MHz. The antenna equivalent Thevenin circuit, impedance measurements and simulations allowed to extract the antenna complex Effective Length characterizing the antenna open-circuit voltage  $V_o$  response to an incident field  $E$ . The Effective Length is constant for low frequencies, and the directivity gain stays almost isotropic.

The designed length and thickness of the poles, the connections and the matched capacitive transmission make the dipole resonating around 115 MHz with a low Q value. This results in a smoothly and slowly varying numeric gain over a wide band from 1 to 100 MHz. Above resonance, the inductive behavior dominates and the gain drops, nevertheless in accordance with the amplifier bandwidth. Validation of the dipole antenna concept was obtained in two main ways: observation of sky radio sources, and sensitivity to the galactic noise via sky background spectrum measurement. Background was measured on site with different reference antennas. While anthropic sources are clearly observed below 20 MHz and in the 88-110 MHz FM band, the background in-between is rather quiet, compatible with the galactic noise

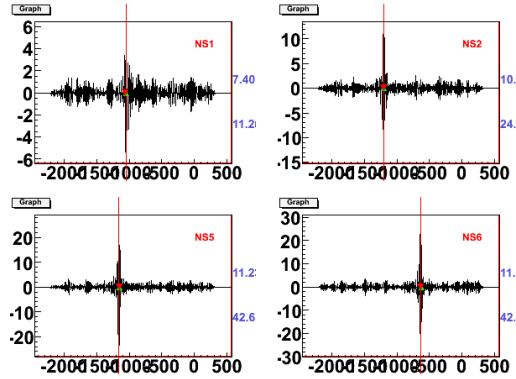


Figure 4: Radio event Filtered signals (in mV) on several antennas. Shower front expected signal location is shown by small triangles.

observation, and above the electronic noise. The 25-85 MHz band is then the most suitable band to look for transient cosmic ray events. In this band where the signal to background ratio is the most favorable, filtered signals were used to tag the hit antennas.

## Data acquisition and Processing

Signals from both array detectors are directed to 7 + 4 chained VME-based data acquisition cards [4]. Each card performs the fast 12-bits digitalization of 4 channels with 300 MHz analog bandwidth. The operational sampling rate is 1Gs/s and with a memory depth of 2560 points stored, and read in  $650\mu s$  for the 4 channels. The sampling allows a  $2.5\mu s$  signal analysis, and the 12-bit coding of a maximum excursion at 1 Volt analog input defines the  $LSB = 250\mu V$ . The noise measured at input is less than  $200\mu V$  RMS. In the present case, all the cards are externally triggered by a distributed NIM signal generated by a dedicated circuit based on a 16-fold multiplicity circuit where the 13 HG PMT signal are input. The remote controlled multiplicity level is set to 5 in running conditions with a gate width of 600 ns. Triggering on the central five detectors leads to an event rate of 8 events/hour.

The acquisition readout and data storage is realized via GPIB interface to two physically inde-

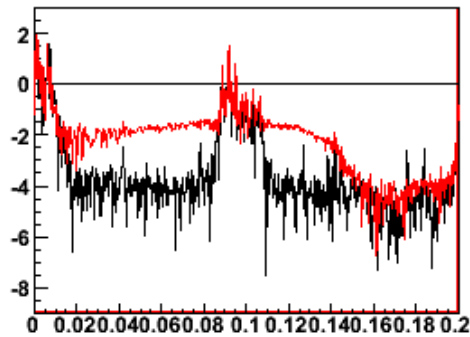


Figure 5: Unfiltered Radio event Signal power spectrum (red) compared to background recorded few minutes later (black) on antenna EO6 for shower at  $E = 2.1 \times 10^{18} eV$  located at (N,W)=(50m,249m)

pendent commercial PCs running under LabVIEW platform, one for the ground detector the other for the antennas. The event files are stored on site in ASCII format and transferred once a day to the Observatory database in Paris. The events on both PCs are synchronized via an external clock from the Observatory server. Ancillary equipments such as a weather station are read for every trigger. To minimize bias in the process, the analysis from the two array data files are performed separately and independently [5]. The two sets of events are folded in one large event by using only the event time tagging. Antenna signals are unfiltered and stored in full band. After a FFT transform is performed, the antenna signals are digitally filtered in the proper frequency band (23-85 MHz) and then inverted back in the time domain. Detection of a pulse at  $5\sigma$  level is used as a time tagging on each antenna; a radio event is identified as hitting 3 antennas at least (figure 4). At the same time the corresponding fullband frequency spectrum exhibits the magnitude and shape of the signal compared to background (figure 5). The narrow angular and time coincidences between the radio and particle wave fronts (figure 6) validate the event.

## Conclusion

The principles of the Codalema Radio detection Array were presented. Radio signals are clearly

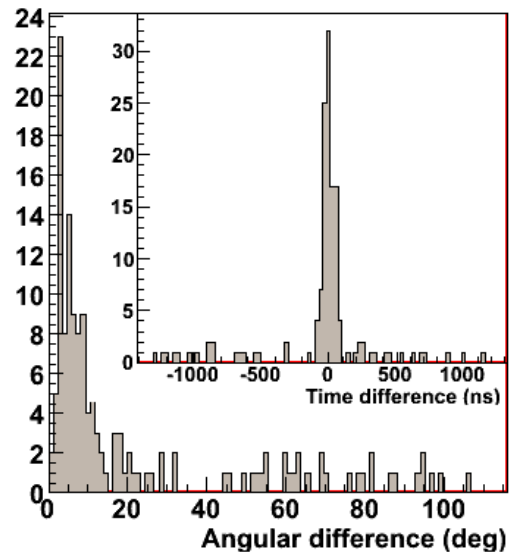


Figure 6: Particle and Radio Wave Front Angular and time differences

observed related to shower detection via a ground particle array. Very simple short dipole antennas are sensitive to shower energy below  $10^{17} eV$ , results will be presented elsewhere in this conference. Future developments concern the area size, the radio self-triggered mode and the antenna wireless autonomous mode.

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