Radio signature of extensive air showers observed with the Nançay Decameter Array

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***Abstract*. The Nançay Decameter Array (DAM) is a high gain, broadband antenna array made of 144 helix spiral, conical antennas, sensitive to both senses of circular polarisation and distributed over a square of 100m×100m. The instrument was integrated into the CODALEMA experiment in mid 2007 and several hundreds of radio events have been recorded, in synchronism with other CODALEMA detectors. The DAM data statistically confirms the characteristics already found by using the CODALEMA cross of dipoles, but also brings new elements. Thanks to its beam forming capability, the DAM appears to be substantially more sensitive to lower energy events ($5\ 10^{16}$ eV and below), but reaches 100% efficiency at same level ($5\ 10^{17}$ eV and above). The observed events deficiency in the direction of the local geomagnetic field confirms that this effect is not due to a simple polarisation effect, since the DAM helical antennas should not be too much sensitive to the orientation of the incident electric field. In some cases, strong variations of the measured electric field (by one order of magnitude, typically) and well below the 100 m spatial scale, could also be noticed. Shower core locations deduced from radio measurements differ from those deduced from particle analysis.**

***Keywords*: cosmic rays, radio astronomy, extensive air shower.**

I. Introduction

Cosmic ray induced extensive air showers (EAS) generate radio electric fields that become measurable beyond $3\ 10^{16}$ eV. Recent monitoring observations of this phenomenon were made by CODALEMA [1] and LOPES [2]. Preliminary results were also obtained in Argentina [3], [4]. These developments aim at gauging the interest of the radio technique for detecting air showers and its application to the field of ultra high energy cosmic ray research. An important milestone resides in the understanding of the signal and its main characteristics, notably the electric field generation mechanism. To succeed, the design of the most effective radio astronomy instrument, suitable for air shower studies, remains to be carried out. Here we report on the performance of a conventional (phased array) radio telescope for such a study.

II. Instrumentation

The Nançay Decameter Array (DAM) [5] is a high gain, broadband antenna array dedicated to solar and planetary radio astronomy. It is made of 144 conical helices of the type used at Clark Lake radio Observatory [6], filling a square aperture of about 100m×100m. This elementary antenna is known to be well adapted to continuum (wide band) radio astronomy, because of its nearly constant gain over a very large range of frequency (10-120 MHz). It appears also very well adapted for searching broadband radio signals associated to cosmic rays.

The antenna array is divided in two half parts of 72 antennas (6×12 in E-W and N-S directions, respectively), wound in opposite senses, giving two sub-arrays with the same characteristics but sensitive, in the main beam, to opposite circular polarisations. Each polarised half-array is further divided in a phasable, regularly spaced, 3×3 matrix of 8 antenna sub-arrays (2×4 antennas in E-W and N-S directions, respectively), allowing for a two-stage phasing scheme, in order to maximize both tracking time and instantaneous bandwidth in observing radio sources (see [5] for further details).

In normal radio astronomy operation, after a first step, analogue beam forming at each sub-arrays, the synthesis of the main telescope beam is achieved by using analogue delay lines between the 18 sub-arrays and receivers cabin. In cosmic rays operation, the delay lines are simply by passed. The 18 sub-array signals are further sampled at 400 MHz, then digitized by using fast, 12 bits ADC boards, with a memory depth of 2560 points (corresponding to 6.25 μs). The acquisition start is triggered by the CODALEMA particle detector array, as described in [9], in exact synchronism with the CODALEMA 24 dipoles radio array.

This procedure allows cosmic rays operation to be carried out continuously without hindering the normal radio astronomy program of the DAM instrument. The drawback for cosmic ray operation is the reduction of the useful instantaneous bandwidth (the signal direction being not, in general, aligned with the main beam of intermediate sub-arrays), which precludes, at the moment, any spectral study of the cosmic ray radio signal.

III. Comparison with CODALEMA dipoles

The cosmic ray events recorded by DAM instrument display overall radio signatures quite similar to those recorded by the dipole array. The layout of the CODALEMA experiment is shown in Fig. 1. The DAM

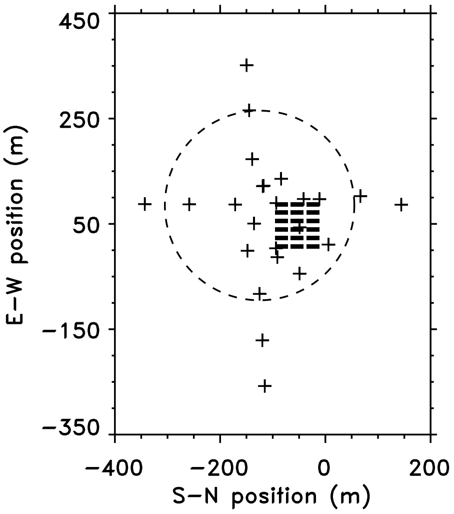

Fig. 1: Layout of the CODALEMA experiment showing the 24 dipoles (crosses), the 18 DAM elements (black rectangles) and the area (dashed circle) delimiting core footprints of the events reconstructed from surface detector array measurements.

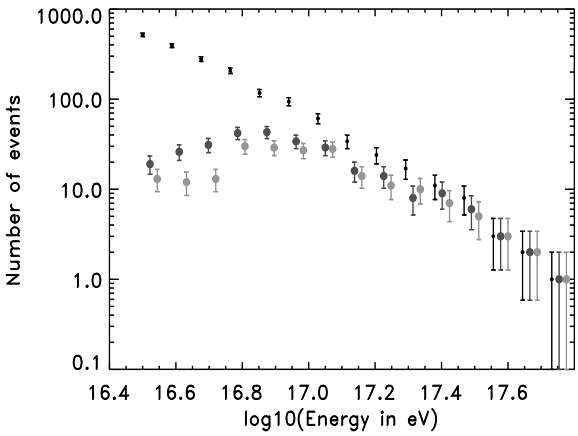

Fig. 2: Distribution of detected air shower as a function of the logarithm of the primary energy estimated with the particle detector array. Thin black dots correspond to the particle detector dataset, large black dots to the DAM array and large grey dots to the dipole array. Bins in energy of DAM and dipoles dataset have been shifted by respectively one third and two third of the bin width to avoid overlaps.

(black rectangles) is displaced by about 100m towards North-East from the surface detector centre.

The comparison was done by studying a set of 2454 events recorded by particle detectors at primary energies larger than $3\ 10^{16}$ eV and whose axis footprints were included within the surface detector area (dashed circle). The last condition allows shower reconstruction from surface detectors data to be reliably performed ([8]). Among those shower events, 353 were detected in radio.

A. distribution in primary energy

Both radio arrays, DAM and dipoles, exhibit a similar behaviour (Fig. 2). The relative efficiency of radio with respect to particle detection, as already well documented (for instance [8]), is rather poor (about 3%) at log10(E) = 16.5 , then it steadily increases to reach a 100% relative efficiency at log10(E) = 17.5 and above.

B. distribution of shower axis directions

DAM data allows the apparent “direction of arrival”, i.e. the direction of radio shower axis, to be reconstructed in the same way than from CODALEMA dipoles data (see, for instance, [10]), but with a lower angular accuracy because of the smaller baseline of the instrument. Nonetheless, all determinations of shower axis directions (from DAM, dipoles or particle detectors) were found in close agreement. Fig. 3 is very similar to the one obtained from the CODALEMA dipole array ([8], [1], [7]). In addition to the limited range of observed zenith distances - mainly due to vertical acceptance of particle detectors -, it exhibits a significant North-South asymmetry, whereas the flux of cosmic rays triggering the particle detectors is clearly isotropic (as expected at this energy range).

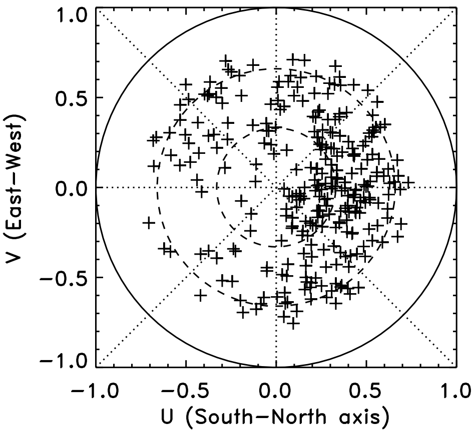

Fig. 3: Direction of radio events detected with DAM array, in projection on the ground (North, West, South, East correspond to right, upper, left, lower sides, respectively).

This confirms the geomagnetic dependence of the electric field emission, which has also been observed by other experiments.

IV. NEW FINDINGS

However, when studied more in details, the DAM events display some significant differences with respect to CODALEMA dipoles events. Among the total 353 radio events studied, 138 were detected by both DAM and dipoles. In addition, 69 events were seen by the dipole array only: this can be well explained by the larger area covered by the dipole array, since the electric

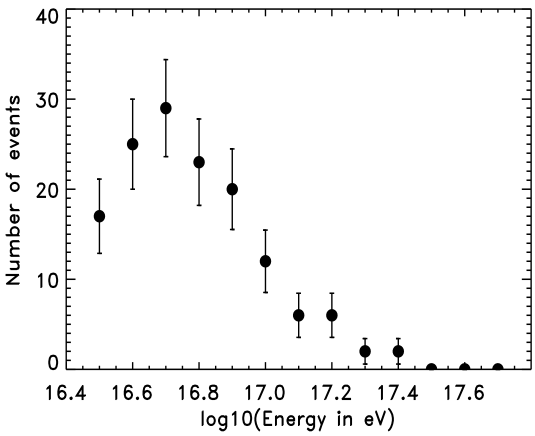

Fig. 4: Radio events detected on DAM array only (i.e. not seen by dipole antennas) are plotted as a function of the primary, estimated energy.

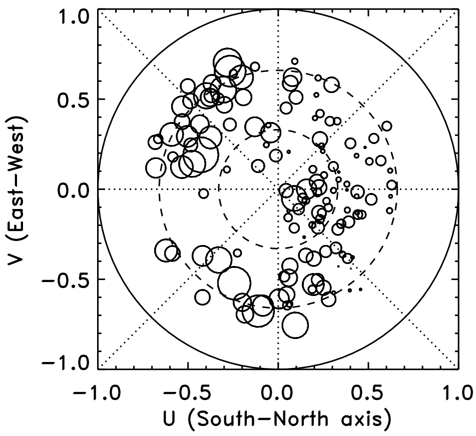

Fig. 5: Direction of radio events that were detected by DAM array but not by dipoles (North, West, South, East are on right, upper, left, lower sides, respectively). For each event, the symbol (circle) size is proportional to the logarithm of the primary, estimated energy.

field amplitude of shower signals is known to rapidly decrease with the distance to shower axis ([8]).
On the other hand, 146 events were seen by the DAM only. This likely is a consequence of the higher sensitivity of DAM elementary antenna, of its polarisation and, maybe, of the smoothing over the DAM instrument aperture, of the electric field inhomogeneity, found - somewhat surprisingly - to occur at short spatial scales.

A. More DAM efficiency at low energy

When looking more carefully at Fig. 2, one can note the higher efficiency of DAM at primary energy below 10^{17} eV. This is illustrated by Fig. 4, in which the histogram of the 146 DAM events in excess with respect to dipoles is displayed as a function of the primary energy. This distribution illustrates the different behaviours of both arrays. Below log10(E) = 16.7, a relatively large number of events are seen on the DAM array only. The DAM efficiency increases regularly until log10(E) = 16.7 whereas the dipole one remains constant. Between log10(E) = 16.7 and log10(E) = 17.5, the dipole array efficiency begins to increase but the DAM array remains slightly more efficient. Finally, at log10(E) = 17.5, both arrays reach 100% efficiency relative to particle detectors.
Indeed, the maximum response of CODALEMA active dipoles ([9]) is located at higher frequency than the one of DAM, log-periodic antennas. Therefore broadband radio signals, with highly negative spectral indices - as shower signals are thought to behave -, should therefore be easier to detect by using DAM antennas. Lower will be the level of the shower signal relative to galactic background, more pronounced will be the effect.

B. Better definition of v x B = 0 minimum

When comparing Fig. 3 with, for instance, the figure 5(top) in [8], one can note that the southern sky half hemisphere is substantially more densely filled up by the DAM than by dipoles. This is illustrated by Fig. 5 where the arrival directions of the DAM events in excess are displayed together with their amplitudes. Two populations can be identified from Fig. 5. The first one is made up of low energy events coming from the North, where the electric field emission process is expected to be stronger. The electric field associated to those low energy events was large enough to be detected by the DAM, log-periodic antennas but not by the CODALEMA dipoles which are less sensitive. The second population contains higher energy events coming from south-east and south-west directions. At this energy, the dipole array does detect some events but incoming mainly from the north direction. This is due to the fact that only East-West polarized dipoles were used to detect those events. On the contrary, the DAM antennas are insensitive to linear polarisation direction (i.e. “circularly” polarized) in the plane orthogonal to the geomagnetic field vector. Thus they might offer the possibility to explore a much larger range of direction of polarization.

C. Electric field inhomogeneity at short spatial scale

As described in section II, the DAM array is sampling the electric field of shower signal over a square of less than 100m$\times$100m at 18 sub-array locations, spaced by 30m and 16m along North-South and East-West directions, respectively. The size of an individual sub-array (8 helix antennas) is 22.5m$\times$6.5m. Within the used filter bandwidth (24-88 MHz), each sub-array has identical characteristics (within at most 0.5 dB $\approx$ 10%), as regularly checked by using radio astronomy calibrators. However, the observed events often exhibit significant variations (up to one order of magnitude) of the electric field amplitude measured at each sub-array. Fig. 6 displays a representative example of such an observed electric field inhomogeneity: the height of the bars is

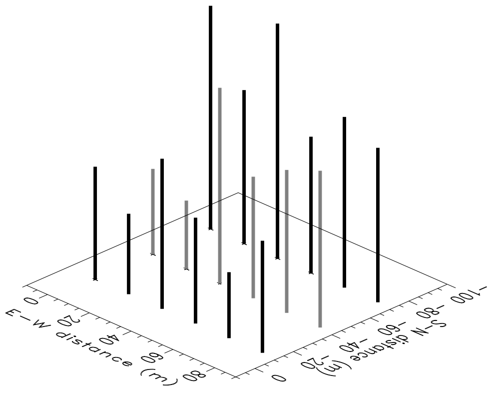

Fig. 6: An example of electric field inhomogeneity at spatial scale well below 100m. Each bar represents the amplitude of the signal (linear scale) measured at the positions of each of the 18 DAM sub-arrays. The South-West direction is backwards relative to the page.

proportional to the measured signal amplitude in units of galactic background amplitude. The corresponding shower, of 3 10^{17} eV primary energy, was hitting the ground $\approx$ 250m south-west of DAM array centre. The shower was coming from the North, at 71° elevation above horizon. Note that the general trend in amplitude signal is consistent with the expected (and measured by dipoles) decrease along S-W to N-E direction (from behind to ahead, relative to the page plane).

D. Shower core locations

The last result was obtained statistically. Assuming that a lateral intensity distribution should also exist in radio, - at least in average -, such a distribution was computed by averaging the measurements of all observed events (18×284 with the DAM) at antenna locations within the "particle" shower reference frame, defined as having its z-axis along the shower axis, its x-axis contained in the meridian plane and being centered at the surface detector centre. In this frame, it is well known that the particle counts exhibit a well centered distribution. As displayed in Fig 7, the radio signal intensity appears to be displaced from the shower centre by about 50m eastwards.

V. SUMMARY AND PERSPECTIVES

We have reported on monitoring observations of radio signals produced by air showers at primary energy ranging from 10^{16} to 10^{18} eV, by using, for the first

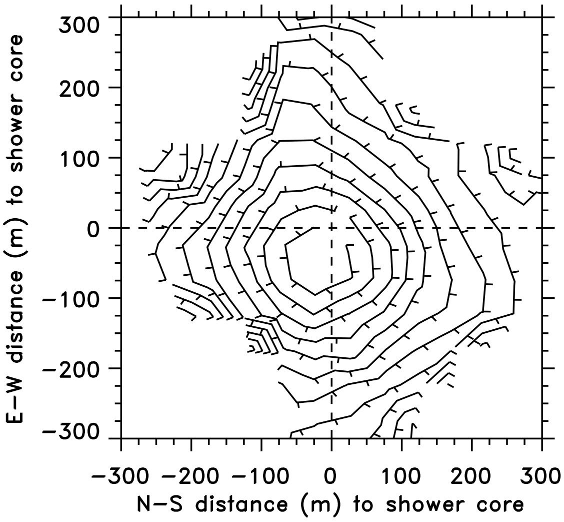

Fig. 7: Electric field amplitude, averaged over the 284 events seen by the DAM instrument, and displayed in the particle shower reference frame, in projection on the ground. Isocontours range from about 2 to 4 times the sky background level. The South is at left, East at bottom.

time, a conventional (phased array) radio telescope, the Nançay Decameter Array.

We have shown that the obtained measurements well complement and sometimes outperform those provided by research prototypes of radio detectors. The gained experience will certainly be used in the follow up of CODALEMA experiment.

In particular, the obtained results have shown the importance of getting a more complete description of the air shower electric field topology. That is, measuring its three components at a given location, as well as varying the measurement point at various spacing and locations over the extent of the shower. On the other hand, the relationship between the particle counting at ground by surface detectors and the full development of the shower through the atmosphere, which is potentially contained in the radio signal, has to be further investigated.

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